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NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

Note: There is an Addendum to this publication containing the PowerPoint presentations.

RTO MEETING PROCEEDINGS 63

Systems Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces

(Concepts de systèmes pour la défense aérienne intégrée de forces internationales mobiles d’intervention en situation de crise)

Papers presented at the Systems Concepts and Integration Panel (SCI) Symposium held in Valencia, Spain, 22-24 May 2000.

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14. ABSTRACT

The meeting proceedings from this symposium on ?System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces? was organized and sponsored by the Systems Concepts and Integration (SCI) Panel of the Research and Technology Organization of NATO in Valencia, Spain on 22 to 24 May 2000. The symposium?s goal was to describe techniques and technologies viable for the lay-out and design of operational air defense systems that meet multinational requirements. The papers were presented under the following headings: ? Description of typical scenarios ? Enabling Technologies for Air Defense Systems ? Sensors (IR, RADAR, UV, LASER) ? Sensor Fusion ? Pointing and Tracking ? Soft Computing, Information Processing ? High Level knowledge-based (KB) Automation ? Data-Link, communication ? System Architecture and Mechanization ? Man-Machine Interface, Visualization techniques ? Interface with Weapon Systems and higher level Battlefield Management ? Systems Design for Interoperability

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air defense; military mobility; airborne operations; integrated systesm; international cooperation; command and control; information systems; armed forces procurement; joing operations; air surveillance; interoperability; crisis management; systems engineering; battlefields; weapon systems; aerial reconnaissance; threat evaluation; NATO; multisensors data fusion knowledge bases; military communication; C4ISR (Command, control, Communication, Computer, Intelligence, Surveillance and Reconnaissance); Multinational forces

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The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS Studies, Analysis and Simulation Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Systems Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces

(RTO MP-063 / SCI-085)

Executive Summary

The subject of the symposium on “Systems Concepts for Integrated Air Defence of Multinational Mobile Crisis Reaction Forces”was very timely with the current NATO multinational air operations in the Balkans. A different approach was followed for the conduct of the paper presentations. Each session of the symposium started with a presentation of the panel’s perspectives and ended up with a presentation of the rapporteur’s summary remarks and closing comments about that session. A total of 19 papers were presented during the symposium with an additional four presentations of the panel perspectives. The keynote address on “Air Defense Opportunities and Challenges for Expeditionary Forces” summarizing all the major issues and the basic trends in air defense for the new millenium. Six papers were presented during the first session on Systems Concepts, covering various aspects of air defense. Four papers were presented during the System Architecture session which were all related to the future air defence system architectures. The third session had six papers related with the integration aspects of the air defense systems. The last session of the symposium was on Interoperability with four paper presentations on the interoperability aspects of air defense systems.

The panel’s perspectives on system architectures revealed some important aspects related to the integrated air defense. Command, Control, Communications, Computer, Intelligence, Surveillance and Reconnaissance (C4ISR) was pointed out as being one of the major issues of the information systems directly supporting the military operations. It is also stated that the C4SIR architecture frame work should embody the operational, the systems and the technical views of an information architecture with defined set of products describing each view. The panel’s perspectives on the systems’ integration focused basically on the system integration at the level of defence acquisition with particular emphasis on the systems of systems approach. The concept of “smart procurement” is introduced as a result of various factors such as cost over runs and slippage, increasing complexity and diversity in defense systems and rapidly changing structure of the defense industry. The smart procurement life cycle is introduced to ease the acquisition of large-scale battlespace systems of systems which can be perceived to be of autonomous or semi-autonomous subsystems in implemented operational terms. This has to be a fully integrated, functionally-based systems of systems concept, yet flexible to allow the evolution of the system to accommodate component obsolescence, technology inserts, etc. Hence, the acquisition cycle is smarter to control programme costs whilst taking advantage of the evolutionary opportunities for system capability provided by technology inserts. The panel’s perspectives on mission management and interoperability put forward the concept of systems of systems for integrated air defense systems and the elements of mission management. Technology push and demand pull of the military community are evidenced to reach the goals for mission system development. The life cycle of a system starting from transformation of goals into process modelling, then to systems and finally to its management are detailed in order to reach a specific goal. The architecture of the mission management function is given in relation to integrated military mission systems. Finally, the application of these concepts to air defense operations and automation are detailed.

Concepts de systèmes pour la défense aérienne intégrée de forces internationales mobiles d'intervention en situation de crise

(RTO MP-063 / SCI-085)

Synthèse

Le thème du symposium sur “Les concepts de systèmes pour la défense antiaérienne intégrée de forces mobiles internationales d'intervention” était en prise directe avec l'actualité des opérations aériennes internationales de l'OTAN dans les Balkans. Une démarche originale a été adoptée pour la présentation des communications. Chaque session du symposium a débuté par la présentation des perspectives de la commission et s'est achevée avec la présentation des remarques sommaires du rapporteur et les mots de clôture de la session. En tout, 19 communications ont été présentées pendant le symposium, avec, en plus, 4 présentations de perspectives de la commission. Le discours d'ouverture sur “ les possibilités et les défis dans le domaine de la défense antiaérienne pour les corps expéditionnaires” a résumé les questions principales et les grandes tendances dans le domaine de la défense antiaérienne pour le nouveau millénaire. Six communications ont été présentées lors de la première session sur les concepts de systèmes, couvrant différents aspects de la défense antiaérienne. Quatre communications en relation avec les architectures des futurs systèmes de défense antiaérienne ont été présentées lors de la session sur les architectures de systèmes. La troisième session était composée de 6 communications concernant les aspects intégration des systèmes de défense antiaérienne. La dernière session du symposium était axée sur l'interopérabilité, avec 4 communications sur les aspects interopérabilité des systèmes de défense antiaérienne.

Les perspectives de la commission sur les architectures de systèmes ont dévoilé des aspects importants de la défense antiaérienne intégrée. Le commandement et contrôle, les communications, l'informatique, la surveillance et la reconnaissance (C4ISR) ont été signalés parmi les questions les plus importantes affectant les systèmes d'information dédiés au soutien direct des opérations militaires. Il a également été constaté que le cadre de l'architecture C4SIR devrait incorporer les aspects opérationnels, techniques et systèmes d'une architecture d'information proposant un jeu de produits bien défini pour chacun des aspects. Les perspectives des membres de la commission sur l'intégration de système ont concerné principalement l'intégration au niveau de l'acquisition pour la défense, avec un accent particulier sur l'approche “système de systèmes”. Le concept de “l'approvisionnement intelligent” est né de différents facteurs dont les dépassements de coûts et les retards de livraison, qui accentuent la complexité et la diversité des systèmes de défense et qui sont en passe de modifier la structure de l'industrie de la défense. Le cycle de vie de l'approvisionnement intelligent permet d'assouplir l'acquisition de grands systèmes de systèmes pour l'espace de bataille, qui peuvent être considérés comme des sous-systèmes opérationnels implémentés autonomes ou semi-autonomes. Le concept visé est celui d'un système de systèmes totalement intégré basé sur les fonctions, mais suffisamment souple pour permettre l'évolution du système afin de l'adapter à l'obsolescence des composants, les ajouts technologiques, etc. Ainsi, le cycle d'acquisition permet de contrôler plus intelligemment les coûts des programmes tout en profitant des possibilités d'évolution des capacités des systèmes offertes par les ajouts technologiques. Les perspectives de la commission concernant la gestion des missions et l'interopérabilité mettent en avant le concept du système de systèmes pour les systèmes intégrés de défense aérienne, ainsi que pour les différents éléments de la gestion des missions. La poussée de la technologie et la pression de la demande sont soulignées en tant que facteurs favorisant la réalisation des objectifs de développement des systèmes de préparation de mission. Le cycle de vie d'un système, allant de la transformation des objectifs en modélisation du processus, à la réalisation des systèmes et enfin à leur gestion, est explicité. L'architecture de la fonction de gestion de la mission est présentée du point de vue des systèmes de mission militaires intégrés. Enfin, l'application de ces concepts aux opérations de défense antiaérienne et à l'automatisation est décrite.

Click inside the blue boxes or on the titles to view the corresponding section

Contents

* These papers are produced in their correct numerical sequence.

SESSION III: INTEGRATION

SESSION IV: INTEROPERABILITY

* These papers are produced in their correct numerical sequence.

Theme

Techniques and technologies for highly automated reconnaissance of and defense against airborne threats for mobile Crisis Reaction Forces.

The disappearance of a direct threat in the wake of the end of East-West confrontation will change the way and direction of innovations in defense technology. New threats develop from the increasing proliferation of military products and know-how in politically unstable countries. NATO will have to react to the resulting changes in security policy – *possibly also by order of the UN*.

In this connection, the ability of mobile Crisis Reaction Forces (CRF) to defend against airborne threats plays an important role. This requires highly automated system components for reconnaissance of and defense against such threats. The treatment of the items included in the Symposium Topics list given below is aimed at elaborating and mastering the techniques and technologies needed for this purpose.

For reasons of

- multinational composition of CRF
- interoperability of systems
- shortage of individual national resources

a multinational approach is indispensable.

The symposium's goal is to describe techniques and technologies viable for the lay-out and design of operational air defense systems that meet multinational requirements.

Symposium Topics:

- Description of typical scenarios
- Enabling Technologies for Air Defense Systems
  - Sensors (IR, RADAR, UV, LASER)
  - Sensor Fusion
  - Pointing and Tracking
  - Soft Computing, Information Processing
  - High Level knowledge-based (KB) Automation
  - Data-Link, communication
- System Architecture and Mechanization
- Man-Machine Interface, Visualization techniques
- Interface with Weapon Systems and higher level Battlefield Management
- Systems Design for Interoperability

Thème

Techniques et technologies pour la reconnaissance hautement automatisée et la défense contre la menace aérienne pour des forces mobiles d'intervention en situation de crise.

La disparition de la menace directe, résultant de la fin de la confrontation entre les Alliés et les pays de l'ancien Pacte de Varsovie, en aura pour effet de modifier l'orientation et la nature des innovations en matière de technologies de défense. De nouvelles menaces sont en train de naître avec la prolifération dans des pays politiquement instables de matériel et de savoir militaires. L'OTAN devra réagir aux changements de politique en matière de sécurité qui en résulteront – *éventuellement sous les ordres des Nations-Unies*.

Dans cet esprit, pour une force mobile d'intervention en situation de crise (CRF) pouvoir se défendre contre des menaces aériennes est d'une importance capitale. Une telle défense nécessite des composants système hautement automatisés. L'examen des sujets figurant sur la liste des thèmes du symposium qui suit, doit permettre d'élaborer et de maîtriser les techniques et les technologies nécessaires.

Pour des raisons de :

- composition internationale des CRF (Crisis Reaction Force)
- interopérabilité des systèmes
- manque de moyens nationaux

une approche internationale s'avère indispensable.

Le symposium a pour objectif de présenter les techniques et technologies préconisées pour la définition et l'implantation de systèmes opérationnels de défense aérienne susceptibles de répondre aux exigences internationales.

Thèmes du Symposium :

- descriptions de scénarios types
- technologies adaptées aux systèmes de défense antiaérienne
  - capteurs (IR, RADAR, UV, LASER)
  - fusionnement des données capteurs
  - pointage et pistage
  - logiciels et traitement de l'information
  - automatisation de haut niveau à base de connaissances KB (Knowledge Based)
  - liaisons de données, communications
- architectures de systèmes et mécanisation
- interfaces homme-machine, techniques de visualisation
- interfaces avec systèmes d'armes et gestion élaborée du champ de bataille
- conception systèmes pour interopérabilité

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Air Defense Opportunities and Challenges

Keynote Address

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The National Security world has changed drastically during the past decade. Certainly, the threat has changed from monolithic and specific to ill defined and global. Operations involve multi-national partnerships, not all of which are predictable. In this environment the need could not be greater for accurate, timely, and complete information to provide situational awareness in support of rapid and informed decision-making. Fortunately, the growth in commercial information technologies provides a basis for meeting these needs for rapid response and the effective application of expeditionary forces.

The US Department of Defense, in general, and the US Air Force, in particular, has embarked on a commitment with an evolving plan to exploit commercial information technologies to create a highly integrated and interoperable Command and Control (C^2) capability. The realization of a rapid response, expeditionary force requires the integrated and interoperable C^2 capability that is summarized in this paper. This capability is a foundation for the Revolution in Military Affairs that has been discussed widely during the past few years.

Considerable investment has been made in C^2 systems and now there is a significant capability that currently supports the military forces. Generally, these systems have been developed independently from one other with the result that there is little integration and, more importantly, very limited flexibility in their ability to interoperate. Consequently, most operators are overloaded with data but underwhelmed with information necessary to support informed and rapid decision-making.

The commercial computer and communication capabilities that have emerged so rapidly during the past decade have the potential to change dramatically the manner in which C^2 capabilities are evolved and enhanced. To achieve the benefits of using these technologies, the Air Force and the DOD must change their business processes of the past. In fact, changes are necessary across the range of Doctrine, Organization, Training, Materiel, Leadership and People (i.e., DOTML-P). The focus in this discussion is restricted to the Materiel aspects of C^2.

The development, acquisition, fielding, and sustainment of C^2 systems, using commercial information technologies, require very different approaches that accommodate the rapid change of the technologies. They must build legacy and new systems into an integrated and interoperable whole. The basic system concept mirrors the capabilities of the Internet and the World Wide Web, modified as required to satisfy the specific needs of the military. In some circles referring to the desired C2 capability as “ic2.com” emphasizes the point.

The emerging approach involves seven major features:

<u>Capability-focused</u>: In the past, development has focused on specific systems that respond to a defined requirement. The resulting systems are tested extensively to confirm that they meet the requirements. Interfaces are prescribed for a few known systems interactions, but little attention has been directed toward integration and interoperability issues that will enable broad capabilities in support of a Commander. Now, we recognize that important operational capabilities must be identified that enable the rapid and effective response to any of the many situations that may arise. The operational vision is depicted in Chart 8. Specific elements are presented in more detail in Charts 9 through 12.

Paper presented at the RTO SCI Symposium on “System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces”, held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

Integrated/interoperability-enabled: Fundamental to the fielding of broad capabilities is the need for elements of the C^2 system to be integrated (e.g., they can exchange data and coexist on workstations) and to be interoperable so that data can be combined, correlated, and fused to provide meaningful information in support of decision makers.

Architecture-based: A framework must be defined and implemented that support the realization of the system integration and interoperability. A layered architecture has been selected as a basis for this framework. Charts 17 and 18 present the layered infrastructure and identify the "plug and play" applications that utilize the common infrastructure.

There are two overarching considerations that dominate the architecture. First, information assurance must be built into every layer of the C^2 system, whether at the desktop or in a specific application riding on the infrastructure. Second, the management of information is the paramount function of the complete system. This function has been denoted as the Joint Battlespace Infosphere (JBI) and must provide the means for transforming heterogeneous data into information useful for the decision-making process. The JBI is discussed in Charts 19 through 22. A key technology that now enables the development of the JBI is mentioned in Chart 23. The eXtensible Mark-up Language (XML) provides a simple and effective mechanism to exchange information for very different data and message sources.

Another key enabler for the integrated C^2 capability is the Common Communications Environment or, as it is called often, the Global Grid. The architecture for the Global Grid is itself layered but the overarching characteristics are presented in Charts 24 and 25. The key enabler for the implementation of the Global Grid, and one that is being used now, are the interface protocols (IP) of the internet. Ultimately, the goal is to be able to communicate with every element of the complete system by providing them with a unique ic2.com name and address.

Experiment-driven: The rapid inclusion of new technologies and capabilities requires strong and frequent interaction between operators, developers, acquirers, and testers. The environment that enables meaningful interactions are experiments. Starting in FY98, the Air Force conducted the Expeditionary Force Experiment 98 (i.e., EFX 98). It has followed with Joint Expeditionary Force Experiment 99 (JEFX 99) and is preparing for JEFX 00 in August 2000.The experiments are intended to try new capabilities and adapt them to the desires of the operators and warfighters. As with any good experiment, failure is tolerated. Consequently, the JEFX experiments are different than "exercises" which have as their purpose training and failure is not tolerated. Positive results from the experiments are then used to drive new acquisitions with the intent that the desired capability is made field-ready and incorporated into the integrated C^2 system through the process identified in the next paragraph.

Evolutionary acquisition/spiral development-executed: In the past C^2 systems have been developed using a "waterfall" process that starts with requirements and completes several years later with operational testing. Accommodation to the pace of commercial information technologies requires a continual working relationship between operators, developers, acquirers, and testers. Capabilities must evolved at a rapid pace with each spiral of the development process providing an enhanced capability. As the capability evolves in accordance with the architecture, the requirements change and recognized deficiencies are corrected. The basic process is depicted in Chart 26.

Distributed test bed environment: To facilitate and speed the development process, a test bed is being developed that is distributed geographically to include relevant capabilities. It reflects the architectural elements and must provide the basis for integration and interoperability testing and architectural compliance. The test bed appears in Chart 26 and is identified as the C^2 Unified Battle Environment (CUBE).

Simulation-based acquisition (SBA): Modeling and simulation is being used to provide a disciplined process for examining the consequences and for making appropriate trades for investment decisions. Architectures (i.e., operational, system, and technical) are defined in detail to develop executable models that enable the realization and testing of architectural alternatives. The use of these models and accompanying simulations are fundamental to the experiment and evolutionary acquisition processes, again as shown in Chart 26.

To conclude, the emerging strategy for C2 to meet the needs of rapid response forces is to move toward the widespread use of commercial information concepts and capabilities. A robust global communications capability, or “global grid”, provides the basis for integrating disparate capabilities that leads to increased interoperability among a broad range of partners, both U.S. and multinational. The Joint Battlespace Infosphere will enable the interoperability that provides desired information wherever it is needed. Because of the network- and information-centric views of the emerging capability, the security of the networks and the information must be considered and included in all layers and elements of the ic2.com. The challenges in realizing this vision are considerable but the uncertainty of the global environment appears to demand the effort.

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Silent-Mode Air Surveillance

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Summary

A new approach to ground-based air surveillance will be outlined. This concept makes use of passive electro-optical sensors for panoramic surveillance in silent mode. Based upon infra-red Focal Plane Array (FPA) detector technology this system is designed to scan the complete hemisphere with a high search frame rate. Surface as well as airborne threats will be detected, tracked and classified with high probability of detection. As opposed to Infra-Red Search and Track (IRST) systems known so far, this new system approach uses a laser range finder to verify its alarms, once these have been pre-classified. With this additional verification process, which provides 3-dimensional target trajectories, the system's False Alarm Rate (FAR) is improved considerably. A powerful signal processing is running in real-time at the system's high search frame rate. Accurate target designation is possible with low data latency to perform fire control for an associated weapon System. Though designed for stand-alone tactical reconnaissance, this system can be interfaced fluidly with long-range radar surveillance systems to use cueing information from every area of the electromagnetic spectrum. Under contract to the German Ministry of Defense (MoD), an Advanced Technology Demonstrator (ATD) of such a silent-mode air surveillance system has been built and field-tested.

1 Introduction

In general, ground-based air defense is a multi-layer concept. Its strategy is to face an incoming threat with graded countermeasures of different intercept ranges. An approaching warhead that leaks through must pass the multiple shields of intercepting fighters, surface-to-air missiles and eventually the high-rate barrel firing of a low-level air defense system, leaving little chance for the threat to home in on its intended target.

In a conventional battlefield situation, this defensive strategy is applied successfully. If a coordinated raid from a pre-known direction is to be expected, medium-range air defense systems such as PATRIOT and HAWK massively deployed near the frontline provide forward protection. In the rear zone, short-range (SHORAD) Surface to Air Missile (SAM) systems such as ROLAND or gun-based systems such as the German GEPARD or the Russian ZSU-23 are deployed along the last line of defense.

Associated with these weapon systems, radars of graded surveillance range early alert to an approaching threat. Relying on a complete wide-area air picture, operations can be conducted as preplanned missions.

However, in today's environment of out-of-area missions, the situation of orderly military forces is no longer given. For forces deployed in regions of limited conflicts and crisis, as well as in peace-keeping missions, the forward line of one's own troops is more likely to resemble a patchwork of hostile areas distributed arbitrarily among areas of friendly troops.

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With modern, short-range, easy to deploy man-pad weapon systems, which have been proliferated vastly all over the world, enemy threat is found to be co-located nearby one's own troops. An air picture as produced by upper level air reconnaissance is not able to provide the situational awareness necessary in a distributed battlefield like this, because this information is useless since it takes too much time to reach the platform under attack.

Even more, the capability of radar-based air defense systems to counter cruise missiles (CM) or unmanned aerial vehicles (UAV) becomes more and more insufficient. These kinds of missiles show improved performance with regard to maneuverability and stealth to run a surprising attack. Following the hiding contours of the terrain and with radar cross-sections considerably faint, these targets are hardly to detect by radar systems.

The use of ground-based radar systems turns out to be questionable, because active systems would cue enemy attacks.

As opposed to the preplanned missions in the past, today there is a need for immediate reaction when information about the enemy's position or about a surprising hostile attack becomes only available at short notice. As a consequence, air surveillance must not rely exclusively on radars, but has to look for other means to provide situational awareness without the drawback of active cueing of enemy detectors. Strategies have to be developed which are able to get along with fractional air pictures. Yet means have to be developed, that are capable of alerting reliably against all kinds of threat on short notice, but with the chance to counter successfully.

2 A New Quality Air Surveillance

An air surveillance system, able to cope with the challenges of a future highly dynamic battlefield should have the following main features:

- Providing an air picture in real time to report sudden actions without delay.
- Operating covertly, since many missions require silent-mode surveillance to avoid cueing of the enemy.
- In situations of an incomplete air picture there is a need for a 24-hour gapless coverage since surprising attacks from anywhere and at any time may be encountered.
- To ensure fire control data quality, the performance provided by radar systems has to be improved in terms of
  - high-precision target coordinates
  - target velocity
  - data output latency.
- The radar problem at low altitudes has to be overcome by a look-down capability into areas of high-level clutter return.
- Rapid overseas and immediate on-site deployment call for an air-mobile and vehicle-transportable system design
- If other sources of surveillance are available, the new system should be able to use this information to improve its own air picture.

In the past, defense industry has made many approaches to meet these requirements by designing surveillance systems based upon infra-red (IR) technology. Those IRST systems did not, however, fulfill the performance requirements for reliable air surveillance and target acquisition. The main drawback associated with these systems was their poor performance with regard to false alarms.

To enlarge the technological basis for the development of improved passive surveillance systems in future, the German MoD started a demonstrator program some years ago. This program became known under the title “ABF” which is the German abbreviation for “Reconnaissance and Engagement of Air Targets”. Bodenseewerk Gerätetechnik (BGT), a business unit of the Diehl VA Corporation, was awarded the contract to build an Advanced Technology Demonstrator for a silent-mode air surveillance system.

In this program, a new approach to tactical air surveillance is made, evolving from BGT’s core business, which is the development and production of IR missile seeker heads. Mastering the latest technology of imaging IR seekers, the idea behind it is to transfer this know-how to the field of passive air surveillance. Real-time image processing as it is used successfully in IR seekers, is intended to give the missing impetus to passive reconnaissance systems with improved false alarm performance.

3 Demonstrating Silent-Mode Air Surveillance

For a passive surveillance sensor to perform wide-area search and target acquisition autonomously and with high reliability in real time, a two-step signal processing concept is applied, based upon fused multi-sensor information.

In this concept (Figure 3-1), the sensor suite of the demonstrator system includes a panoramic search sensor platform with passive IR sensors and a tracking and verifying sensor platform with a high-resolution IR sensor and a laser range finder.

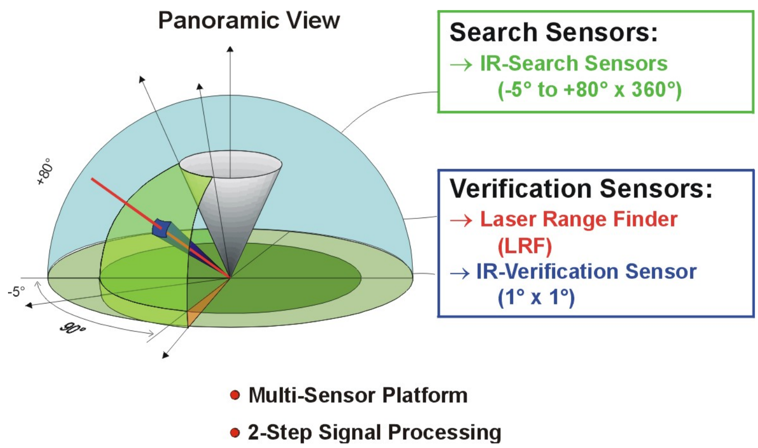

Figure 3-1: Surveillance Volume

3.1 Search sensor platform

The task of the search sensors is to frequently scan the hemisphere looking for inbound threats, whereas the verification sensors are used to check whether a tentative track seen by the search sensors is a real target or a false alarm.

As targets may approach from any direction, the search sensors’ field of regard (FOR) has to extend from ground to almost zenith. In particular, a look-down capability will be required to detect targets approaching from low altitudes in a terrain-following mode. In azimuth, full panoramic coverage is necessary. This results in a wide FOR of 85° by 360°.

With the demonstrator, modern matrix Focal Plane Arrays (FPA's) are used to image the panoramic search volume. To achieve a good signal-to-clutter ratio, the spatial resolution of the search sensors has to be adapted to the problem of detecting point targets in front of a radiating background. For the detection of distant objects, high spatial resolution is a prerequisite. However, the total amount of detector elements rises intensively with increasing geometrical resolution. To give an example, if a resolution of 1 milliradian were to be achieved using currently available IR FPAs with 256^2 elements per detector, a minimum of 95 detectors would be needed to cover the FOR in a staring mode.

Therefore, a design has to be chosen which is able to get along with an affordable number of detectors: The solution is given in Fig. 3-2 where only 4 FPAs are shown, being multiplexed onto a set of distributed optical channels, each pointing in a different elevation direction.

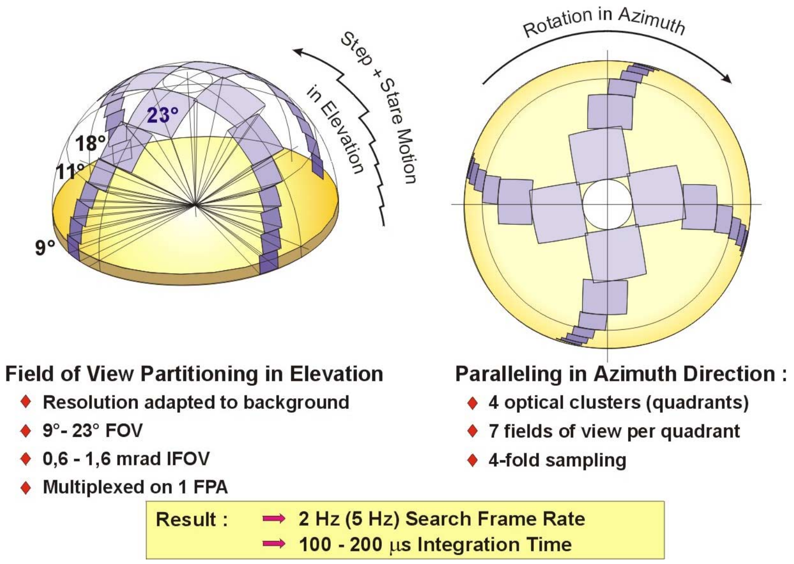

Figure 3-2: Hemispherical Sampling with FPAs

To achieve a 360° coverage of the panorama in azimuth, the whole platform is rotated slowly, including 4 quadrants with their respective detectors and elevation optics clusters. Due to the 4-fold optics, the search volume is sampled 4-times during one revolution of the platform. The slow rotation in turn allows a longer integration time of the FPAs, resulting in a longer dwell time on target for a better detection range.

If image distortion is to be less than the size of one pixel element, a 100 – 200 µs integration time is possible by sampling the hemisphere with a 2 – 5 Hz search frame rate.

Given these parameters, the search sensor platform is well suited for detecting in time any target entering its search volume. Good radiometric sensitivities are achieved, by using high aperture optics. Depending on the amount of energy radiated from the targets, this results in comfortable detection ranges. As an example, Fig. 3-3 shows different layouts of the sensors in terms of their Noise Equivalent Irradiance (NEI).

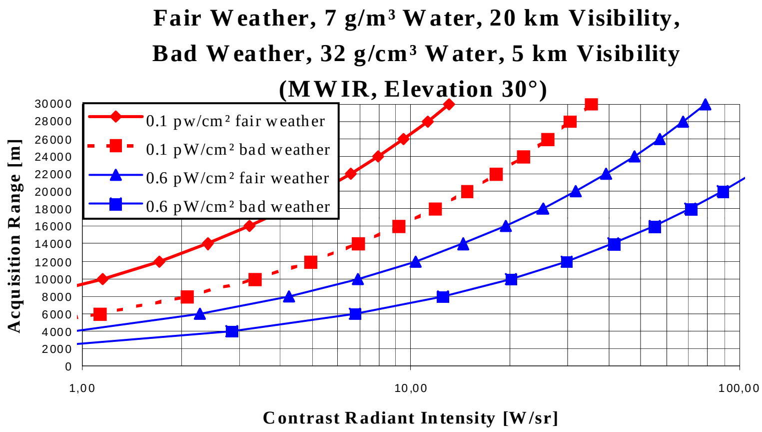

Figure 3-3: Typical IR Acquisition Ranges

Detection at a signal-to-noise (S/N) ratio of 5 has been assumed. As an obvious performance issue of any IR sensor, their viewing range limits with weather conditions have been depicted in the plots, too.

3.2 Track and verification sensors

The passive search sensors have to detect possible target events and establish first tracks of tentative targets. However, the ability to separate threatening targets from clutter, noise and other non-hostile targets is, in general limited for passive IR sensors. Operating on 2-dimensional images only, the amount of information provided is insufficient, as commonly used IRST systems show.

To improve the false alarm rate of the ABF demonstrator beyond the IRST level, additional information is acquired by the track and verification sensor unit.

This unit includes a high-resolution IR sensor boresighted to the line of sight of a Laser Range Finder (LRF). Once a tentative track has been established by the search sensors, the verification sensors' line of sight is directed instantaneously to the track coordinates indicated by the search sensors with the help of a rapidly steerable mirror gimbal. A closed loop control using the verifier's IR image locks the LRF's line of sight onto the target for precise laser ranging. The target in-range velocity is determined by means of consecutive range measurements.

4 Signal Processing

When the system is running in its search mode, a pattern of some hundred single FOVs covers the hemisphere. Given a 256^2 matrix detector and assuming a 2 Hz search frame rate, the data rate accumulates up to the order of gigabits per second. Image-processing algorithms have to translate this stream of pixels into useful data for a combat system.

On each FOV, real-time image processing is running, permanently looking for possible targets hidden in noise and clutter. In Fig. 4-1, a single frame is enlarged for illustration.

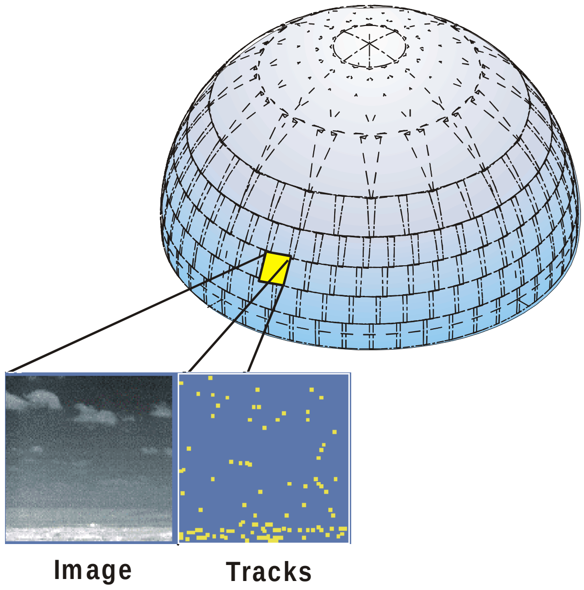

Figure 4-1: Multiple Frame Event Detection

Compared with a missile seeker FOV of, say, 4°x 4°, a hemispherical FOR of a surveillance system consists of roughly 1,200 missile FOVs. If only the FAR of a single missile seeker were to be achieved, the image processing of an IR surveillance system would have to be improved at least 1,200-fold. Moreover, since the baseline operation of a surveillance system is for 24 hours, compared to the few seconds' mission of a missile, the necessary improvement in the suppression of false alarms is tremendous.

To work-off this huge amount of data in real time, a powerful signal processing hardware is required.

Real-time image processing of this kind is found in imaging IR (IIR) seeker heads where BGT has acquired experience for many years. As a key element for fast front-end computing, BGT has developed a special-to-type parallel processing computer called Systolic Array Processor (SAP). This computer is designed to do pixel data processing of FPAs row by row, in parallel and at high speed. Meanwhile, this hardware is a proven design used in several military full-scale development an production programs such as IRIS-T or IR-RAM.

5 Target Classification at Weapon Interface

Every single event in the FOR showing a measurable contrast to its surrounding neighborhood is tracked for a sequence of image frames. Image processing algorithms are designed to hold in memory hundreds of tracks simultaneously. Most of the tracks turn out to be unstable because their events have been created by noise. Some tracks, however, will remain persistent as they belong to a possible threat or clutter.

Stationary image events will be eliminated by high-pass filtering. This is equivalent to forming a clutter map of the stationary background and suppressing this information.

The remaining tracks produced by the search sensors are analyzed further. Evaluating the statistical correlations of a moving background such as drifting clouds, moving trees or sea glint flicker, provides a powerful means to sort out targets mixed with such background, because of their different statistical significance.

This kind of prioritization which uses the statistics of target dynamics as opposed to ratings based upon the comparison of target colors is stable with variations of signal amplitudes which is a problem in a weather-dependent changing environment.

To verify whether a stable track is clutter or a target, additional information about its dynamic behavior is provided by the verification sensors. The track and verification sensors provide

- range
- in-range velocity
- high-resolution IR features, e.g. helicopter rotor frequencies

with a high frame rate governed by the LRF pulse rate.

Using Kalman filtering techniques, a higher dimensional state vector of the target is calculated. For example, a 6 degrees of freedom (6-DOF) model of the dynamic behavior of a track, turns out to produce stable and reliable target features which allow a reliable distinction between false and true alarms.

As a result of this discrimination, which runs in real-time, too, threatening targets are classified and their dynamical state vector is available at the weapon interface.

Precisely measured target data such as

- class of target, e.g. helicopter, aircraft, missile, subsonic or sonic
- target bearing and elevation in the order of less than a milliradian
- target range and velocity vector
- target acceleration
- type of target trajectory
- time to target impact

are transmitted with high frequency to the weapon system. Real-time signal processing provides low data latency which is an indispensable prerequisite for fire control.

Mission success of the engagement action could be monitored and tracked by help of this system, if required. Therefore, the feasibility shown by the demonstrator program will shorten the distinction between surveillance devices and fire-control devices.

With its highly dynamic pointing capability, the verifier unit is capable of a simultaneous multiplexed tracking of multiple targets.

6 Target Acquisition and Engagement Sequence

The overall functional sequence starting from first detection to weapon handover takes place within a few seconds. In Fig. 6-1, the timeline plots of typical air targets are shown to illustrate the course of target acquisition, weapon alignment and engagement by an example.

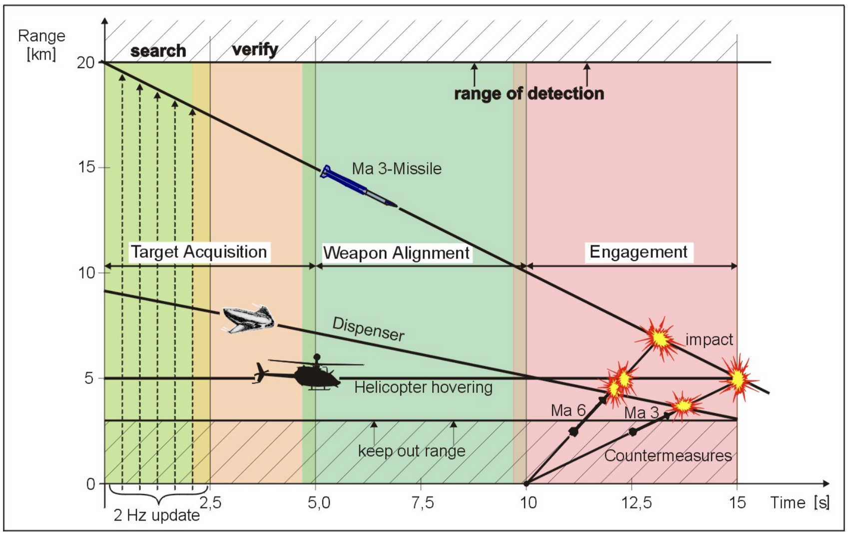

Figure 6-1: Surveillance and Engagement Timeline

First, the system is operating continuously in its search mode. A clutter map has been established, having raised the system's sensitivity for the detection of suddenly changing events. Once a missile's signature has crossed the search sensor's threshold of detection, only few additional detections are necessary to establish a track. Within a few seconds, the system is able to decide whether this track might be a candidate of a possible threat or if the track was simply caused by noise. Potential threat tracks are handed over to the verifier to form 3D tracks and for threat classification. This step lasts one or two seconds, depending on the verifier's mechanical slew rate and the LRF pulse frequency.

As can be seen from the diagram, roughly 5 seconds after its first detection, the system is able to "declare target" to the associated weapon system.

The weapon has to be pointed to the designated target coordinates and weapon release is possible immediately, if the firing rules allow this.

Considering a certain time to go for the engagement, a comfortable keep-out range can be achieved in this example, even in the case of an attack by a Mach 3 missile.

7 Demonstrating New Technologies

With the ATD, the feasibility of new technologies in passive surveillance devices is to be investigated.
For an improved FAR suppression, the spin-off from missile seeker technology is a new approach to be applied.

The most prominent feature in this field is the application of SAP chip processing which allows fast filtering techniques to weed out in real time the things that are target like from the things that are really targets.

In conjunction with the SAP, modern IR technology is applied which uses matrix FPAs for frequent sampling of the total search volume. Their high frame rate allows multiplexing of more than one optical channel on one detector without degradation of the remaining hemispherical scanning efficiency.

Within the optical channels, mirror arrays fabricated by means of micro-mechanical techniques are used to mechanize this optical MUX function. With Micro-Mirror Arrays (MMAs), fast and arbitrary switching of optical channels is possible. Switching is electronically addressable which allows any switching sequence required. This offers the possibility to sample certain areas of the search volume adaptively.

Under this condition, each IR sensor of a quadrant would normally be running with its basic frame rate of 200 Hz, resulting in a 2 Hz sampling rate of the full FOR. If tentative targets were identified by the SAP processor, it would send a command back to the MMA to switch such optical channels pointing to the areas of interest more frequently. Additional image samples are provided by the FPA's spare capacity of up to 400 frames per second.

This feedback would be accomplished on line. The region of interest within the search FOR would then be converted to a higher frame rate, while the other areas would remain under the basic sampling rate. The update at a higher rate would enable a faster track generation resulting in an adaptively improved system reaction time.

8 Field Testing of the Demonstrator System

Incorporating the main technology items described, a hardware demonstrator has been built which is able to show the main functional principles of passive surveillance in real time. To save cost, compromises had to be made with regard to the physical size of the demonstrator and no effort was made on miniaturization and packaging.

In autumn 1999, first field tests were carried out with the ABF demonstrator at a German test range in Meppen. In a realistic scenario, the entire spectrum of air targets such as SAM's, drones, helicopters and jets as well as countermeasures was engaging the ABF system. In more than 100 sorties, all kinds of attack missions such as dive, loft or pop-up maneuvers with attack aircraft and low level ground attacks with helicopters were flown. SA-7 missiles were fired ballistically in a head-on but offset attack mode for safety reasons. These tests carried out over a period of several weeks allowed the system to be evaluated in various situations, different clutter environments and with changing weather conditions.

Figure 8-1 shows a photo of the sensor suite on the Meppen test range.

Figure 8-1: ABF Demonstrator Sensor Suite

In Figure 8-2, a plot of the man-machine interface (MMI) is shown indicating the information displayed for the operator.

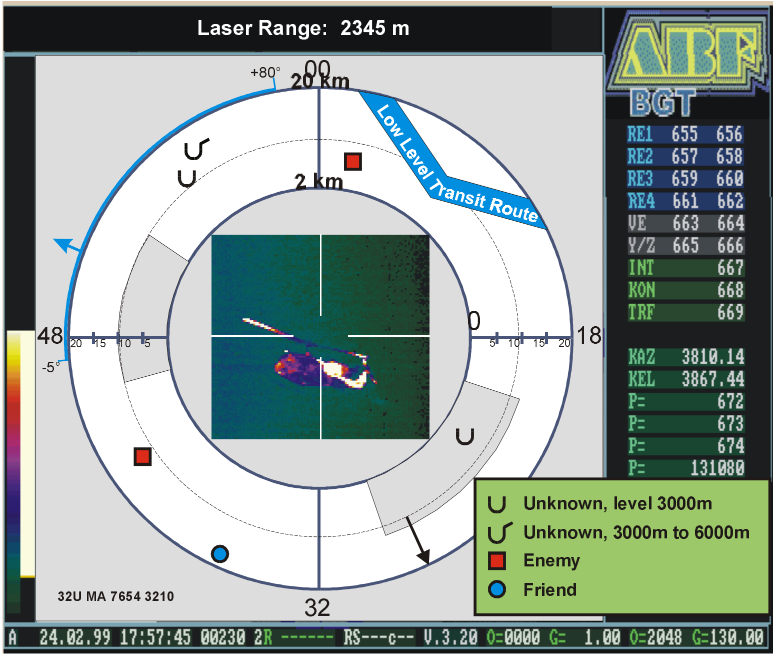

Figure 8-2: ABF Demonstrator MMI

The area which is kept under surveillance is plotted as two concentric circles indicating the 2 km and the 20 km bounds with the ABF sensor suite in the center. Reported alarms are marked by symbols, their position showing range and bearing of the target inbound. In the center of the plot, the instantaneous IR image of the verification sensor is visualized.

During the extensive field trials it was shown that the verifier was able to discriminate targets from clutter and noise with high reliability. Target alarms were reported within the range and time limits necessary to assure a sufficient keep-out range for a virtual engagement. The target plots reported by the demonstrator showed no false alarms, confirming the superiority of the 2-step system concept using the verification principle.

9 Operational Outlook

Intended for tactical use, lightweight IR technology offers the basis for a mobile, easy-to-deploy surveillance system that provides protection against incoming air targets of all kinds.

To improve the range coverage with IR surveillance one could easily deploy several IR surveillance systems in the direction of the expected threat. Fig. 9-1 shows typical deployment situations depending on the concept of operations.

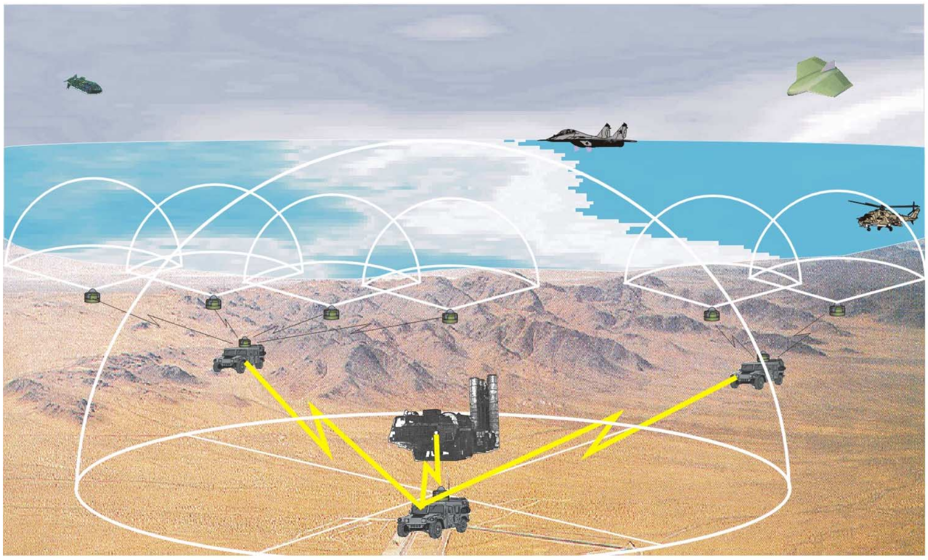

Figure 9-1: Deployment of Silent-Mode Air Surveillance Systems

In general, the deployment of an IR surveillance system will be embedded into existing command structures. Interoperability is required and a passive surveillance system has to be adaptable to commonly used interfaces such as Link 16 or JTIDS/MIDS (Fig. 9-2).

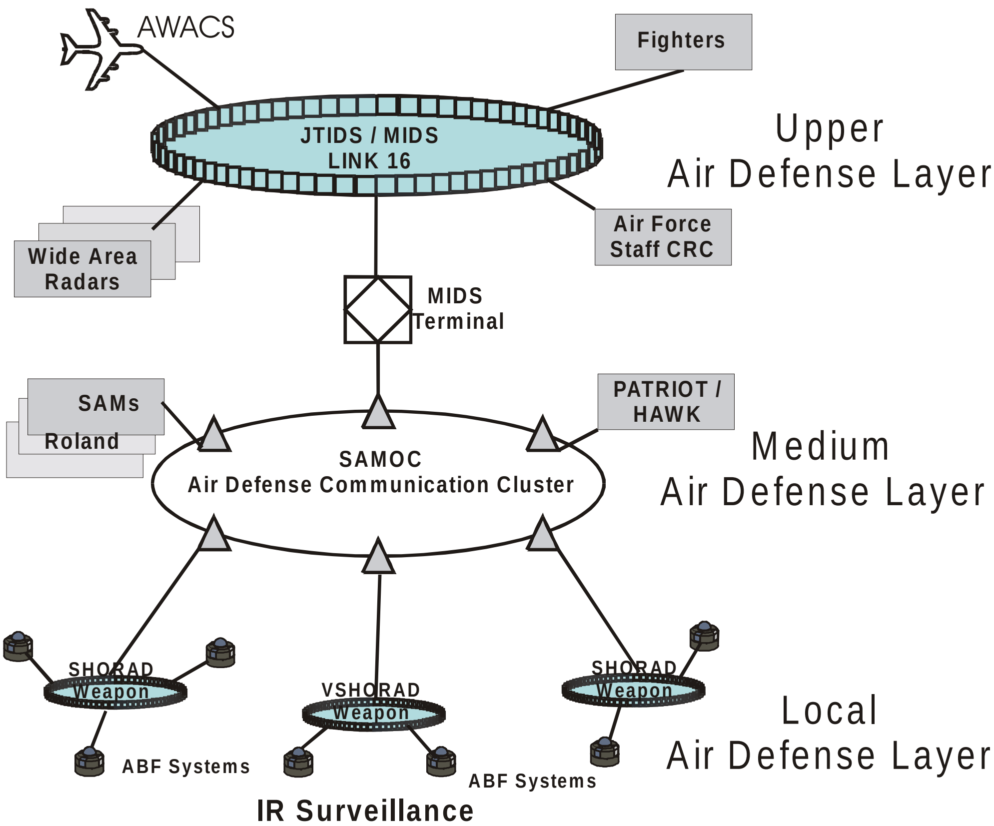

Figure 9-2: IR Surveillance Integrated into Existing Air Defense

In a joint operation of deployed forces as depicted in Figure 9-2, an IR surveillance system will make use of any information provided by the array of diverse sensors tapped to the information links. For example, the early warning radar plot of a distant threat could be used as a-priori information, as well as the cueing signals of Electronic Support Measures (ESM) to enhance the overall performance of the IR surveillance system.

In the command post of a Surface to Air Missile Operating Center (SAMOC) the sensor information of all distributed sensors will be displayed on the commander's display, including the situational air picture of the short range IR surveillance systems in real time. The SAMOC in turn will allocate firing rules to the (V)SHORAD weapon systems linked to IR-surveillance systems taking into account their requirement for immediate engagement.

Of course, ground-based use is not the only employment of passive surveillance technologies as demonstrated by ABF as an experimental system.

Ship defense is another possible application for IR surveillance. As an addition to other self-defense sensors, a shipboard IR surveillance system will have specific responsibilities for the low-elevation region where radar is least effective. Anti-ship cruise missiles are approaching barely above wave height where the ship's search radar is boggled by sea-clutter problems. If the environment is littoral, land clutter degrades the picture even more. Here is where an IR surveillance system comes in, which is able to cope with a very clutter-intense background scene.

Last but not least, aircraft have an even greater need for passive search capability. The technologies as applied with the ABF demonstrator also provide the background for a passive missile approach warning device based upon IR sensor technology and its real-time image processing capability associated with.

10 Conclusion

The ABF experimental system demonstrates the feasibility of a silent-mode surveillance and target acquisition system of high efficiency. Since IR sensors obviously are range-limited by physics, its use is constrained to the end-game of an engagement. This means that threatening targets are already on a closing-in track when detected for the first time by an IR surveillance system. Therefore, the only chance to survive lies in a fast reaction time of the system which is in the order of a few seconds. If this situation is compared to the task of conventional reconnaissance with radars, which is to provide long range air pictures, an IR system provides tactical reconnaissance for a local area only, but in an extremely high dynamic environment.

As a consequence, such a system will be operated nearby, and in tight conjunction with, a weapon system for short range air defense.

Its lack of range performance, if compared to radars, is compensated for by high speed signal processing providing precisely measured target data.

The demands for detection probability and FAR are extremely high since the silent-mode system will be deployed as an ultimate shield in the inner air defense layer. Detection, acquisition and target classification take place within a seconds' time-frame immediately before release of a countermeasure. In a timeline so tight, there is no chance to have a man in the loop. The only provision is for mission abort if there is an unforeseen event.

The accuracy of the data provided by high-resolution IR optics is suitable for cueing ground-based weapon track radars. A consequence of its real-time processing capability is its low data latency which offers the possibility to use those data for fire control. However, when closing the fire control loop, IFF (Identification Friend or Foe) information has to be taken into account.

Though silent-mode surveillance systems obviously could be used as stand-alone, normal operation will be somehow in connection with radar surveillance systems to form a synergic supplement. For example, IR surveillance could be employed to improve radar surveillance. Acting as a “gap filler”, an IR system could be deployed in areas of radar shadow in certain geographical terrains.

Since IR does not present any multi-path or ducting problems, an IR system with look-down capability in a cluttered background scenery could be used to improve the well-known radar degradation at low altitudes.

Of course, in adverse weather conditions radar is the only means to get an air picture. However, in today’s and in future conflicts there will be missions which forbid the use of active systems. With IR, 24-hour surveillance is possible, weather permitting, without revealing one’s own position.

The technological possibilities as demonstrated by the Advanced Technology Demonstrator ABF not only point out an alternative passive air surveillance system for ground-based use, but also will give impetus to the development of ship-borne systems as well as to airborne warning systems used for self-defense or for the protection of high-value targets.

11 Acknowledgements

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UK Soft Vertical Launch - A Flexible Solution to an Integral Concept for Ground & Naval Air Defence

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Summary

The paper describes the need for versatile and flexible systems in supporting Crisis Reaction Forces, and the role that soft vertical launch can play in meeting that need. The concept of operation is described together with the configuration and results of a demonstration programme of live firings. Plans for continued development are outlined as is the vision for future operation.

Introduction

Current UK Air Defence (AD) systems were specified and designed during the cold war era. During this period the nature of any anticipated conflict was well defined and well understood. UK forces would be part of a NATO alliance defending Western Europe from advancing Warsaw Pact Forces. This then was a quasi-static battlefield situation with the enemy Concept of Operations (Conops) well understood. This in turn led to a well defined situation for air defence where the location of sites could be planned and, if necessary, surveyed.

In contrast, the situation now is completely different. The location of any conflict is unknown, the enemy and associated Conops is undefined. The level of intensity of combat is also unknown and therefore the requirement for AD is very difficult to quantify. What is known is that the sophistication of threat weapons, and the proliferation of such weapons, is increasing. Ownership of low level cruise missiles (LLCMs) and tactical air to surface munitions (TASMs) is becoming more widespread as is the military use of unmanned air vehicles (UAVs) for attack as well as surveillance. An increasing emphasis on making aircraft more stealthy will complicate the threat diversity.

Countering this range of air threats makes the task of the air defender complex. Add to this the requirements to reduce defence spending and the system designer is faced with a dilemma – more performance is needed against a wider threat spectrum for lower cost.

Joint Operations of a Crisis Reaction Force

The evolving geopolitical and economic climate is making less probable the likelihood that any future conflict or dispute will escalate into major war. European forces are now more likely to become drawn into peace keeping operations and/or operations to defend a small friendly nation against a larger aggressor. The cost of such operations is however significant both in political and financial terms.

To meet this situation the concept of the Crisis Reaction Force (CRF) has been introduced. These CRFs may have to deploy at short notice, and at great speed to any location. This may be done under the control of NATO or an individual country. Especially for NATO operations the benefits of equipment inter-operability would be considerable in terms of cost and logistic re-supply.

For CRF operations, a joint operating area (JOA) is set up defining the battle space within which the Naval, Army and Air forces will operate. This necessitates control of information for situation awareness that, in turn, requires a pan NATO integrated communication system. Casualties in such operations are inevitable but must be minimised to make operations acceptable to the general public (voters) of the nations supplying the

Paper presented at the RTO SCI Symposium on "System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces", held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

forces. The deployment of such a force therefore necessitates the appropriate layered defence system comprising surveillance sensors, fighters, surface to air missiles (SAMs) and passive defence measures to protect the joint assets. *Unless total Air dominance can be guaranteed absolutely then not to deploy such measures is politically unacceptable.*

Clearly, for weapon systems to be cost effective for occasional joint operations they need to be developed with extended Service Life and associated minimum Life Cycle Costs as primary design drivers; to do this the following criteria are considered as key:

- Commonality - weapons capable of being deployed by different service platforms.
- Inter-operability - joint services capable of deploying variants of common weaponry.
- Flexibility - meeting the increasing diversity of missions within the future operating environment.
- Modularity - to allow flexibility of capability within tightly constrained military budgets.
- Versatility - being able to deploy a weapon mix to meet the warfare requirements.

UK Approach

In 1993 the UK began to address the problem of what type of ground based air defence (GBAD) system would be needed in the future to protect battlefield assets against attack from this wide threat spectrum.

From the start it was considered unlikely that there would be any major advances in GW technology and that improvements in weapon performance are more likely to accrue through miniaturisation or better integration of proven technologies. Thus, if conventional weapons are to form the backbone of the next generation of AD weapons then it is essential that more cost efficient missiles and associated systems such as launchers are procured.

The UK research work evaluated, through a combination of system studies, mathematical simulation and bench testing, the key technologies needed for cost effective air defence. From the onset of this work the method of launch was identified as a key enabling technology. In particular, containerisation was seen as a key to creating a stable environment and thereby offering the potential of extended shelf life.

Via an iterative process, see Figure 1, the UK MoD research programme has now identified the key technologies for GBAD and has now embarked on a series of demonstrator programmes to prove these technologies and thereby reduce the risk of subsequent development.

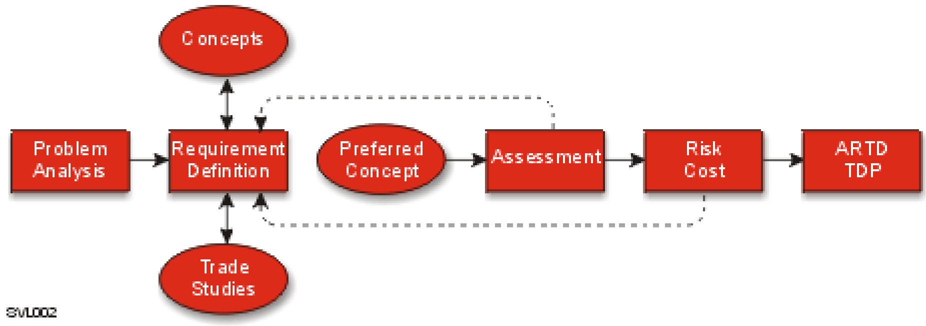

Figure 1 : Systems Approach

One of these technologies, soft vertical launch (SVL™), was seen as fundamental; the rest of this paper describes the UK implementation of this technology.

From the onset of this technology development, the SVL™ programme has been a partnership between government and industry and thus is very much aligned to the new UK Smart Procurement Initiative.

Vertical Launch for AD

To counter the perceived future threat, ground based air defence (GBAD) missile systems will not only need a high single shot kill probability (SSKP) but also the ability to cope with saturation raids and provide a rapid re-engagement facility. High rates of fire and a large number of 'ready to fire' missiles are the consequence of this requirement. The requirement to deploy and re-deploy rapidly in a range of scenarios immediately pointed to vertical launch (VL) as an option to be considered rather than the more conventional trainable launch currently employed by UK ground forces.

The launch method and how it can impact on the cost effectiveness of the overall weapon system is described in Figure 2. This highlights the relationship between design and effectiveness showing how the launch method can influence the system architecture of the weapon, its flexibility, its performance, availability and cost. This in turn can impact on the system effectiveness, force mix and therefore cost effectiveness.

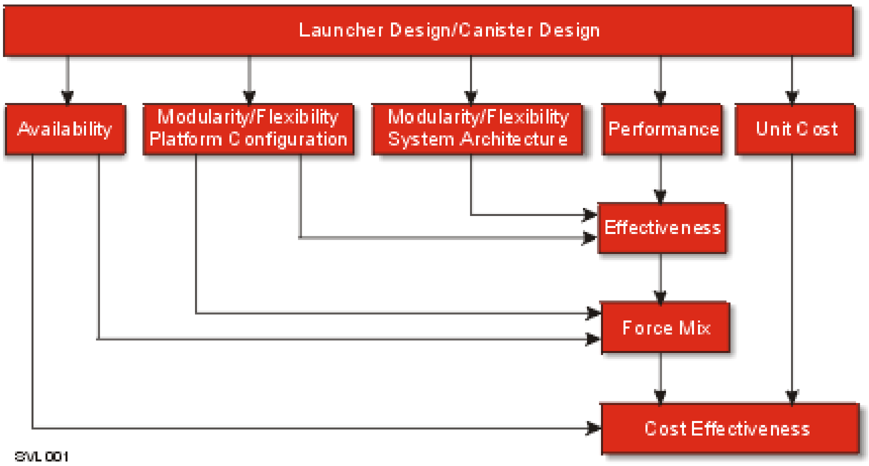

Figure 2 : Impact of Launch Method

A programme of work began several years ago where MBD carried out a combined system and operational assessment study for DERA into the application of VL to Army air defence. Vertical and trainable launch systems were compared. The work demonstrated that significant advantages can be forthcoming with the adoption of VL for the next generation GBAD systems –

- all-round, simultaneous, multiple engagement coverage,
- greater firepower for the same mass,
- lower overall mass, costs and improved A, R & M,
- deployment flexibility - no free line-of-fire required in front of the launcher,
- faster reaction times in the presence of all-round threats and rapid into action benefits,
- scope for commonality with Naval systems,
- more scope for planned product improvements,
- logical solution for large missiles.

The advantages offered by VL over traditional naval deck-mounted launchers were also applicable: VL enables more missiles to be embarked, provides an increased rate of fire and reduces 'topside' signatures.

However, there remained several disadvantages of VL for GBAD not least of which was the problem of efflux management. Alternative VL techniques were developed and evaluated by MBD in conjunction with DERA from which emerged the concept soft vertical launch. A follow-on study set out to investigate SVL™, comparing it with other VL technologies. The categories of VL are described below:

(a) Hard launch. For example, Vertical Launch Seawolf (VLSW), where the missile motor is ignited while the missile is in the launch canister. This approach requires efflux management. The missile accelerates rapidly and conducts turnover with a high vertical velocity component.

(b) Cold launch. In contrast to all other Western launchers, the missile rocket motor is ignited only after it has been “pushed” out of its canister and turned over. An example is the SA-N-6 that entered the Russian navy in the late 80’s on board Kirkov-class and Slava-class cruisers.

(c) Soft launch. SVL™ is akin to cold launch in that the missile rocket motor is ignited after it exits the canister, however missile ejection is more precisely controlled such that the missile is subjected to much lower launch loads and requires less energy to complete the launch and turnover sequence. The technique also offers the prospect of programmability of missile ejection characteristics. The technique has been developed by MBD in conjunction with DERA.

The systems approach to select a preferred VL method covered:

- operational requirements,
- missile system and kinematics,
- ground launcher system and platform interfacing,
- missile turnover system and capability,
- system effectiveness, and minimum range.

From the study a preferred option emerged. This is a canistered round from which the missile is soft vertically launched. This choice was shown to provide the most flexible, versatile, modular and operationally effective solution for a future, mobile GBAD system.

SVL™ Merits

Figure 3 illustrates the likely impact of SVL™ on a conventional vertically launched missile.

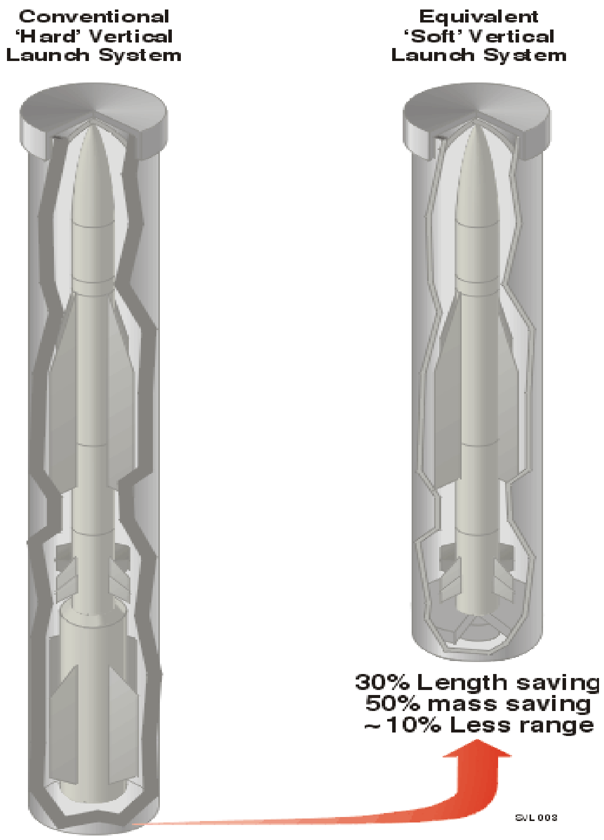

Figure 3 : Relative Comparison of SVL™ & HVL Missiles

The following is a brief benefits summary that SVL™ offers over conventional VL methods:

- Potential for reduced acquisition and through life costs.
- Longer maximum range (for a given mass when compared with hard VL).
- Army/Navy commonality.
- No efflux management requirements thereby improving the modularity and evolution potential.
- Can be a simple, lightweight construction and be placed in restricted spaces.
- No unwanted launch debris.
- Capable of reduced launch ejection loads.
- Improved minimum range capability due to a more direct turnover trajectory that can enable earlier target acquisition by the missile seeker.
- Reduced probability of disclosure of launch position due to reduced smoke trails and launcher heating.
- More benign environment for other platform mounted subsystems.
- Can be used to launch a variety of missile types and countermeasures.
- Capable of adaptation to horizontal launch of existing equipment

SVL™ - Concept Description

Soft vertical launch, in contrast to more conventional VL systems, ignites the rocket motor after the missile has been launched and directed towards the target. The GBAD concept is illustrated in Figure 4. The missile is ejected from the launch tube by a piston driven by means of hot or cold gas, similar to an ejection seat. MBD are developing a powered piston approach that allows the missile ejection to be more precisely controlled such that the missile is subjected to much lower launch loads and requires less energy to complete the launch event. The piston is caught and retarded before it leaves the canister.

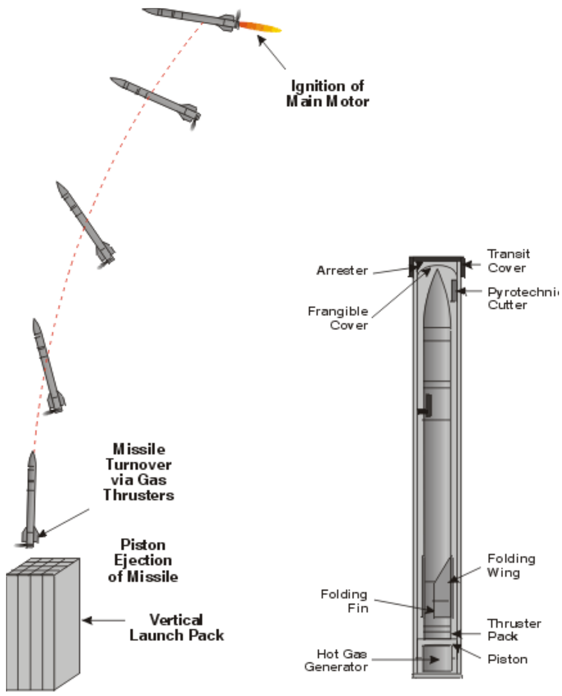

Figure 4 : SVL™ Concept

The ejection system imparts the missile with an exit velocity allowing it to achieve the optimum turnover altitude within the required time. All ejection effects are contained in the canister. All ejection loads are transferred through the canister down to the surface.

For GBAD, the missile is turned over towards the target predicted intercept point by means of a solid propellant, rocket powered, thruster providing lateral control in pitch, yaw and roll. Once turned over, the missile boost motor is then ignited. A smoother and more direct missile turnover is possible enabling rapid target acquisition, by the seeker, for minimum range engagements.

This approach eliminates the need for a complex efflux management system and a simpler, lightweight launcher can be used. This in turn means that there is no restriction to launch site or its proximity to ground troops. Deployment in urban areas is only limited by the requirements of surveillance and alerting devices.

The SVL™ launcher would consist of the tube with electrical interfaces for operation and test together with the ejector mechanism. This would be a unified design made in selected dimensions that could be configured to provide multiple launch containers. Once loaded with the missile the tubes would be hermetically sealed.

SVL^{TM} - Concept of Use

For GBAD operations the launch containers can be deployed on a variety of standard UK Army vehicles, either tracked or wheeled. At the launch site these containers can remain located with the vehicle or be deployed remotely.

Alternatively, containers deploying canistered SVL^{TM} missiles could be temporary structures on board ships. These containers could be transported with an amphibious force, or helicopter, for use on land. The container could therefore be deployed as a multi-role and multi-service launcher (see Figure 5).

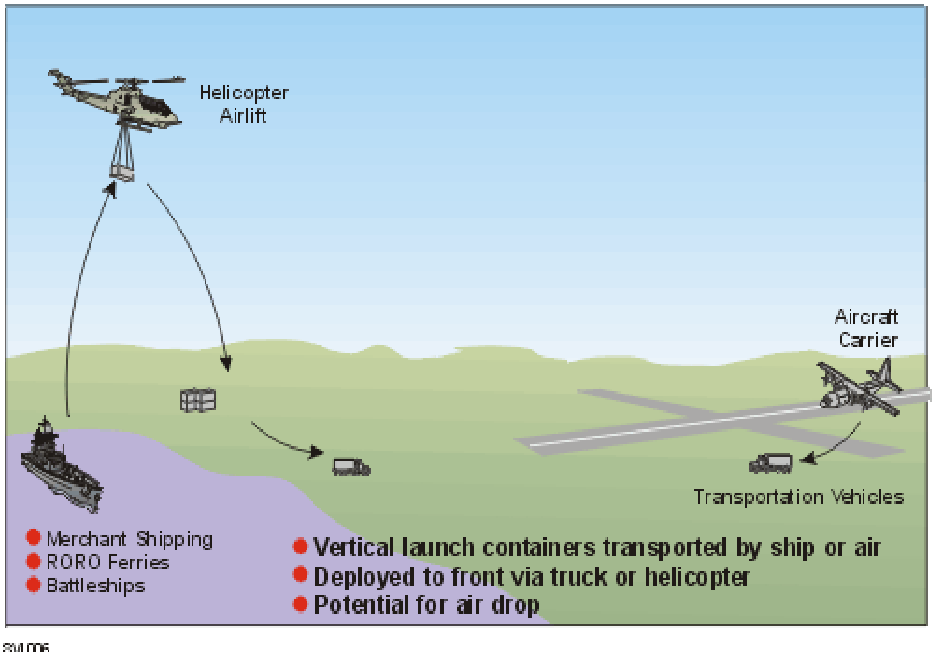

Figure 5 : Joint Service Use

SVL^{TM} is a technique that can be used to launch short or longer range missiles of differing types, thus providing the potential for different threats to be engaged using the same launcher. It also has the potential to be used for horizontal launch of missiles from platforms that cannot accept a severe launch environment (blast, noise or heat) such as small craft and helicopters.

Thus SVL^{TM} facilitates a more flexible response to target variety and offers the potential to change the weapons mix without affecting the overall configuration of the carrier platform. Figure 6 illustrates the concept for a SVL^{TM} launcher that has been configured to launch a mix of weapons - short and medium range missiles, countermeasures, and potentially micro-UAV's.

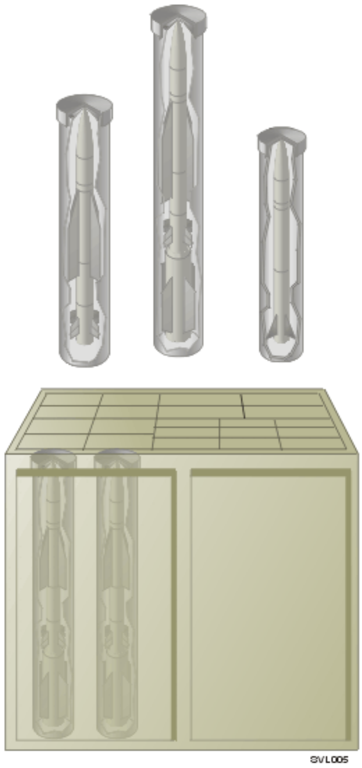

Figure 6 : Multi-role Launcher

Applied Research Technology Demonstrator

In 1997 the Soft Vertical Launch Applied Research Technology Demonstration (ARTD) programme was initiated by DERA Farnborough and carried out by MBD.

SVL™ ARTD - Phase 1

The aims were to demonstrate the proof of principle of soft vertical launch, and examine the applicability of the approach to larger missiles.

The technical approach to be demonstrated was similar to that described in the previous section. Missile turnover to a near horizontal attitude had to be achieved within a height of 30m, in 1 second.

A low cost, re-usable, cold gas, launcher was developed to soft vertically launch a 60kg SHORAD representative missile from a fixed ground location. Following launch the missile was to be turned over to near horizontal by means of a solid propellant, rocket powered, thruster providing lateral control in pitch and yaw. Once turned over, the missile was to be held at a selected heading and attitude by the thrusters.

The autonomous missile control system used to carry out the turnover sequence included proven, off-the-shelf, ASRAAM technologies - the inertial measurement unit and missile processors. Available hardware provided a low risk, quick and low cost method of demonstrating autonomous missile control. The required heading and attitude were communicated to the missile during the pre-launch sequence.

Pre-trials activities required the use of mathematical models and MBD's Synthetic Environment (SE) tools to predict the behaviour of the missile and its subsystems. A simulation based visualisation of its predicted pre-trial behaviour is shown in Figure 7.

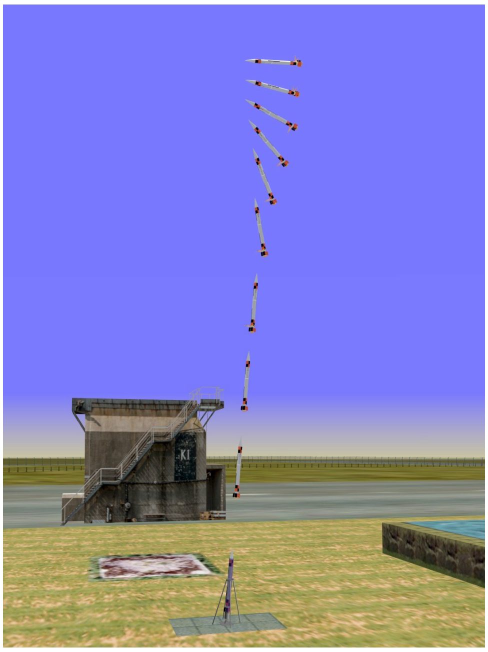

Figure 7 : Synthetic Environment SVL™ Prediction

A photograph of the missile flight from one of the three successful SVL™ firings at a UK trial's site is shown in Figure 8.

Figure 8 : SVL™ Demonstration Firing

The ARTD demonstrated the vertical launch of a 60 kg missile without the need for efflux management. Soft launch was achieved using a simple and compact launch tube. The ability to control the missile velocity and acceleration during the stroke length was demonstrated and the launch event clearly subjected the missile to relatively reduced launch loads that can benefit both missile and platform (see Figures 9 & 10).

Figure 9 : SVL™ Launch Phase

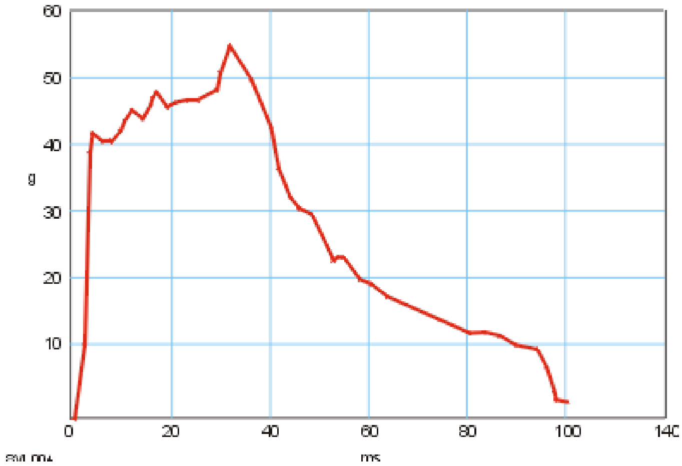

Figure 10 : Launch Accelerations

The successful launch of the missile using the basic piston approach also provided confidence for the future development of enhanced piston concepts. A simple device retained the piston within the tube resulting in no launch debris. The launch event also produced a low acoustic and visual signature.

Turnover was successfully achieved using an existing MBD, 8-nozzle, proportional control, thruster design that was adapted for the SVL™ application. Once ejected each missile was turned over rapidly, and stable attitude control was demonstrated by the use of lateral thrusters only. The thruster design concept is clearly viable for the SVL™ application.

The complex manoeuvres performed by the missile under thruster control would be difficult to achieve using alternative technologies e.g. TVC.

Application of Synthetic Environments (SE)

MBD piloted the use of Synthetic Environment (SE) tools during the SVL™ ARTD to demonstrate its risk reduction potential.

SE was used to visualise the system behaviour early in the programme (see Figure 7). This aided both the customer and subcontractors to understand the concept of operation. It also assisted in resolving problems and reduced the risk in the early design stages, by providing a more visible solution.

SE also assisted in missile integration and test. By combining simulations with hardware-in-the-loop, SE was used to demonstrate 'virtual trials' by exercising the missile electronics and control laws. It was possible to stimulate the system to explore tolerances to external influences (wind and launch angle). The SE tool was used to conduct a virtual trial, twelve months ahead of the real trials.

This approach can potentially reduce the number of (costly) firing trials required.

During each firing the missile behaviour was monitored by means of a recoverable, onboard, flight recorder. This data was processed by the SE to provide a simulation 'replay' of the missile flight. This was compared with the actual trials data to provide a confidence check of system behaviour (see Figure 11).

Figure 11 : Actual vs SE SVL™ Replay

Phase 1 Conclusion

The Phase 1 ARTD was a major success and clearly demonstrated the SVL™ principle and the viability of the concept for application to future ground-based and naval air defence.

A detailed system study also showed that SVL™, using the piston technique, is applicable to larger missiles - a 250 kg concept was analysed. Its use would enable such missiles to have a reduced minimum range compared to conventional VL methods, without compromising the maximum range capability. A Phase 2 ARTD then followed.

SVL™ Phase 2 ARTD

The aims of the Phase 2 demonstration are threefold and build on the successful work conducted during the Phase 1 SVL™ ARTD:

- To demonstrate the SVLTM technique using a hot gas powered launcher to eject a SHORAD representative missile.
- To demonstrate stable missile control transition following vertical launch turnover from thruster control at near zero speed to full aerodynamic control at missile speed.
- To demonstrate a flight weight missile turnover mechanism capable of pitch, yaw and roll control, and packaged around the missile blast pipe.
- To demonstrate virtual trials throughout system development using the Synthetic Environment application and measure its ability to reduce risks on programme costs and timescales.

This programme is being carried out by MBD for DERA Farnborough. Phase 2 is a three year programme and began early 99. Four soft vertically launched missile firings are planned during late 2001.

Technical Approach

The MBD SVL™ Phase 2 scheme is illustrated in Figure 12.

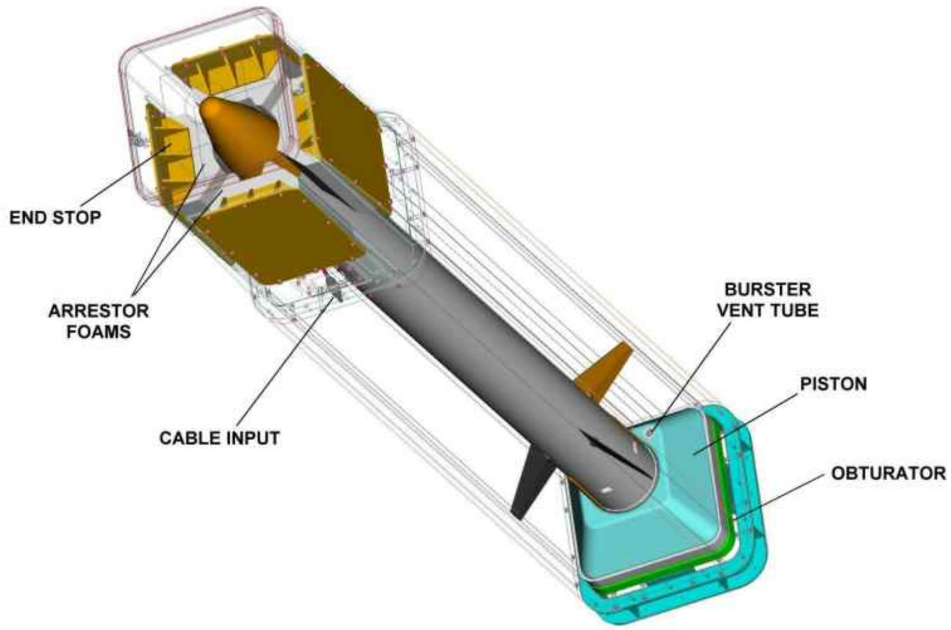

Figure 12 : SVL™ Phase 2 System Configuration

The 65 kg missile will be ejected vertically from a lightweight, tube using a hot gas powered piston technique. A square tube, desirable from both design and logistic standpoints, is made possible due to low launch pressures resulting from the novel SVL™ technique being developed by MBD. Hot-gas is proposed as the energy source where long-term standby is required, and where a one-shot device is more appropriate.

On initiation, the gas pressure, augmented by thrust, forces the piston upwards ejecting the missile. The piston, sliding within the launch tube, is caught and retarded at the end of its stroke. The ejection system imparts an initial velocity (of approximately 30 to 40 m/s) to the missile allowing it to reach the required turnover altitude and velocity within the specified time constraint (approximately 1 second from missile first movement).

The missile will incorporate a lateral thruster system, containing 8 thrusters in linked pairs to provide pitch, yaw and roll control, which will be initiated on exit from the launch tube. The thruster unit will be powered by an independent, annular, on-board gas supply and actuated via linkages to the fin servo system.

When the missile reaches the required height the boost motor will be ignited and during the initial phase of flight a stable handover in missile control from the thruster system to the fin actuation system will be demonstrated.

The missile will contain the ASRAAM missile electronics, inertial measurement unit and fin actuator.
MBD are extending the use of SE to demonstrate both virtual 'static and dynamic hardware-in-the-loop' trials. Its application will be monitored to measure its ability for reducing risks on the programme cost and timescales.

SVL™ Vision

SVL™ is a new and alternative vertical launch approach that has operational and integration advantages that will benefit ground based and naval air defence systems for joint operations.

It provides logistic efficiency through containerisation, can be platform independent and provides for a flexible, lightweight, responsive firepower system.

The technology offers the potential for a new generation of compact, lightweight, vertical launch missile systems that can be used with towed and self propelled vehicles, The launch packs can be integral with the vehicle, located with the vehicle or be deployed remotely (see Figure 13).

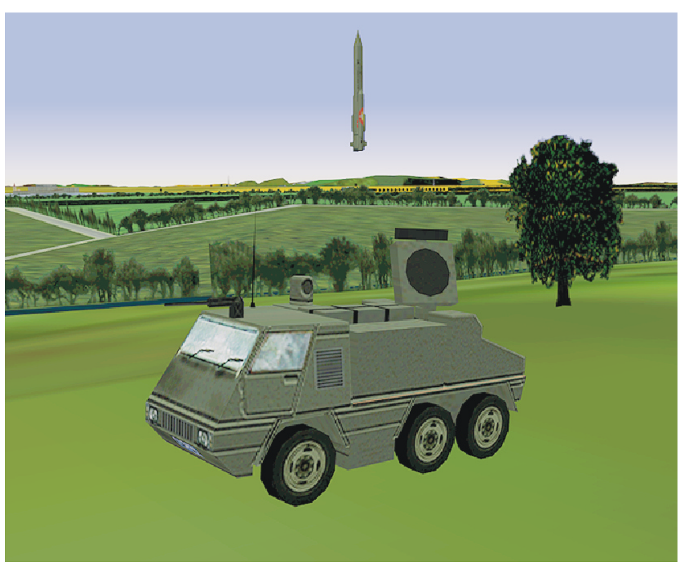

Figure 13 : SVL™ Integral with Vehicle Option

A potentially attractive concept is the possibility of launching SVL™ munitions from within transportable, modular containers that are appropriate to sea and land platforms allowing for commonality.

SVL™ launchers are particularly applicable to ships taken up from trade (STUFT), as well as fighting and support ships, because of the potential SVL™ offers for lightweight and modular structures that can be temporarily fixed and then removed. These structures have the added advantage of being able to be transported with an amphibious force, or helicopter, for use on land.

It is a technique that can be used to launch a mix of weapons using the same launcher. This facilitates a more flexible response to target variety and offers the potential to change the weapons mix without affecting the overall configuration of the carrier platform.

Standard ISO containers could be packaged with a weapon mix of encanistered SVL™ munitions from which the appropriate missile, countermeasure, and possibly micro-UAV, could be launched. The ISO container could include both the missile, and a fire control system with links to the navigational system and communications.

Alternatively, the fire control system could be housed in another ISO container and an interface with the navigation and link data system would be required. For fighting ships an interface to the ship weapon control system would be required.

In summary SVL™ technology offers many benefits compared with the current launcher systems available. The technology provides the opportunity to provide a flexible response system to the commander in terms of positioning of weapons, quickness of response and versatility in weapon load.

Conclusion

In order to meet the increasing requirements for the engagement of modern air-attack assets, the effectiveness of systems deployed by joint forces must be configured to provide a multi-purpose and multi-service capability.

SVL™ has the credentials to be considered as an enabling technology to satisfy this capability. Ground based and naval air defence weapons can potentially reduce their overall weapon life cycle costs by adopting the comparatively lower cost, lightweight and compact launcher configuration. The concept provides for a minimal required force structure, consistent with low manning deployment. By being modular, it can be appropriated for land and sea applications and would require less maintenance costs compared with hard VL systems.

The potential application of SVL™ on various types of ground based and shipping platforms, e.g., towed and self-propelled vehicles, military fighting ships, support and patrol ships and logistical support ships, indicates an initial role of SVL™ for point defence in the context of VSHORAD/SHORAD, ILMS and FILADS and could be expanded if required due to the versatility of the launcher.

Patents are pending to cover the method and technologies employed on SVL™.

Airspace Surveillance for Air Battle Management

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Introduction

Winning the air battle will be crucial in any future military campaign. Gaining the ability to use the air to our own ends, while denying its use to the enemy, requires adequate weapons, command and control (C2), communication and information systems (CIS) and sensors. In particular, air defence requires the support of airspace surveillance sensors – which is the topic of this paper.

This paper focuses on the future requirements for airspace surveillance (to support the management of the air battle), some of the options for future surveillance sensors and how they contribute to meeting the requirement.

Scope

The paper is concerned with the airspace surveillance required to support the management of the air battle, or in other words the Recognised Air Picture (RAP).

The paper addresses the airspace surveillance required to support future warfighting and non-warfighting missions (not just air defence), the limitations of current sensor types and the technical sensor based options to meet the future requirement. This has allowed the identification of a number of emerging capability gaps and the potential approaches available for filling these gaps.

The paper addresses ongoing developments in operational doctrine and threat. In particular, the development of manoeuvre warfare doctrine, the impact of stealth technology and the proliferation of attack helicopters (AH), unmanned air vehicles (UAVs), and cruise and stand-off missiles.

The paper does not address the surveillance required to support ballistic missile defence, ground based air defence, maritime anti-air warfare or the sensors on board combat aircraft. However, it recognises the influence of these other areas on the overall sensor mix.

The final decision on any future sensor mix will need to take into account a wide range of factors over and above simple sensor performance.

Context

Strategic context

Since the collapse of the Berlin Wall and the birth of the ‘New World Order’, NATO planning and the planning of individual NATO nations has shifted from being based primarily on fighting World War III to planning for a range of operations. These include:

- Article V operations (though of considerably more limited scope than in the Cold War);
- major regional contingencies (e.g. the Gulf War);
- peace enforcement (e.g. Kosovo);
- peace support (e.g. Bosnia);
- support to the civil power (e.g. Northern Ireland, in the case of the UK);
- disaster relief (e.g. after hurricane Mitch or the recent typhoon in Mozambique).

Paper presented at the RTO SCI Symposium on “System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces”, held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

The impact of this change has been particularly large on UK Air Defence forces. In the Cold War, the UK Ministry of Defence procured many systems specifically for the air defence of the UK. Now, however, the procurement of (almost) all air defence systems must be based on their capability to be deployed to and used within a non-UK theatre of operations.

There is not likely to be a requirement for an air defence capability in all of the above operations. For example, it is unlikely that there will be any need for air defence when repairing the damage done by a hurricane, earthquake or flood. Therefore, if there is no air threat then there is no need for an air defence capability (and little need for a RAP). Therefore, the range of operations which need to be considered in the context of this symposium run from those involving peace support and the policing of no-fly zones to limited wars and regional contingencies.

Operational context

Within the range of possible operations and campaigns there are a number of typical situations, or scenarios, within which the air defence system will need to operate. These are as follows:

- regional conflict in which the multinational force deploys in response to an aggressor attacking another, possibly NATO, country. This has two sub-cases: in the first, the multinational force deploys unopposed and begins military operations at a time of their choosing (e.g. the Gulf War); in the second, the multinational force is attacked/opposed during deployment (e.g. the Korean War).
- regional tension in which the multinational force deploys in response to posturing/threatening activity.
- late phase of a regional conflict in which multinational ground forces have advanced into enemy territory (possibly to regain territory captured earlier) (e.g. the Gulf War).
- operations other than war (also known as combined diplomatic military operations) including peacekeeping, peace enforcement, the enforcement of no-fly zones and service protected evacuations.

Many of the above scenarios are broadly similar to those for which NATO nations have been planning for many years in that they are primarily combat operations. However, the last set (operations other than war) are different and of growing importance. Therefore, it is worth considering these operations and the role of multinational forces within them.

Peace support operations

The end of the ‘Cold War’ removed the threat of the imminent outbreak of World War III and of a massive direct threat to NATO countries. It also allowed the UN Security Council to take a more active role in world affairs; no longer do the permanent members of the Security Council (USA, USSR, UK, France and China) almost automatically block resolutions with their veto.

However, the ‘Cold War’ had given a misleading impression of stability in a number of areas of the world. It had suppressed underlying tensions and the risk of nuclear war had obscured the emerging security threats. Thus, since the ending of the Cold War, many ethnic, territorial, religious and other differences have flared into conflict.

With a Security Council more prepared to sanction operations, to settle these conflicts and maintain international stability, the demands on the world’s military and civil organisations has increased. Thus, the NATO nation's Armed Forces find themselves involved in these operations. Peace support is a particularly good example of how the demands on the military have changed.

During the ‘Cold War’, if the UN sanctioned a peace support mission the peacekeepers followed the Scandinavian model. They (military and civil) were neutral, used minimum force, acted with the consent of all parties and without enforcement powers. They froze the conflict and used political means to obtain a settlement. The permanent members of the Security Council were not involved in these operations. (The two exceptions are France, UNIFIL mission in the Lebanon, and the UK, UNICYP in Cyprus.) The permanent members were, in general, perceived as biased and the focus of their military was on countering security risks from their super-power opponents.

Post ‘Cold War’, the UN Security Council has become more active in addressing threats to international stability. They are now prepared to sanction not just peacekeeping operations but peace enforcement operations. Operations in support of peace now range from the traditional through to the military enforcement of peace. Also, the permanent members of Security Council are active in peace operations.

Peacekeeping: Peacekeeping operations are undertaken under Chapter VI of the UN Charter or sanctioned by the Organisation on Security and Co-operation in Europe. They have the consent of all the major parties to a conflict, to monitor and facilitate the implementation of a peace agreement.

Peace enforcement: Enforcement operations can only be undertaken under Chapter VII of the UN Charter. They are coercive and may lack entirely the consent of the parties to the conflict. The aim is to establish peace or enforce the UN mandate.

The aim of peace operations (keeping and enforcement) is to create a stable environment where all parties to the conflict can move towards a consensual agreement. This agreement is normally built over a long period. It requires delicate skill to build and an appreciation of the impact of all operations, especially forceful action, on the belligerent parties, the media and support for the operation.

Peace support operations can largely be characterised by the degree of consent and violence. Within humanitarian operations, the parties receiving the aid generally want the military to be involved and any violence is likely to be small scale and localised e.g. riot control and banditry. Peace enforcers, acting without consent, may encounter organised military resistance, although this will tend to be in dispersed geographical pockets. Kosovo provides a recent example of large scale, and geographically extensive, organised military resistance to peace enforcement.

It is possible for peace support operations to degenerate. Peace enforcement can become full-blown conflict for a variety of reasons, including the peace enforcers becoming partial, or perceived to be partial, to one side. Similarly, it is possible for peacekeeping operations to degenerate into peace enforcement.

The emphasis in these operations is on:

- *Reassuranc*e, to restore the belligerents’ confidence in every parties peaceful intentions, by dispelling apprehensions and confirming positive opinions and impressions. For example, demonstrating the peacekeeping force's impartiality and commitment to peace, and providing information on other parties' passive stance.
- *Support*, to strengthen the belligerents' domestic infrastructure, provide aid and give help and corroboration. Humanitarian operations are principally support.
- *Deterrence*, to dissuade the belligerents from actions that obstruct peace, by persuading them the cost outweighs any potential gains. This supports diplomatic activity to avert conflict and is based on the peacekeepers’ evident capability, readiness to use that capability, sense of purpose and resolve. It is also based on the belligerents' values and the inference they draw from any action or counter-action. Deterrence can be:
  - *Implicit* - the demonstrated ability of being able to watch the belligerents’ activities and therefore to respond, or
  - *Explicit* - the proven ability to exact rapid retribution that will inflict unacceptable damage to the belligerents’ values.
- *Coercion*, to compel the belligerents, with force, to follow a course of action. The force is applied to meet a political rather than a military objective, but at the risk of escalating the conflict. The use of coercion must be carefully and deliberately considered.

Tactical context

The air defence system must have the capability to deal with all types of air vehicle, of any allegiance, including:

- fighter and fighter bomber aircraft;
- high value air assets (HVAA), such as tankers and airborne early warning (AEW) aircraft;
- civil aircraft;
- cruise or stand-off missiles;
- helicopters;
- unmanned air vehicles (UAVs);
- tactical ballistic missiles.

Fighter and fighter bomber aircraft are the traditional targets on which surveillance information is required. There is still a need for surveillance of these targets, for example when supporting a no-fly zone, engaged in symmetric[1] warfare with a capable opponent or constrained by rules of engagement (ROE) from attacking enemy airbases.

High value air assets (HVAA) and civil airliners are large targets that fly at, relatively, high altitudes, so are generally easy targets for the sensors to survey. Thus they are not key drivers of the sensor mix, unless considering the vital task of identification.

Cruise and stand-off missile proliferation represents an emerging threat to multinational operations. These weapons (using, for example, combined GPS and inertial navigation) are able to hit targets of known location (e.g. infrastructure targets) with only minimal support from reconnaissance, intelligence or surveillance assets[2]. This makes them attractive to less sophisticated adversaries and those who would expect to have to engage in asymmetric warfare with a Western coalition. In particular, they could pose a significant danger to the ports and airbases that are vital for multinational forces entering an operational theatre.

Attack helicopters are increasingly taking over the close air support role and gaining a deep strike role, so their importance as targets that must be detected, tracked, identified and dealt with is rising.

UAVs are becoming more widespread. Most are used in the reconnaissance role, so present a major threat to the ability of our land forces to successfully conduct manoeuvre warfare. Historical analysis has highlighted the importance of preventing enemy air recce, which will be increasingly carried out by UAVs, in achieving success in manoeuvre warfare.

Proliferation of tactical ballistic missiles (TBM) represents a recognised threat to multinational operations. However, this paper does not consider the specific problems associated with TBM surveillance.

Surveillance Requirement

'Can't see, can't fight'

Airspace surveillance means the detection, tracking and identification of air vehicles. To be useful, the surveillance data must be provided to those who need it and in a suitable format (i.e. the airspace surveillance system is tied together with appropriate communications and picture compilation systems in order to support the commander or decision maker).

In terms of the OODA loop, the airspace surveillance system provides observation and supports orientation.

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[1] Symmetric warfare applies to conflicts, like World War II or the Iran-Iraq war, where the advantage in a campaign or environment can swing from one side to the other. Asymmetric warfare applies to conflicts like Vietnam or Gulf War where one side continuously dominates an environment, such as the air or sea, and the other side may utilise unconventional methods.

[2] Increased support would allow the power of these weapons to be more fully exploited.

General requirement

Surveillance only needs to be good enough to support the required decision or task. It is possible to identify a number of high level tasks which surveillance should support. These tasks include (in warfighting operations):

- Provide picture of enemy/hostile activity: to provide intelligence about posture, etc. (i.e. general situation awareness).
- Warn own forces of the presence/activities of air vehicles: to allow appropriate passive and active defensive measures to be implemented.
- Locate/identify enemy bases/infrastructure and/or supporting forces: to support/allow attack by friendly assets.
- Locate/identify targets in flight: to support/allow attack by friendly assets[3].

In peace support operations the above may be modified and extended to include:

- Provide a picture of all parties' activities: both to reassure and deter.
- Provide proof of activity: for example, to prove to the media or United Nations (UN) security council that an agreement is being broken.

The accuracy, timeliness and completeness of the surveillance required to support each of the above tasks (and the detailed instances of them) will be different for each task (and instance). However, in general, the level of accuracy, timeliness and completeness increases as you move down the above lists.

The key requirement for airspace surveillance is that which relates most directly to air defence and force protection, namely locate/identify targets in flight to support/allow attack by friendly assets. Note that force protection tasks (such as air defence) tend to impose the most rigorous and time critical requirements.

The specific requirement can be different for different types of air vehicles or in different types of conflict. The requirement set also determines how difficult it is to fulfil that requirement (i.e. can it be done and is it affordable).

Specific requirements

When considering the requirement for the surveillance of hostile fighter or fighter bomber aircraft, this can be set in a number of ways and at a number of different levels. For example, the objective can be to provide sufficient surveillance to support the intercept of hostile fighters by friendly fighters that are already airborne and on a combat air patrol (CAP). This would only require surveillance cover extend roughly 50-100 nautical miles in front of the friendly fighters. However, a requirement to be able to support the scrambling of fighters from ground alert in time to allow the intercept of hostile fighters by some predetermined point, leads to a requirement for surveillance cover to extend much further forward in order to provide the increased warning time required.

Similarly, the difficulty of providing a system (and the associated surveillance) to defeat cruise missiles and stand-off missiles depends on the level of requirement. The objective could be to provide:

- Point and local area defence (e.g. key military and infrastructure targets such as HQ, bridges, ports and airfields);
- Area defence (e.g. defend an entire region including civilian population centres);
- Counter weapons of mass destruction (WMD) (e.g. destroy missiles at sufficient range to protect friendly countries and forces – in other words, the destruction of missiles outside friendly territory (and thus often over enemy territory));
- Conventional counter force (e.g. location of launch points with sufficient accuracy and timeliness to support the attack of the launcher).

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[3] Including the tracking of air vehicles from their point of origin to support Identification By Origin (IDBO).

Surveillance Problems

The provision of the required surveillance is made difficult due to a number of factors.

Atmosphere and weather

The need for long range surveillance, coupled with the problems of atmospheric absorption and clouds means optical and infra-red systems normally cannot obtain the required ranges: except in certain specialist applications, such as at detection of ballistic missiles and other high altitude targets by high altitude or space based sensors. Thus radar is the primary sensor used to provide the required surveillance, and the following discussion concentrates on radar sensors.

Low level and slow

Targets that fly at low levels (i.e. at a low altitude) cannot be detected at long ranges by microwave ground based radars as they are below the radar horizon.

The need to detect low level targets at long ranges is the primary driver behind airborne early warning systems (such as the E-3). But such airborne systems are looking down to see these low level targets, so are looking for them against a background of clutter. This does not present a major problem when trying to detect a fast moving target as moving target indication (MTI) or doppler processing can be used to detect the target despite the clutter. However, the ability to detect slow moving targets such as helicopters and propeller driven UAVs flying at 60-90 knots will be limited by the clutter.

Stealth

At present only the US is fielding ‘stealthy’ combat aircraft (i.e. the F117, B2 and F22). The cost of such aircraft is liable to mean that they are very unlikely to be deployed by opponents, other than in very small numbers, before 2020 (at the earliest): compare this with UK plans for FOAS in 2017+. However, it is much more likely that future combat aircraft, and aircraft modification or update programmes, will result in fighter and fighter bomber aircraft becoming a bit more ‘stealthy’.

The relatively simple shapes of missiles and their shorter development cycles make the emergence of a ‘stealthy’ missile threat much more likely. Western nations are planning to field ‘stealthy’ stand-off missiles around 2000-2005, so the technology to do this is liable to leak or proliferate by 2010-2015.

The potential impact of this is considerable. Consider for example a radar system capable of detecting a target with radar cross section of 1 m^2 at 200 miles (with some given probability of detection etc.). The impact of alternative assumptions about cruise missile radar cross section (RCS) on detection range and surveillance area (assuming circular coverage) is shown in table 1.

RCS		Range (miles)	Area ($miles^2$)
1 m^2	0 dBsm	200	125,500
0.1 m2	-10 dBsm	112	39,500
0.01 m^2	-20 dBsm	63	12,500
0.001 m^2	-30 dBsm	36	4,000
0.0001 m^2	-40 dBsm	20	1,300
0.00001 m^2	-50 dBsm	11	400

Table 1 - impact of stealth

Clearly 'stealthy' cruise missiles that combine a low RCS, with a low altitude flight path and the capability to hit fixed targets will pose a significant air defence problem.

ECM

Electronic counter measures (ECM), or jamming, can be used to degrade radar performance. Improvements in ECM systems increasing their responsiveness, directivity and choice of signal, coupled with reduced size and potential reductions in cost, may lead to an increase in the threat presented to the surveillance system by ECM.

Identification

Identification consists of two functions: classifying air targets by allegiance (e.g. friend, neutral, hostile) and class/type (e.g. UAV, fighter or F-16C).

The changing nature of the Western way of war (i.e. growth of peace support operations, reduction in perceived public acceptance of casualties (particularly fratricide) and the CNN factor) has led to the Rules of Engagement (ROE) becoming more restrictive. This increases the level of confidence required in the identification of target allegiance: it may also impact on the requirement for type identification as in the future different ROE may apply, for example, to manned and unmanned systems.

The ability to positively identify the allegiance and type of friendly platforms, through use of co-operative techniques (in other words IFF systems and use of data link messages such as the PPLI messages from JTIDS equipped platforms) and procedural methods, is generally good. However, the positive identification of small friendly unmanned systems (such as stand-off missiles and UAVs) may present problems. Other problems may arise from the multinational nature of future operations particularly those involving non-NATO nations, as these nations are less likely to be equipped with fully compatible co-operative identification systems.

At present the identification of the allegiance of hostile platforms relies almost entirely on procedural means, with support from some sensor systems (particularly ESM). Therefore, there is a problem with obtaining positive identification of the allegiance and class/type of hostile (and neutral) air platforms.

Tracking

The current Recognised Air Picture is primarily built up using a number of ‘turn and burn’ microwave radars, which provide target updates at 10-12 second intervals (assuming no missed plots). Thus maintaining tracks during high speed manoeuvring (e.g. combat) is unlikely.

Further, the picture is not built using all the plots produced by these radars, but is created by selecting the best tracks from the set of tracks produced by the individual radars. Thus the overall tracking ability is not greater than the sum of the individual tracking abilities; instead, the best track is selected.

This will lead to problems in the future if there is an increased need for proof of activity in peace support operations. For example, it may become necessary to be able to provide sufficiently continuous and accurate tracking to allow the presentation, perhaps ultimately in an international court of law, of ‘evidence’ of activity. For example, it may be necessary to be able to provide ‘evidence’ that an aircraft took off from a particular location, flew to a target, where it released a weapon, and then returned to its origin. Similarly, it might be necessary to prove that the multinational force shot down the pilot who carried out the attack, rather than his wingman.

Manoeuvre warfare

Operational doctrine is also changing and developing. In particular, there has been a general move away from attritional warfare to manoeuvre warfare. Thus ground combat forces are planning to fight a manoeuvre battle. This may mean that at some stage in a regional conflict they will have advanced deep into enemy territory (possibly to regain territory captured earlier) and in doing so bypassed enemy ground forces. However, there will still be a need to provide air defence of these advance units, which might lead to the need to orbit an E-3 over the bypassed enemy ground forces. This is not ideal as they may still have working SAM systems.

Similarly, there would be value in providing surveillance of enemy airborne air defence forces to the depth at which offensive air systems will operate. This becomes increasingly difficult as the range of offensive air systems increases and the range of defensive missile systems increases, which leads to increased stand-off ranges for AEW aircraft.

Capability Gaps

The above discussion has highlighted the following surveillance problems:

- *surveillance of* '*stealthy*' *cruise missiles and stand-off missiles*;
- *surveillance of helicopters and UAVs;*
- *positive identification of hostile (and neutral) air vehicles;*
- *providing* '*evidence*' *of activity in peace support operations*;
- *surveillance in the face of jamming*;
- *surveillance to support manoeuvre warfare or offensive air*.

The depth and importance of these gaps determines which require the most urgent attention.

Surveillance Options

Deciding what to do about these capability gaps is a complex and highly interconnected problem. Above all, any potential solution must be able to be implemented in the real world, so must be affordable. Thus, it is no use setting too demanding a requirement. In addition, it is necessary to consider a range of other factors over and above simple surveillance capability such as deployability, reliability, vulnerability and critically the need to interoperate with allies and coalition partners.

Setting a goal requires balancing the depth of the gap, how critical the gap is to success and the ease of overcoming the gap.

Technical capabilites

There are a number of future sensor developments or options which may well have an important part to play in overcoming these gaps. A number of the options are discussed below[4].

HF radar. There are three particularly interesting HF radar options:

- The first is the use of HF skywave radar to detect (fixed and rotary wing) aircraft and ships at very long ranges (between 500 km and 3000 km - ignoring any double bounces) by reflecting the radar beam off the ionosphere. HF skywave radar's primary drawback is the very large antenna array required, which severely limits deployability.
- The second is the use of HF surface wave radar, where the radar is sited on a coast so that the radar energy can couple into the salt water. This allows the radar to detect aircraft, and ships, down to sea level at ranges out to roughly 300 km.
- The third is the use of a much smaller HF radar using near vertical incidence scattering from the ionosphere to detect helicopters at ranges of up to 600 km.

VHF/UHF radar. Most stealth is designed to work at microwave frequencies and is thus less effective at longer wavelengths. Also, as wavelengths get longer then target resonance effects are observed which can increase the effective radar cross section of a target. Thus a missile which is 'stealthy' at microwave frequencies may not be 'stealthy' at VHF/UHF frequencies. Therefore, ground based or airborne VHF/UHF

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[4] Space based systems may well have a role in the longer term. Such systems would naturally provide the depth of coverage required.

radars are useful as a counter to stealth, and through increasing frequency diversity provide increased resistance to jamming.

Microwave radars. There are a number of options available for improving the performance of microwave radars including:

- Use of E-scan radars (also known as active phased array radars) where the ability to electronically change the beam shape and pulse characteristics in a flexible and responsive manner means that 'stealthy' targets can be more easily detected (using, for example, alert-confirm techniques), tracks can be updated more frequently if required (thus improving tracking accuracy), non co-operative target recognition (NCTR) techniques can be used to positively identify hostile air vehicles, and the radar can search for targets which have been detected by other (perhaps less accurate) sensors.
- Use of bistatic and multistatic techniques as a counter to stealth. Some stealth techniques deliberately reduce the signal scattered directly back towards the transmitter, and increase the signal scattered in other directions. Similarly, most stealth treatments are primarily concerned with reducing the forward sector signature of a target.
- Increased sensor integration. Low level targets (such as cruise missiles, helicopters and some UAVs) may be seen intermittently by a number of sensors (e.g. those associated with ground based air defence (GBAD) systems). If these sensors report their detections/tracks then the overall picture (i.e. RAP) is liable to be significantly improved. Similarly, the integration of the data collected by systems such as JSTARS and ASTOR, which are designed to provide an MTI picture of slow moving ground targets and which may also detect slow moving air targets (such as helicopters and possibly UAVs), would improve the air picture.

Network sensors. There are a number of options that could provide a network sensor capability. Such a network would be intended to provide robust and (very importantly) low cost detection of targets that are otherwise difficult to detect (e.g. cruise missiles, helicopters and UAVs). They may employ a variety of sensor techniques including forward scatter radar (where a target is detected as it flies through a network of low power transmitters and receivers), acoustic sensors, ESM and electro-optic sensors.

Figure 1 provides a simplified view of which of these various sensor options helps to overcome each of three problem areas (stealth, low level targets and ECM).

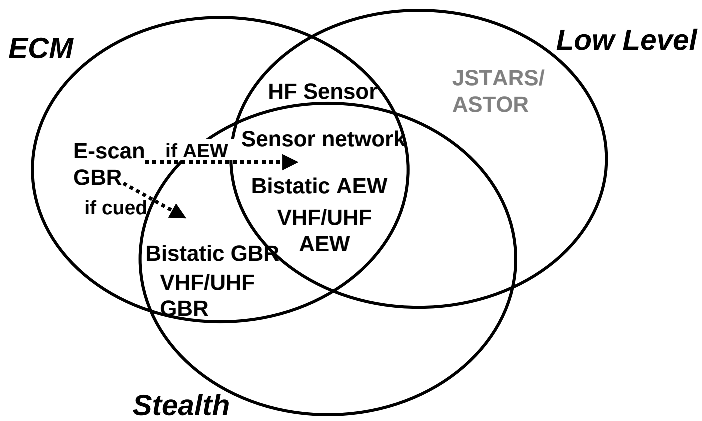

Figure 1 - sensor capability

Figure 1 is in the form of a Venn diagram, with three interlocking problem areas. The sensors are then placed on the diagram to show in which areas they offer improvements in capability. Thus a sensor at the intersection of two areas (e.g. HF sensors) offers improvements in both areas (e.g. low level coverage and jamming (through increased frequency diversity in this case)).

Figure 2 is the same as figure 1 with the addition of a rough representation of tracking accuracy and the ability to provide positive identification. Tracking accuracy is indicated by the size of the text: the larger the text, the more accurate the tracking capability. Identification capability is added round the edge of the diagram.

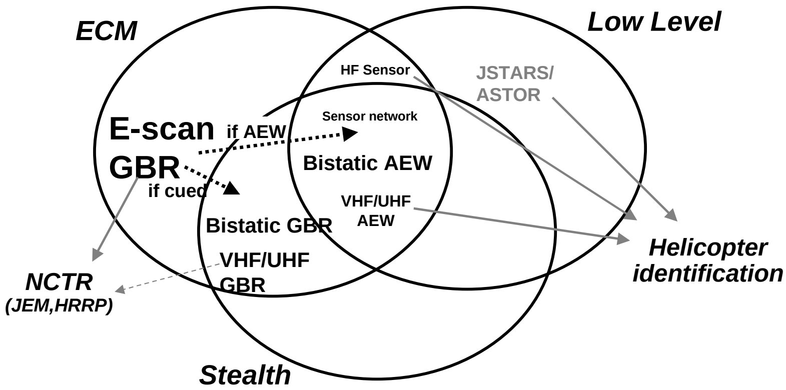

Figure 2 - further sensor capability

Tying the sensors together

The various sensors need to be tied together by an effective communications and picture compilation process in order to provide the information required by the commander. The variety of means available add extra layers of complication, and of options, to the decision making process about what surveillance system we need in the future.

Conclusions

This paper has concentrated on the surveillance required, and capability of the sensors to provide sufficient surveillance, to support future air battle management in both warfighting and non-warfighting operations.

The paper has not addressed the surveillance required by individual weapons systems (such as ships, fighters and SAM systems), but has concentrated on the wider requirements for a Recognised Air Picture. It has not addressed the requirements for Ballistic Missile Defence, as the author does not feel qualified to comment on the specific surveillance difficulties associated with BMD. However, clearly a TBM has a massive launch signature when compared with a cruise missile, flies significantly higher and is physically larger, but timelines are shorter.

The broad look at future requirements has highlighted the following existing, emerging and deepening problems (or capability shortfalls):

- *surveillance of* ‘*stealthy*’ *cruise missiles and stand-off missiles*;
- *surveillance of helicopters and UAVs;*
- *positive identification of hostile air vehicles;*
- *providing* ‘*evidence*’ *of activity in peace support operations*;
- *surveillance in the face of jamming*;
- *surveillance to support offensive air or manoeuvre warfare.*

The quick look at the capability of various radar sensor developments to fill these gaps has identified a range of technical options that can be used to overcome these gaps. However, without a full analysis of all the various factors (not least of which are cost and integration within multinational operations) it is not possible to say what the future mix of airspace surveillance sensors to support air battle management, and support air defence in multinational operations, should be.

Abbreviations:

AEW	Airborne Early Warning
AH	Attack Helicopter
ASTOR	Airborne Stand-Off Radar
ATI	Air Target Identification
BMD	Ballistic Missile Defence
C2	Command and Control
CAP	Combat Air Patrol
CIS	Communication and Information System
CNN	Cable News Network
dBsm	decibel square metres
DERA	Defence Evaluation and Research Agency
E-scan	Electronically scanned (e.g. active phased array radar)
ECM	Electronic Counter Measure
ESM	Electronic Support Measure
FOAS	Future Offensive Air System
GBAD	Ground Based Air Defence
GBR	Ground Based Radar
GPS	Global Positioning System
HF	High Frequency
HQ	Headquarters
HRRP	High Resolution Range Profile
HVAA	High Value Air Asset
IDBO	Identification By Origin
IFF	Identification Friend Foe
JEM	Jet Engine Modulation
JTIDS	Joint Tactical Information Distribution System
MTI	Moving Target Indication
NCTR	Non Co-operative Target Recognition
OODA	Observe Orientate Decide Act
PPLI	Precise Position Location Indicator
RAP	Recognised Air Picture
ROE	Rules of Engagement
RCS	Radar Cross Section
SAM	Surface to Air Missile
TBM	Tactical Ballistic Missile
UAV	Unmanned Air Vehicle
UHF	Ultra High Frequency
VHF	Very High Frequency
WMD	Weapons of Mass Destruction

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Basic Distributed Control Model and Technology for Mobile Crisis Reaction Forces and their United Air Defense

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Abstract: The paper investigates the use of the distributed processing and control model and technology, WAVE, operating in open computer networks and providing integral solutions of complex problems on a high semantic level, for a variety of system organization and management levels and tasks in relation to the mobile Crisis Reaction Forces and their integrated air defense. The technology hides most of traditional communication and organization routines like message passing, intelligent agents, mobile agents, remote procedure calls, remote method invocation, distributed object brokers, etc., within the system implementation, allowing application programs to be extremely powerful and compact. Based on a free migration of cooperative program code in both physical and virtual worlds and parallel spatial matching of the systems navigated, while creating and modifying the systems themselves, the technology allows for an unlimited scaling, and works equally well with any number of computers and any network topologies, which may be loose, dynamic, and open.

1 Introduction

Crises appear in different, often unpredictable points of the world. Their scale may range from local regions in particular countries to the whole continents or even world-wide. Typical examples may include forest fires, earthquakes, flooding, nuclear plant accidents, viral diseases, ethnic conflicts, coups, etc. Separate countries with often limited national natural, technological, technical, and human resources may be unable to withstand the problems occurred. That is why critical may be the use of united, rapidly composable and deployable international forces, where the dissimilar resources from different countries should be united within the common disaster or conflict relief mission.

Efficient computerization of the international Crisis Reaction Forces (CRF), which may be required to operate in highly dynamic and hostile environments, is vital for keeping their integrity, external and internal controllability, and high survivability. Radically new information and networking technologies may be needed oriented on solving the mission problems in a parallel and distributed mode, pursuing both local and global, often dynamically changeable, goals. These technologies should allow for an efficient merge of distributed heterogeneous information and command and control systems of constituent forces from different nations, supply and re-supply of limited, both crisis relief and own mission support resources, runtime re-composition and recovery from indiscriminate damages, high overall awareness with collective decision-making, and quick reaction on multiple external threats.

Advanced military-oriented mobile CRF, due to high level system organization based on computerization and networking, may be capable of withstanding considerable enemy forces and solving very complex military tasks in a highly flexible mode, often without involvement of traditional heavy armor techniques. As an example of a possible development of CRF may be the organization of Future Combat Systems (FCS) – a US army vision of 2025, with the related project just announced by DARPA. FCS will represent strategically deployable, tactically superior and sustainable force, with quick reaction capability, air-mobile operation, lightweight units (not more than 20 tons each), increased lethality, survivability, mobility, and deployability. They are also expected to have effective distribution of sensors and integration of robots into the force, overall networked organization and networked fire, high common situational awareness and understanding.

Paper presented at the RTO SCI Symposium on "System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces", held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

A very important but extremely complex problem for international mobile CRF, with their distributed, changeable and dynamic organization and structure, is an efficient air defense in order to protect from aerial attacks, rockets, artillery, mortars, and aerial observation, always preserving integrity and uninterrupted functionality. The following tasks are among the many to be solved efficiently for the air defense of CRF: quick discovery of hostile aerial objects throughout the internationally controlled region; identification, tracking and behavioral analysis of multiple targets; global assessment of the aerial threat with making collective decisions; optimization of the use of distributed antimissile weapons; interface with other weapon systems and manned or unmanned fighter planes; participation in the higher-level battlefield operations and management.

The rest of the paper is organized as follows.

Section 2 shows the need of radically new information and networking technologies capable of supporting such dynamic distributed systems as CRF, because traditional cultures and approaches to organization of distributed networking projects inevitably lead to huge communication, synchronization and control overheads, numerous seams and multilingual patches. The interpreted WAVE distributed control model, language and technology, allowing for high-level semantic solutions in the space navigation mode, with unlimited program code mobility, may be a real candidate for the integration of CRF-like systems. It hides most of traditional organization and management routines within the language implementation, making parallel application programs extremely simple, powerful, and compact.

Section 3 gives a brief overview of the extended WAVE language capable of describing parallel and distributed solutions in both physical and virtual worlds. General organization of the recursive language syntax and basics of semantics are given, with details concerning representation of space and movement in it, data structures, different types of spatial variables which may be stationary or mobile, elementary operations, and control rules setting proper constraints coordinating parallel conquest of space.

Section 4 provides some information about the implementation of WAVE by a network of the language interpreters, and describes a general organization of the interpreter which can execute parts of WAVE programs (waves) while sending other parts to another interpreters. Forward and backward data and control echoes being other communication messages, with the overall integrity of self-evolving spatial processes provided by the dynamic distributed track system. The interpreters can also reside on mobile platforms, being invoked at runtime in proper locations on the demand of space-navigating waves.

In **Section 5**, a review of a number of existing practical applications of the WAVE technology is provided, which include integration of distributed databases, intelligent network management, distributed interactive simulation of dynamic systems like battlefields, distributed multiuser virtual reality, road traffic management, and modeling collective behavior of robots. A number of projects have been successfully demonstrated via the Internet with computers distributed between different countries.

Section 6 describes advantages of organization of mobile CRF in WAVE, among which high integrity, flexibility, and external controllability may be of particular importance for advanced military campaigns, with WAVE interpreter being installed in both manned and unmanned platforms. The section provides solutions in WAVE of some basic CRF management operations. First, it describes parallel creation and reconfiguration of a hierarchical command and control infrastructure establishing subordination between the army units. Second, it defines and recursively implements a typical command and control process, with commands being executed at different levels, and modified and sent further down to the subordinate levels, with the execution confirmation ascending the hierarchy. Third, it provides an exemplary solution of a typical resource management and distribution task, where some limited resource from a central storage is physically delivered to army units that requested it, where the decision concerning a particular amount allowed to each requesting unit is made via the established command hierarchy. The section concludes with a multiple management scenario, where different local scenarios, on behalf of army units, regularly interact with each other via the infrastructure, in order to find a balanced distributed solution satisfactory to all parties, one scenario performing a global moderation.

Section 7 is concerned with the use of WAVE for organization of a united air defense of CRF. The main task here is to integrate into one system the radar stations belonging to different army units, which may be of short range and not capable of covering the entire air space alone. To keep the whole space under control, the stations must communicate. To optimize communications, a radar neighborhood infrastructure is dynamically created, maintained, and regularly updated in WAVE, through which most communications between radar stations should take place. The main mobile tracking algorithm in WAVE is demonstrated which, after having seized an aerial object, follows it via the neighborhood infrastructure, providing the object's handover between radar stations. Many such objects may be tracked independently and in parallel. Possible payload of this basic algorithm is discussed like collection of the object's itinerary, analysis of its behavior, and invocation of antimissile weapons. The latter may also need networked solutions to be towed by mobile software agents to the proper regions in space to meet the targets.

In case of being lost, the objects can be rediscovered by other stations, with new mobile processes uniquely assigned to them. Using additional stationary and/or mobile coordination processes in WAVE, interacting with the mobile tracking processes, it is possible to make a non-local optimization of the use of limited antimissile hardware, keep an overall awareness of the level of aerial threats, as well as find suitable system solutions interactively. Many other air defense related problems of mobile CRF may be described and solved in WAVE in a similar way, while keeping the whole system as a highly intelligent reactive and self-protective distributed brain.

Section 8 concludes the paper, summarizing main features of WAVE and outlining prospects of its use for advanced military systems.

2 In a Search for the New Organization and Coordination Technologies: WAVE

CRF will need distributed system solutions, as different, often dissimilar, pieces of the mission information may potentially be located in any computer and in any vehicle, and no central databases or centralized processing, control and management may be welcome, in order to reduce the system's vulnerability to a minimum, as any parts of the system may be indiscriminately damaged in a campaign.

2.1 Traditional overhead of networked solutions

In single-processor solutions, written in traditional application languages, everything is used to be at hand, and full and direct control over any resources is guaranteed. Changing any strategy or tactics may need a single operation only (just changing the program counter on a machine level). For CRF, to provide fully distributed solutions, the whole project should be considered as broken into many pieces (see Fig. 1) which have to be distributed in space and, moreover, may move physically, constantly changing absolute and relative to each other positions.

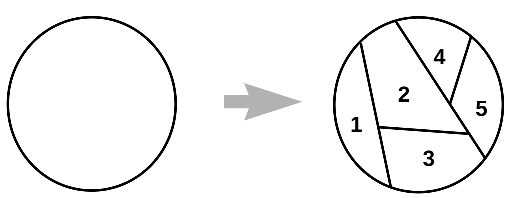

Fig. 1. Breaking an integral single machine solution into multiple pieces for distribution

Making these pieces, located now in different computers, work together properly, often results in a huge communication, synchronization and (multilevel) control overhead, with involvement of other languages and techniques for gluing and linking. This inevitably leads to system heterogeneity, multiple patches, and seams. The overhead often outweighs, by orders of magnitude, the useful work done in a single machine solution (see Fig. 2). Distributed networked systems also take considerably longer time to understand, design, debug, test, and produce.

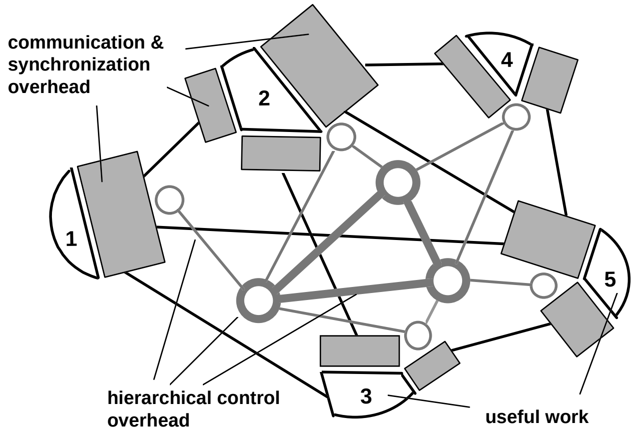

Fig. 2. Traditional communication and control overhead of distributed networked solutions

All this puts forward, especially for such dynamic distributed systems as CRF, a necessity of special formalisms and technologies that would allow to reduce the difficulty of achieving distributed computerized solutions, while making them comparable in complexity, say, to programming on a single machine. Such formalisms should orient primarily on integration, control and management, rather than computation, and should allow for the description of distributed system solutions on much higher than traditional levels, in order to hide the diversity of communication routines, patches and seams, currently needed to be programmed explicitly in traditional distributed projects, within the implementation. The WAVE model and technology discussed in this paper are just oriented on meeting and fulfilling these objectives.

2. 2 Distributed computation and control in WAVE

WAVE is a special parallel and distributed coordination and computation model operating in open networks [1]. It is technically based on a universal control and data processing module, communicating copies of which are distributed throughout the system to be controlled. The static or dynamic network of the modules is governed at the top by a high level distributed processing language, WAVE, allowing for parallel navigation and supervision of the whole system or its arbitrary parts and interaction with multiple users. The said modules being copies of the WAVE language interpreter, which may have both software and hardware implementation. Navigating in space, WAVE also creates persistent distributed virtual, or knowledge, networks, shared by differed users and other navigational processes, effectively supporting scaleable control, simulation, and virtual reality systems. Any other systems and technologies, in a variety of other languages, can be accessed, integrated, and controlled in WAVE.

The WAVE language describes a stepwise parallel flooding, or coverage, of physical or virtual spaces, as depicted symbolically in Fig. 3, providing distributed seamless solutions of complex system problems without traditional message passing, RPC, clients-servers, agents, mobile agents, objects, etc., usually causing huge programming overhead. These and other techniques are used *on implementation levels only*, completely relieving programmer from traditional routines and making coordination and management programs extremely powerful and compact.

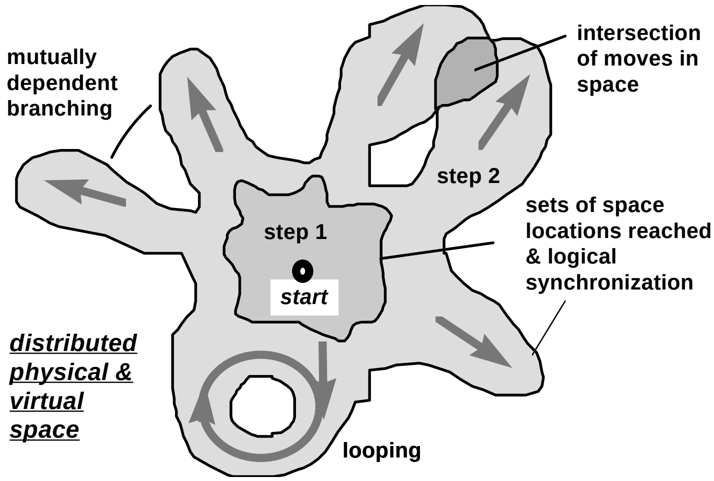

Fig. 3. Seamless integral distributed navigation & supervision & processing in WAVE

3 Extended WAVE Language

3.1 General organization

WAVE language programs (called “waves”) describe multiple actions in distributed, both physical and virtual worlds (respectively, PW and VW), as well as in their combinations. Every elementary activity provided by the language is said to be performed in a *node* which represents a proper point of physical or virtual space. Nodes may be temporary, just identifying locations where and when the activity is applied, or persistent, expressing established concepts or facts which may exist independently, as they are, and remain arbitrary long time.

Waves, starting from some point (node), propagate in space, sequentially or in parallel, causing the appearance of new nodes, or entering the already existing nodes, created (and, possibly, occupied) by other waves. During the propagation, waves may form and leave links between nodes reflecting different kinds of inter-nodal relations. Arbitrary actions can be performed in nodes, including changing the node and/or link contents, as well as removing the nodes together with the adjacent links. Additional, temporary data may be left at nodes and shared with other waves, while other data can move with waves further, as their property. The data may represent pure information, physical matter or combination thereof. Staying and doing computations in nodes, waves may also search physical or virtual spaces to a given depth, by launching subordinate waves for collecting and bringing back (remote) data, to be processed further in the current nodes. They can also change data in (remote) locations and interact with other waves through the shared access to the same nodes.

Multiple waves, evolving simultaneously in the same or in different nodes, may be covered by distributed recursive control set up by *rules*, evolving and propagating in space together with the waves. Rules coordinate cooperative, competitive or independent conquest & supervision of space in both breadth and depth mode. They also provide creation of distributed virtual networks by linking the newly formed or already existing nodes, perform spatial merging and parallel processing of multiple remote results, as well as allow WAVE to be used as a traditional sequential or parallel programming language.

WAVE has an extremely simple, recursive, syntax, shown in Figure 4, where coordinated propagation in space can be integrated with the collection, return, and processing in the space locations of data obtained in another, possibly, remote locations, via another space propagation. Words in Fig. 4 represent syntactic categories, braces show zero or more repetitions of a construct with a delimiter at the right, square brackets identify an optional construct, and a vertical bar separates alternatives. Others being the language symbols: semicolon allows for a sequential, while comma for parallel or arbitrary order invocation of waves (under some rules, comma may serve as just a separator between branches), and parentheses are used for structuring waves.

Sequential steps, or *zones*, develop from all locations/nodes of the set of nodes reached (SNR) by a previous zone, while parallel steps, or *moves*, develop from the same nodes, adding their SNRs to the SNR of the zone. SNR may contain nodes repeatedly, reflecting splitting & intersection of waves in the same locations, and subsequent SNRs may have nodes of the previous SNRs, thus allowing for loops in space.

```
wave      →   { zone ; }
zone      →   { move , }
move      →   value | { move act } | [ rule ] ( wave )
value     →   constant | variable
variable  →   nodal | frontal | environmental
act       →   control_act | fusion_act
rule      →   forward_rule | echo_rule
```

Fig 4. WAVE language recursive space-navigating syntax

Moves have a recursive definition and can be of three types. First, they can point at a resulting value directly (as a constant or variable). Second, they can form space navigating & data processing expressions consisting of arbitrary moves separated by elementary operations, or acts, where moves may return (local or remote) results on the demand of acts, or assign the results to (local or remote) variables, or do the both. Third, they can themselves be arbitrary waves (in parentheses), optionally prefixed by control rules. This simple recursive definition of moves allows for an extremely powerful and compact expression of arbitrary complex, parallel and distributed space navigation, data processing and control operations, which can be carried out in a fully distributed and highly parallel mode.

3.2 Some language details

Representation of space. Any point in a continuous PW may be represented and reached by its absolute coordinates, as a *node*. Moving to other points/nodes can use the absolute destination coordinates or coordinate shifts from the previous node. It is also possible to move to the already existing nodes, reached by other activities within a certain range from a given center point, and many such nodes may be reentered simultaneously. PW nodes are temporary and exist only if activities (waves) stay in them. VW nodes have names, being also their contents, by which they may be referred to globally. They also have unique addresses, which may be used for their quick direct access. Nodes may be interconnected by links, links having names or contents too. Movement in VW may be done by direct hops using node names and addresses, or by following links (using their names and orientation), this movement can be done in a selective or broadcasting mode. VW nodes are persistent: after creation, they exist until deleted explicitly; this is accompanied by a deletion of adjacent links. Node and link names may be any strings of code, including programs to be executed (in WAVE or any other language). VW nodes may be associated with proper locations in the PW, and PW nodes may have addresses and may be dynamically linked to VW or other PW nodes, resulting in a deep, seamless, integration of both worlds within the same space-conquering & processing formalism.

Vectors. The only datastructure of WAVE, symbolically called a *vector*, is a dynamic collection of elements separated by a comma and enclosed in parentheses, if more than one element. Vectors have dual data & program nature, being treated as evaluated waves. All acts in the language are defined over vectors and operate on their multiple values. The latter may be numbers or strings where strings in single quotes represent information (braces are used to represent program strings to be optimized), and in double quotes -- physical matter. Different acts over vectors treat them either as ordered sequences or sets. Special syntax of waves and the possibility of creating arbitrary virtual networks navigated subsequently by other waves, allow us to work easily with arbitrary datastructures of any existing or imaginary languages, and in a highly parallel and fully distributed mode.

Variables. There are three types of distributed dynamic variables the spreading waves operate with. *Nodal*, or stationary, variables (identifiers prefixed by N or M) are created in nodes and may remain there, shared by different waves traversing the nodes. *Frontal* variables (identifiers starting with F) travel with waves, replicating when waves split. *Environmental* variables (each having a special name) access different properties of the navigated PW and VW worlds, also providing impact on the worlds in their different points.

Acts. Acts, operating on their left and right operands, may form arbitrary complex world navigating & data processing expressions, directly working with both local and remote values. *Control acts* permit, direct, or halt program and data flow through nodes where they are interpreted, can inject new executable wave code into the program. *Fusion acts* provide data processing, returning results to be used by other fusion or control acts, they can also access external systems. A number of fusion acts can be applied to physical objects and their storage, while other operations on physical matter may require special external functions.

Rules. *Rules* establish a variety of constraints upon the distributed development of waves. *Forward rules* coordinate spreading of waves in space. Among them, *branching rules* split the wave and coordinate parallel or sequential development of different branches. Other forward rules include repetition of spatial navigation, remote logical synchronization, protecting access to common resources, granting autonomy to waves, allowing spreading waves to create distributed networks, etc. *Echo rules* accumulate, generalize, and process states or results (including remote) reached or produced by the embraced wave, returning them to the rule activation node for further assessment and processing. Rules operate using a powerful internal track & echo system allowing for a generalized, as well as detailed, supervision of distributed solutions, which may spread over arbitrary large territories.

4 WAVE Implementation

The WAVE language is executed by a network of software or hardware interpreters interacting copies of which should be installed in different parts of the systems to be managed.

4.1 The interpreter architecture

General organization of the interpreter is shown in Figure 5. It consists of the three main functional modules: *parser*, *data processor*, and *control processor*. These divide between themselves the responsibility of handling different interpretation data structures, performing specialized operations of the language parsing, execution, and exchanges with other interpreters, where the operations in different units may overlap in time. The interpreter, if to be installed in (manned or unmanned) mobile platforms, may also contain special software or hardware modules coordinating continuous motion in space, providing vision of the environment, manipulating with physical objects, etc., as well as making communication with other interpreters using radio, radar, laser or sonar channels. The communication module finds other interpreters (vehicles) in space by the given search parameters and exchanges with them waves, echoes and remote results via incoming and outgoing queues. Links between the modules are shown in Figure 5 together with main types of information moving along them.

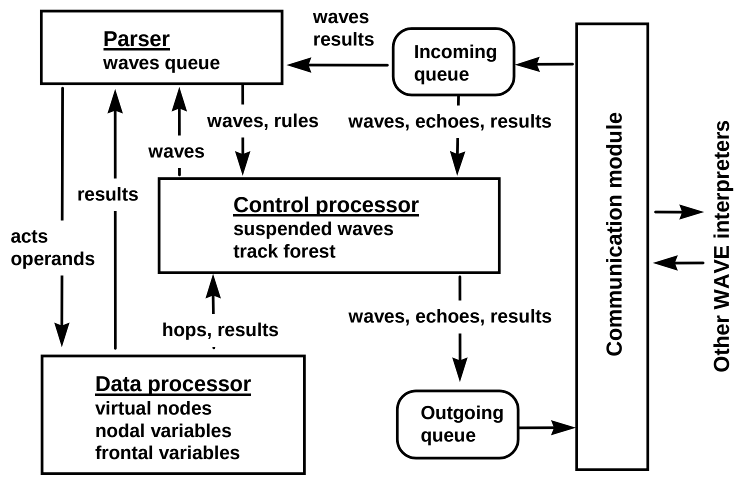

Fig. 5 The WAVE interpreter architecture

4.2 Distributed interpretation in dynamic networks

WAVE interpreters may be stationary, say, as hosts or special coprocessors working via the Internet, or embedded into mobile, both manned and unmanned, platforms. The same space processing formalism allows for a unified coordination of a variety of stationary and mobile systems, as well as their combination.

Predominantly stationary applications of WAVE have been discussed in detail in [1]. Highly dynamic solutions in WAVE may be linked with implementation of flexible parallel scenarios by groups of cooperating mobile robots [2-5], where waves are executed by communicating interpreters which process data related to different nodes in a physical world, and move further if encounter hops to new PW locations. If an interpreter has not completed jobs in some node and has to perform a physical hop, or if a broadcasting hop leads to a number of PW positions, another interpreters may be requested to perform the hops in space, into which the rest of wave may be loaded directly from (and by) the current interpreter (interpreters thus charging each other directly, without an external help). Different strategies of runtime invocation of new interpreters can be used for the evolving spatial scenarios in WAVE [3].

Some general picture of the execution of a unified WAVE scenario in an integration of stationary computer network with mobile manned or unmanned platforms, the latter engaged on a demand of the scenario, may look like the one shown in Figure 6.

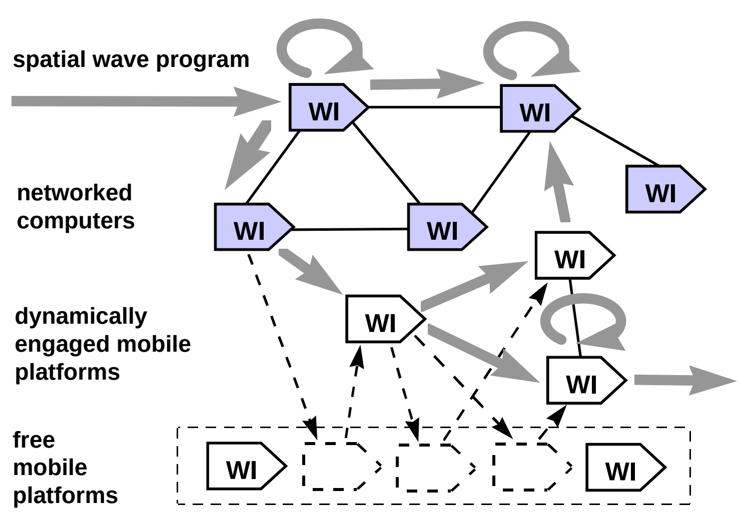

Fig. 6. Unified organization of stationary and mobile networked systems in WAVE

5 Examples of Existing WAVE Applications

Having a long history of development, implementation, and testing in different countries, including world wide experiments via the Internet, WAVE may have efficient applications in a great variety of fields. Some practical examples and results obtained are listed below.

Distributed databases. WAVE was used to create, integrate, and manage large distributed, heterogeneous databases, where any data record can potentially be located in any computer. Integrating dissimilar databases located in different computers and written in other languages, WAVE added an efficient multiuser management layer to the whole system [6,7,9]. Highly parallel and intelligent databases were written purely in WAVE too, allowing for advanced distributed inference and data mining [1,8].

Intelligent network management. Based on a mobile cooperative code freely spreading, self-replicating and recovering in networks, WAVE was efficiently used for management of open computer and communication networks. Having integrated standard network management systems retrieving large amounts of data related to routers and hosts, WAVE was used to extract proper knowledge from the raw data and add top level topology and traffic analysis, improving the overall network performance [10]. A number of key management functions for the cellular networks have been implemented and demonstrated in WAVE, tracking mobile users without (or with minimum use of) central databases [1,11]. Mobile IP protocols, combining the use of computer networks and mobile communications, have been modeled in WAVE too [12].

Distributed interactive simulation. WAVE was used to organize interactive multiuser simulation of large dynamic systems. A distributed system modeling air battles between different types of aircraft was demonstrated, which also integrated aerodynamics modules written in other languages [13-15]. The system comprised dynamic terrain (like radioactive clouds) spreading gradually between computers (and the screens), to be avoided by planes. The system allowed any user to observe both the global battlefield picture and any its local, possibly remote, parts.

Distributed multiuser virtual reality. Creating and processing dynamic distributed knowledge networks, WAVE was used for distributed multiuser virtual reality systems and multicomputer graphics. Efficient integration of the basic VR language, VRML, with WAVE has been implemented and demonstrated [16-18], allowing for dynamic generation, processing, and visualization of VR scenes on many computers. Parallel techniques for creation and transformation of dynamic images in distributed virtual spaces has been programmed and demonstrated [1,19].

Road traffic management. WAVE proved to be useful for advanced road traffic management systems based on distributed computer networks, which are free from traditional bottlenecks caused by the use of centralized or hierarchical databases. A horizontal system describing part of the UK highway network was implemented and demonstrated in WAVE on many computers, with optimal routing for multiple cars, rerouting in case of traffic jams and road damages. The system also simulated the chase of suspected vehicles by police [1].

Modeling collective behavior of robots. Based on mobile cooperative control code spreading in virtual networks, WAVE was successfully used for modeling collective behavior of automatic vehicles moving through space and avoiding obstacles, finding paths through complex mazes, and reaching proper destinations. The vehicles were able to both cooperate and compete for the space and jobs to be done, while pursuing common global goals [1,2].

WAVE public domain. More information about some former projects may be obtained from the WAVE public domain webpages in Germany [20], and UK [21].

6 Organization of Mobile CRF in WAVE

6.1 Advantages of WAVE

Installing communicating copies of the WAVE interpreter in main units of advanced mobile CRF (see Figure 7, in relation to FCS) may provide highest possible integrity and controllability of such systems, which my become capable of performing complex tasks and pursuing both local and global goals in a totally distributed manner, under the guidance of ubiquitous and interactive wave programs.

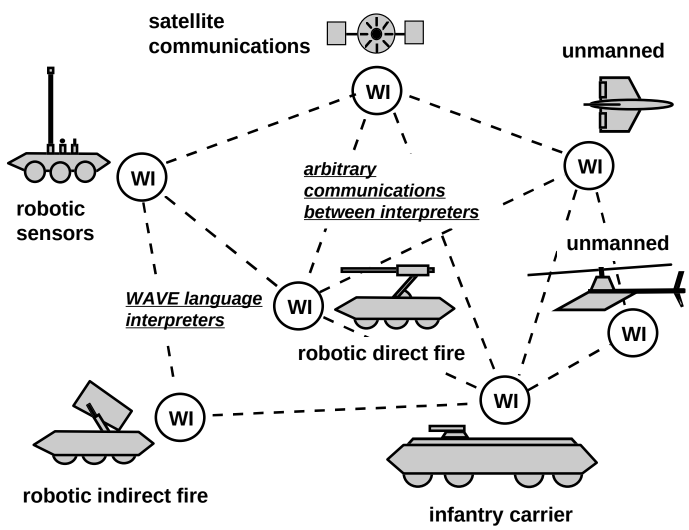

Fig. 7. WAVE interpreter as a universal integration module for advanced mobile Crisis Reaction Forces

WAVE may be particularly useful for solving the following CRF problems:

- Linking distributed heterogeneous military databases.
- Integrating dissimilar command and control systems of different nations into a united C4I infrastructure.
- Self-analysis and self-recovery after indiscriminate failures and damages.
- Support of openness and runtime recomposition and reconfiguration of the international force.
- Automated collection of readiness & operability & statistics, global assessment of distributed situations.
- Efficient integration of unmanned platforms into the force mix.

The following sections provide some elementary examples of using WAVE for the integration of (mobile) CRF.

6.2 Parallel creation and reconfiguration of a united infrastructure

Any topology may be represented in the WAVE syntax in a most compact manner, as a linked graph template, and created in a parallel and fully distributed mode, by deployment and self-evolution & spreading of this template in space. The following program, starting from unit1 (chosen as top of the command hierarchy to be formed), creates oriented links named “infra” between army units, as shown in Fig. 8, in a template flow & unwrapping mode:

```
direct # unit1;
create(
  (+infra ## unit2; +infra ## unit6),
  (+infra ## unit3; +infra ## unit4,
                    +infra ## unit5
  )
)
```

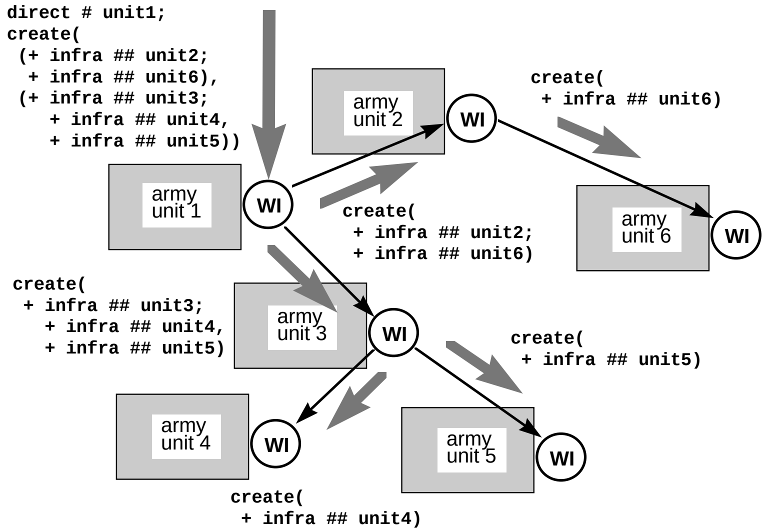

Fig. 8. Runtime creation of a united command and control infrastructure

Any created topology can be easily modified in WAVE by another template which will evolve on the existing topology, dynamically matching it. For example, starting from unit5 and deleting existing link to unit3 in parallel with creation of a new “infra” link to unit2, directed to unit5, the following program-template is sufficient, causing the effect shown in Fig. 9.

```
direct # unit5;
  (any # unit3; LINK = nil),
  create(-infra ## unit2)
```

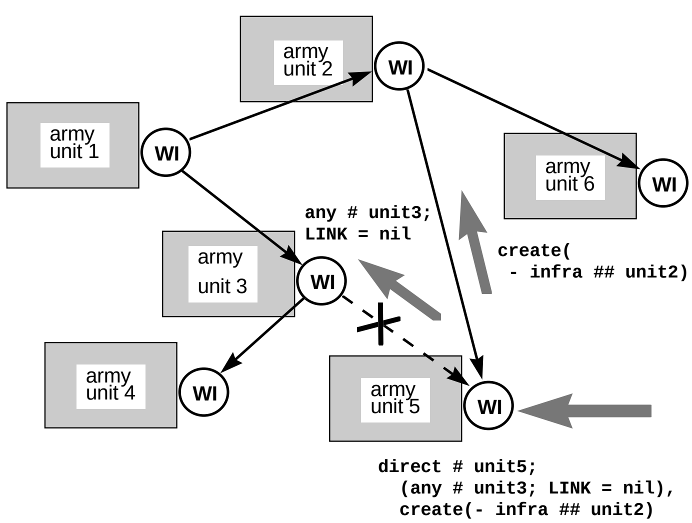

Fig. 9. Runtime reconfiguration of the united infrastructure

6.3 Basic command and control scenario in WAVE

Any command and control systems can be easily created, activated, and simulated in WAVE. The following program, using the above-mentioned infrastructure, implements traditional command and control process, where top level command or mission scenario, applied to the top of hierarchy, is executed in a top-down manner, with acknowledgments moving bottom-up.

At each level, the command is executed locally, according to the peculiarities of this level, and then transformed and modified for the levels below, replicated and sent in parallel to all direct subordinates for further execution & modification. Only after full completion and acknowledgment of the command execution on its and all subordinate levels, a unit reports to its direct superior. The program is based on a recursive navigation procedure `Fcommand_and_control` shown below, which also displays on a terminal confirmation of the acceptance of the command on each level, as well as termination of execution of it on all levels beneath the current level (on different terminals, if the system is distributed).

```
Fcommand_and_control = {
 Flevel += 1;
 sequence(
  TERMINAL = ‘entered level: ‘&& Flevel,
  (Fcommand, Flevel) ? execute_at_level,
  (Fcommand =
    (Fcommand, Flevel) ? transform_detail;
   + infra #; ^ Fcommand_and_control
  ),
  TERMINAL =
   ‘executed and controlled at and below level: ‘
   && Flevel
 )
}
```

where external procedures `execute_at_level` and `transform_detail`, taking into account the peculiarity of different command levels, may have fully human execution, human participation & interaction, or be fully automatic. The activation program using this recursive procedure, applied to `unit1` together with the command to be executed by the whole united force, is as follows:

```
Fcommand = <top_command_or_mission_scenario>;
direct # unit1; ^ Fcommand_and_control
```

The distributed hierarchical command and control process, set up by this program, is shown in Fig. 10.

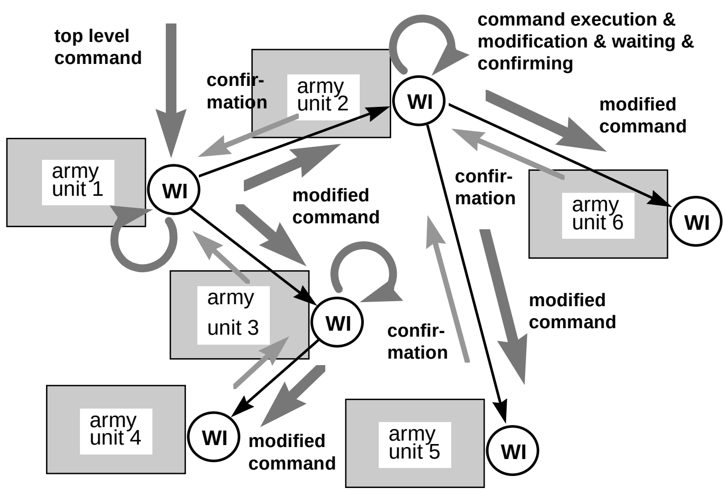

Fig. 10. Traditional hierarchical command and control scenario as a recursive spatial procedure in WAVE

6.4 Solving resource management problems

Let us consider the solution via the created infrastructure of another very vital problem: supply and re-supply of some physical resource to different units of the international force. This resource may be limited, and therefore should be divided proportionally to the extent of local needs, and subsequently physically delivered to proper units from some storage. The following program makes regular top-down checks of the resource demands in units, as a difference between its needed and actual levels, sums up and returns these demands in parallel back through the hierarchy, and analyses on top level the difference between the resource level in the storage and the received sum of demands. Another top-down parallel process makes decisions about the amount of the resource to be supplied to each unit that needs it: If there is enough resource in the storage, the needs are satisfied in full; otherwise the allowed amount for a unit depends on the amount in the central storage, sum of the demands from units, and the unit's demand. After making decision via the control infrastructure, the needed amount of the resource is subsequently physically delivered from the storage directly to the units, to optimize delivery routes (see Fig. 11).

```
Fexplore = {
  + infra #;
  Nrequest = Needed-(Nlocal_resource ? amount);
  Nrequest, ^ Fexplore
};
direct # unit1; Fstart = ADDRESS;
Nglobal_resource = “20 tons of product”;
repeat(
 Famount = Nglobal_resource ? amount;
 Frequest_sum = sum(^ Fexplore);
 ( Frequest_sum != 0; Famount != 0;
   or(
    ( Frequest_sum <= Famount;
      repeat(
       + infra #;
       leave(
        Nrequest != 0; Fwithdraw = Nrequest;
        Nlocal_resource +=
         ( direct # Fstart;
           (Nresource, Fwithdraw) ? withdraw
         )
       ), nil
      )
    ),
    repeat(
     + infra #;
     leave(
      Nrequest != 0;
      Fwithdraw=Famount* Nrequest/Frequest_sum;
      Nresource +=
       ( direct # Fstart;
         (Nresource, Fwithdraw) ? withdraw
       )
     ), nil
    )
   ); quit !
 ), 120 ? sleep
)
```

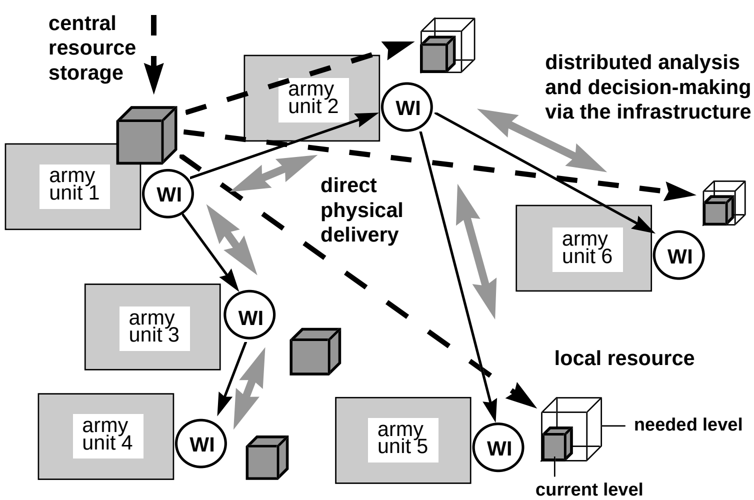

Fig. 11. Resource management via the command infrastructure with direct physical delivery

6.5 A more complex cooperative management example

Cooperative solutions of much more complex problems arising in the united CRF may be effectively organized in WAVE too. An example is shown in Fig. 12, where the initiative starts not from a single point, as in the examples above, but independently from four different points, with four separate (parallel and distributed) optimization scenarios evolving via the infrastructure. Imagine that these scenarios must find a satisfactory solution for all units that launched them (i.e. 1, 4, 5, and 6) by negotiations via the infrastructure, spreading own operations and data to other units if needed. Scenarios 2, 3, and 4 may, for example, reflect local problems in the units that started them, with local vision of their solutions, whereas scenario 1, launched on top level, may moderate solutions for other scenarios, to find an overall optimum. This optimum may have to take into account the results of local optimizations, the latter may need regular re-launching within the global balancing act. All these processes may be highly interactive.

As can be seen from Fig. 12, the locally issued scenarios may invoke a non-local optimization for them as, for example, scenarios 3 and 4 via the superior for them unit2. Scenario 2, starting at unit4, spreads activity one-way only, to unit3, and launches an optimization process for unit4 there, whereas the final solution is found and brought back to unit4 only by the global scenario 1, which regularly navigates the whole hierarchy in both ways, and also coordinates the interaction between scenarios 3 and 4. Efficient program code in WAVE can be easily written for this and many other similar cases.

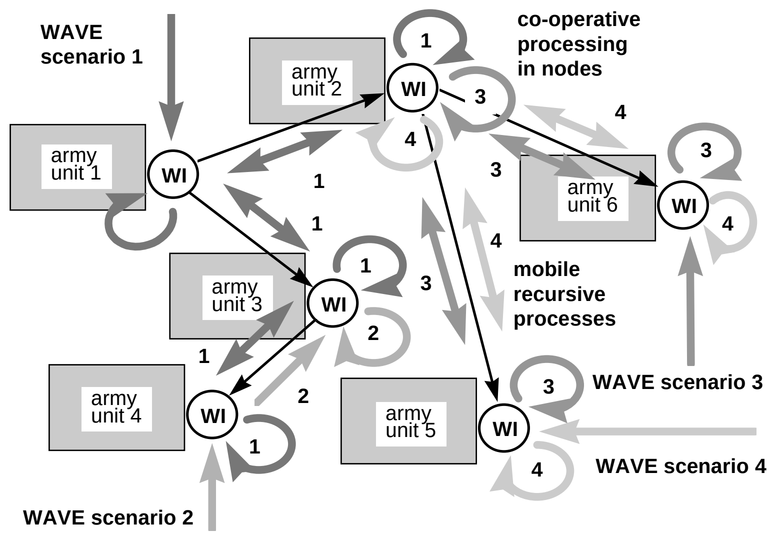

Fig. 12. Cooperative management with multiple interacting scenarios navigating the infrastructure in parallel

7 United Air Defense of CRF in WAVE

7.1 Advantages of using WAVE

WAVE may provide high integration of local air defenses of international forces into a powerful networked system covering the whole region controlled by CRF, with the following possibilities and advantages:

- Simultaneous indissoluble aerial observation of large regions, independent discovery of multiple targets.
- Parallel tracking of many aerial objects and their seamless handover between controlled regions.
- Distributed situation assessment and high collective awareness of the existing aerial threats.
- Intelligent distributed automated, as well as fully automatic, decisions.
- Global optimization of the use of limited international observation and antimissile hardware resources.

- Globally coordinated antimissile fire using networked manned & unmanned ground based and aerial systems.
- Distributed interactive simulation of air defense scenarios, for training troops against the aerial attacks.

Let us consider exemplary solutions of some related problems in WAVE.

7.2 Dynamic forming and updating of a distributed observation infrastructure

Mobile radar stations associated with army units (which may be of short range) may not cover the needed aerial region alone, and may have to communicate frequently to keep the overall observation integral and continuous. To make this communication highly selective and avoid huge network traffic (when each unit communicates with each other one) in tracking aerial objects, very useful may be the establishment of a dynamic neighborhood infrastructure, with virtual links between units reflecting the fact their radar stations cover adjacent (generally overlapping) regions of space, with subsequent communication between the radars only through this infrastructure.

We consider here a program that puts a process into each unit which regularly checks the physical distance from itself to other units, and if it is less than the sum of their radar ranges, a “neighbor” link is set up between the units. On the other hand, if the neighbor link already exists, but the physical distance between nodes exceeds the sum of their radar ranges (i.e. the mobile nodes have moved apart), such a link must be removed. The needed frequency of activation of such a process in each unit, which has to contact all other units in order to maintain a precise enough neighborhood network at each moment, depends on the speed of units, and may not cause serious overhead in the overall system performance, as CRF units are mostly ground-based and their speed is much lower than the speed of aerial objects to be tracked. The following program, working in parallel in all units/nodes, dynamically creates and constantly updates the radar neighborhood infrastructure, where the creation of new links and removal of outdated ones is allowed by only one of the adjacent nodes, to prevent an unnecessary competition:

```
direct # any;
repeat(
  Flocation = WHERE;
  ( direct # any; ADDRESS < PREDECESSOR;
    or(
      ( (Flocation, WHERE) ? distance <= 80.0;
        or( neighbor # PREDECESSOR,
            create(neighbor # PREDECESSOR)
        )
      ),
      (neighbor # PREDECESSOR; LINK = nil); done!
    )
  ),
  300 & sleep
)
```

An example of the created infrastructure is shown in Fig. 13, which may coexist with other virtual infrastructures in WAVE, say, with the command & control one discussed earlier. The created and regularly updated radar neighborhood infrastructure allows us purify, formulate, and solve different discovery, tracking, analysis, handover, decision making, antimissile hardware optimization, and object destruction problems in a distributed network mode, without central resources.

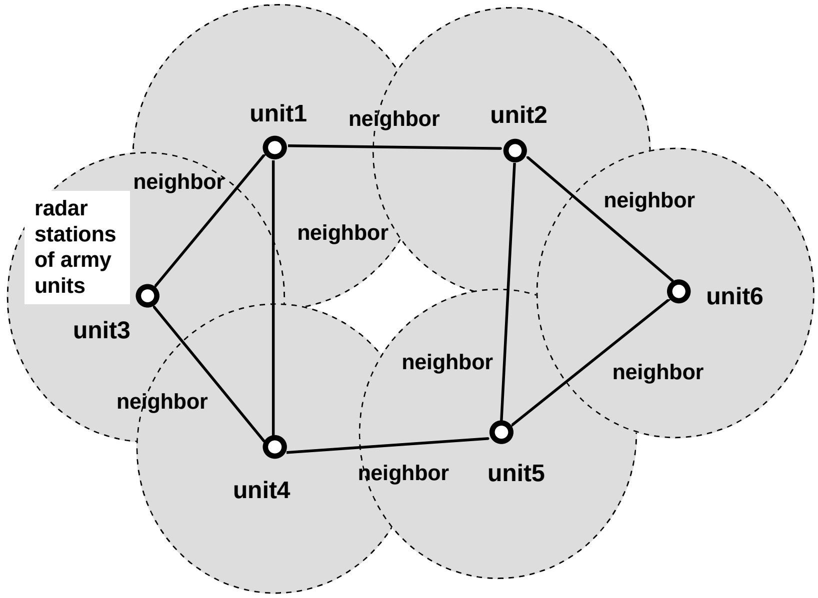

Fig. 13. Runtime creating and updating a radar neighborhood infrastructure

7.3 Simultaneous object tracking and handover between controlled regions

The basic object tracking algorithm using advantages of the mobile wave code, may be as follows. When an intruder object is seen originally by some radar station and identified as a target with distinguishing parameters (type, size, speed, etc.), a mobile tracking process is launched which keeps in view this object and *has the sole authority* of chasing it. Only one such authorized mobile process is created when the target enters the area under CRF control, possibly, in a competition between the stations seeing the target, where closest to the object station may be a winner.

The tracking process regularly checks the vision of the object by the current station, as well as by the neighboring stations by launching subordinate processes in them. If the target gets closer to a neighboring station seeing the target too, the whole process moves itself to this station via the neighborhood infrastructure and continues the target observation there, moving again if the target becomes closer to another neighbor, and so on, thus following the object moving in a physical space via the computer network. If the space coverage by radar stations is not continuos, the chased target may be lost by the tracking process, the latter self-terminating in this case. A new unique tracking process can be launched if the object is rediscovered by some other, non-adjacent, station, which will continue chasing the object via the neighbor links between the radar stations. The following WAVE program, applied initially in all radar stations, implements this algorithm:

```
direct # any;
repeat(
 ( Nold = Nobjects_seen;
   Nobjects_seen = 40 ? observe; Nobjects_seen;
   IDENTITY = VALUE; IDENTITY !~ Nold;
   Fdistance = IDENTITY ? distance;
   or(
    ( neighbor #; IDENTITY ~ Nobjects_seen;
      Fdistance > IDENTITY ? distance
    ),
    release(
     repeat(
      2 ? sleep; Min = infinite;
      sequence(
       ( neighbor #; IDENTITY ~ Nobjects_seen;
         Fdistance = IDENTITY ? distance;
         # PREDECESSOR; Fdistance < Min;
         Min=Fdistance; Mnext=PREDECESSOR; quit!
       ),
       or(
        (IDENTITY ? distance == nil;
         or((Min != infinite; neighbor # Mnext),
            (TERMINAL=IDENTITY && ':lost'; quit!)
         )
        ),
        (Min<IDENTITY?distance; neighbor#Mnext),
        nil
       )
      )
     )
    )
   ); quit !
 ), 1?sleep
)
```

The work of the program is depicted in Fig. 14, with the main mobile tracking process regularly launching subordinate exploration mobile agents checking the neighboring stations. These agents, in their turn, producing echo agents bringing information back to the main process.

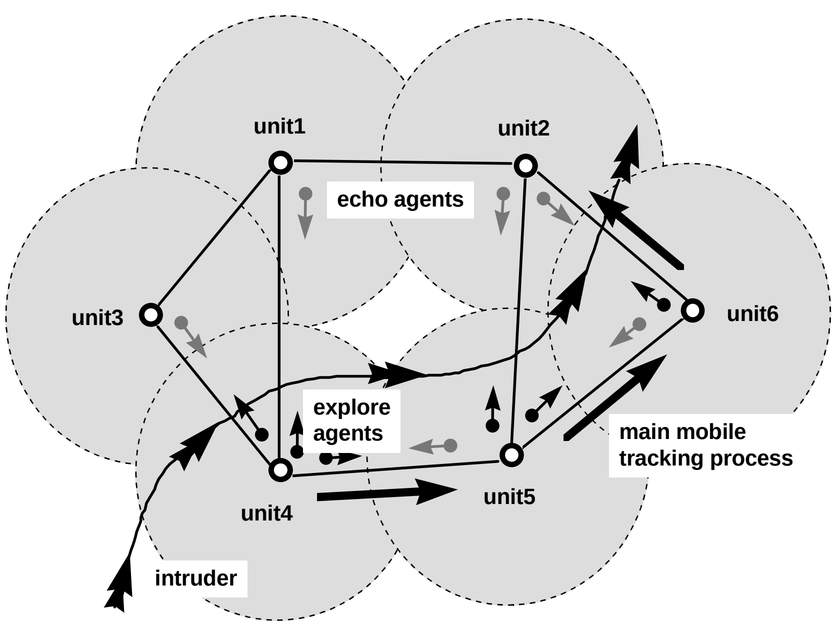

Fig. 14. Distributed networked tracking and handover of aerial objects in WAVE with subordinate mobile agents

The program above describes only the chase in space, and does not specify any payload the tracking process might have, which can easily be added to it. A possible payload (also mobile or being activated as stationary standard procedures in nodes) may include counting the time the object is seen, accumulating its itinerary, measuring its average speed, determining its closeness to sensitive ground-based or aerial components of CRF, etc., in order to decide whether the object is hostile and assess potential threat from it. The final decision to destroy the object can be made, and which hardware is needed for this. New mobile branches of the tracking process may be activated for guiding antimissile rockets via the neighborhood network too, as they may also need crossing boundaries of regions covered by different radar stations, to reach the target. Mobile processes chasing the target and towing the antimissile rockets may cooperatively optimize the collision point, giving a final command for a direct pursuit and destruction. These processes my also check the result, and activate and tow another rockets through the network in case the target survived, and so on. All such dynamic distributed functions can be efficiently implemented in WAVE.

The program discussed above allows for the creation of an unlimited number of mobile tracking processes for different targets, and these processes can develop and migrate simultaneously in the radar station network, as shown in Fig. 15. Any cooperation between individual tracking processes may be provided, also with other, stationary, processes in nodes, to find dynamic optimum solutions for reducing threats and the best use of antimissile weapons. All stationary and mobile processes, including the remote ones, may be highly interactive and may involve human operators in complex situation assessment and decision making processes.

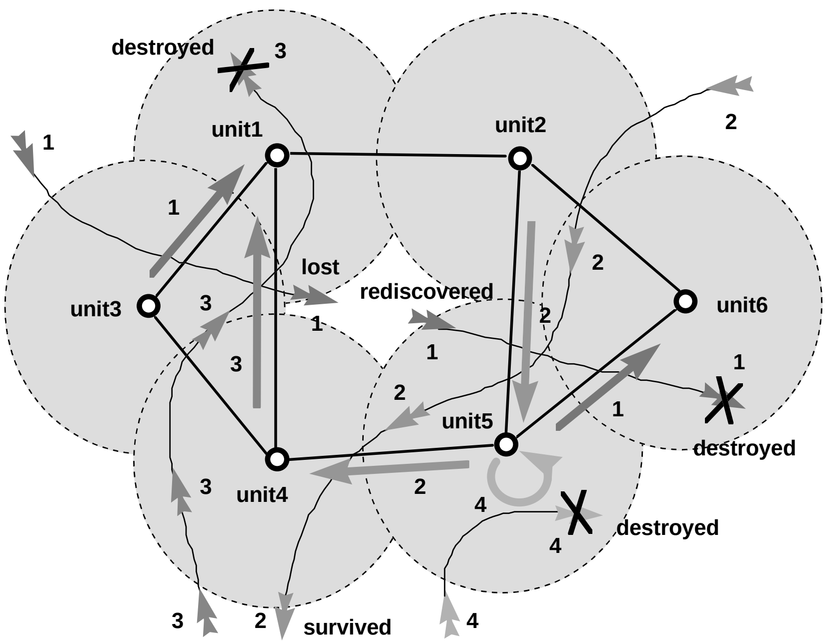

Fig. 15. Simultaneous chasing and destruction of multiple hostile objects in WAVE

A variety of other problems and methods related to integrated distributed air defense of CRF may be solved in WAVE, some of them having already been successfully tested and demonstrated via the Internet. For example, the network of radar stations model was distributed between Germany, UK, and California, and multiple models of alien objects, fighters, and observation, or spying, objects were moving between the continents and countries and interacting with each other throughout the Internet space.

8 Conclusions

As can be seen from this paper, WAVE may serve as a possible basic model and technology for efficient integration and management of advanced multinational CRF and their united air defense systems. It is dynamically deployable, lightweight, mobile, both computational and control networking technology, based on evolving active spatial scenarios or patterns, rather than on communicating agents. Particular hardware or software agents and their interactions emerge dynamically, on the implementation levels only, and only if and when required or available, during the pattern's parallel conquest of space. This allows us to have extremely compact and powerful distributed networked solutions of complex problems (usually about 100 times shorter than in C or Java).

WAVE effectively supports the whole spectrum of system organization levels: from basic network management to the description of high level mission scenarios, distributed interactive simulation, multiuser virtual reality, cooperative robotics, and self-protection from external influences and threats. Due to its volatile, virus-like, fully interpretive nature, WAVE also allows for an efficient self-analysis and self-recovery after indiscriminate damages, as was tested in different projects. Other system models and technologies can be efficiently integrated, expressed and implemented in WAVE, which offers highly integral and seamless solutions for open, dynamic, and heterogeneous systems to which mobile CRF and their air defenses belong.

Most of the existing distributed programming philosophies, and resulting languages and technologies are currently based on the concept of agents [22]. The overall system behavior is considered as a derivative of work of many agents and their multiple interactions, and may often be unpredictable for large dynamic systems, or at least hard to supervise and contain. WAVE, on the opposite, offers a unique opportunity of programming the desired goal-driven whole behavior as a starting point, in the form of high-level active spatial scenario or pattern evolving in space. This may be of paramount importance for advanced military applications which will require highest possible system organization and integrity, in order *to defeat other system organizations, and win the battle*.

Acknowledgments

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PANEL PERSPECTIVES ON SYSTEM ARCHITECTURES

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SUMMARY

In a changing world, the U.S. Department of Defense has to cope with increased uncertainty about requirements, rapid changes in technology, changes in organizational structures, and a widening spectrum of missions and operations. One way to deal with these uncertainties is to be able to rapidly mix and match organizations with composite capabilities to suit a particular situation. To do this requires an unprecedented level of interoperability in information systems. To achieve this flexibility, DoD has looked to information architectures that can provide current or future descriptions of a "domain" composed of components and their interconnections, actions or activities those components perform, and rules or constraints for those activities. These architectures, while they will change over time, will change at a much slower rate than the actual systems they represent. Because of their stability, they can act as important guides to acquisition decisions as well as defining operational concepts. One domain of *information systems* that directly supports military operations is Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR). The goal is to describe architectures using multiple views that answer operator's questions regarding the operational capability that systems built conformant to the architecture can provide. Another goal is to support the acquisition community in its efforts to acquire interoperable system. A seamless process from knowledge elicitation to architecture design and evaluation is desired.

The C4ISR Architecture Framework document issued by the U.S. Department of Defense specifies three views, the operational, systems, and technical views, of an information architecture and defines a set of products that describe each view. These architecture views are to serve as the basis for C4ISR system development and acquisition. The Framework does not provide a process for architecture design, but provides guidance to the architect regarding the architecture design process. Furthermore, the emphasis on architectures has raised some questions regarding the roles of the architect and the systems engineer.

Paper presented at the RTO SCI Symposium on "System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces", held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

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Future Short Range Ground-based Air Defence: System Drivers, Characteristics and Architectures

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Introduction

The widening political uncertainties and World instability of the last decade has led to the West moving away from maintaining armed forces largely to assure national survival. Now it looks towards maintenance of peace through promoting stability and countering regional aggression, and towards humanitarian operations including peace enforcement. This had led to a growing emphasis on expeditionary forces and away from the concept of "forces in place".

Short range ground-based air defence (GBAD) systems provide an essential defence capability for mobile expeditionary forces and provide the persistence which other air defence elements lack. Today's forces, however, face not just uncertainty, but capability gaps against the increasingly diverse air threat.

The end of the Cold War has overturned the assumed military imperatives. A threat now needs to be defined as a combination of two elements: Capability and Intent. Existence of one without the other is insufficient to establish a requirement for a capability, and both are subject to potentially rapid change. For GBAD, new attack technologies, including cruise missiles, unmanned air vehicles, attack helicopters and tactical air-to-surface weapons, plus the ability to obtain such technology off-the-shelf, may provide a first-class capability to any potential aggressor which has the political will to resource it. It is this potential level of Capability which sets the requirements for air defence. Meanwhile, assessment of intent based on traditional cold-war enmities and groupings has been largely overturned. The proliferation of weapon and sensor technologies, regional instabilities and the ease with which politically unstable countries may obtain near state-of-the-art equipment makes the definition of Intent volatile, changeable and difficult to assess.

Furthermore, both will alter with time, and a flexible methodology which can cope with change is needed for future systems analysis. The timeframe assumed for this paper is 2015 onwards. For any specific timeframe, however, assessment of the required capability for GBAD will be driven by the perceived air threat and the operational imperatives, the latter particularly including the need for interoperability of command and control in a multi-national joint environment.

Over the last decade, the UK's assessment of GBAD requirements for the future systems timeframe has been based upon a clean sheet approach, eschewing legacy systems and current assumptions. The studies in this timeframe have taken an assessment of the technological capabilities of future air vehicles together with an assessment of the potential operational environment that might condition their use. Initially, studies tended to concentrate upon actual warfighting scenarios as these are considered to be simultaneously the most stressing for defining the required capability, and of most relevance to operations in support of ground forces.

The increased operational emphasis on crisis reaction forces has, however, added a new dimension to the operational environment, implying a greater reliance on ad hoc groupings and committal to areas where little or no infrastructure may exist. The importance of information in wider peace support extends the range of operational conditions to be studied.

Aim

The aim of this paper is to describe how ground-based air defence concepts for the timeframe beyond 2015 may be synthesised from an assessment of the operational drivers and the technological factors, to produce robust modular concepts applicable to both warfighting and peace support regimes.

Paper presented at the RTO SCI Symposium on "System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces", held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

Scope

GBAD referred to by this paper is that of very short and short range air defence of ground-based assets in a crisis reaction context. It assumes that, although the scenarios will be multi-national, and operations will be conducted in a joint service environment, organic ground-based air defence of national forces will continue to be broadly a national responsibility. Although this paper is based on fundamentally UK studies, these have, however, taken place with considerable international liaison and participation in NATO fora, notably the RTO SCI Task Group on sensor fusion in SHORAD.

The paper does not specifically address the air defence (AD) of strategically- or politically-important assets which are not directly relevant to ground-based operations. Neither does it address ballistic missile defence, although system concepts derived by the methodology are routinely assessed for possible residual capability against such targets.

Methodology

The top-down study methodology is shown in Figure 1. The process follows the classic *thesis, synthesis, antithesis* approach whereby concepts are proposed either top-down or bottom up, synthesised in a system context and then tested in a range of operational scenarios to provide a basis for further concept development.

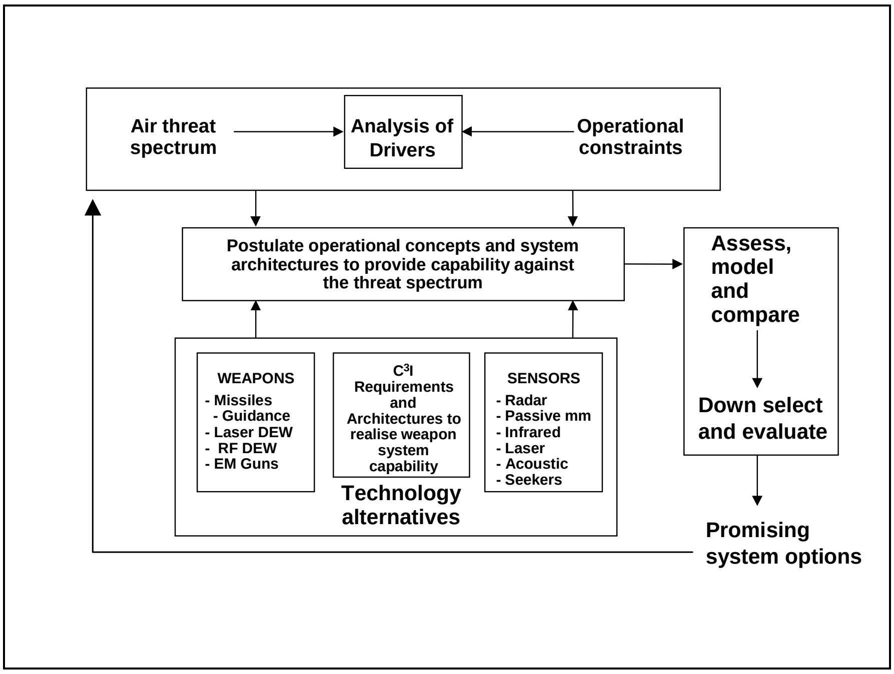

Figure 1: Overview of study methology

The first stage is to assess the developing threat and the operational conditions, which includes predictions of air threat technology advances and technology counters at the system and sub-system levels. The operational implications of this interaction are extrapolated into an assumed military doctrine relevant to the timeframe, that is developed through a combination of user experience and assessment against the principles of war. The UK perception tends to be that the Revolution in Military Affairs is more evolution than revolution, and although the rapidity of change provides great challenges, none of the new conditions are striking at the fundamental principles of war. In an uncertain and volatile future, these principles are held to provide the most robust framework for assessing potential system concepts.

Performance against each element of the derived threat array is assessed at a system level. No single threat element (eg., the ballistic missile) is allowed to dominate the concept development process, although the operational drivers (eg., non-line-of-sight helicopters) will carry more weight. The aim is for a flexible and balanced concept which has an assessed capability against the broad range of potential threats. This reflects both the reality of uncertainty and the need for capability in a wide range of circumstances. This process is iterative and results in a gradually-refined concept which is relevant for the timeframe.

Results from technology watch and developments in the operational environment are brought into, and may drive the need for, subsequent iterations. Sensitivity analysis is carried out using a mixture of modelling and "soft" techniques, such as multi-criteria analysis, to refine the concepts as additional research data become available or are derived from systems studies.

The developing operational context

Analysis of the new spectrum of conflict indicates that forces must be trained and equipped for full warfighting in order to be in a position to discharge properly peace support functions. Similarly, it is generally accepted that materiel designed for "high intensity" operations, operated with extreme competence, is the best way to deter conflict at any level.

In a classic warfighting scenario, there are broadly two aspects on which to base an assessment: the diverse threat stream expected in the future; and the operational realities of the battlespace. The former includes specific target types, numbers and profiles, and may include multiple simultaneous threats. The latter involves the need to be able to move, survive and fight on the battlefield without compromising operational security.

In a peace support context short of warfighting, additional imperatives need to be taken into account. The manoeuvrist approach espoused by "The British Military Doctrine" already puts an emphasis on the OODA (Observation, Orientation, Decision, Action) loop, and the use and deployment of information to get inside the decision loop of the enemy, so as to surprise him, or to challenge him with conditions to which he is unable to produce a timely response. The development of information warfare at the geo-strategic level, and its application as command and control warfare at the operational level, will place additional demands upon the supply, interpretation and exploitation of information.

It seems inevitable, therefore, that in order to keep inside the decision loop of the enemy, be this in terms of conventional or asymmetric warfare, there will need to be an increasing emphasis on information-gathering sensor-based systems. The need for increased situational awareness is assessed to make weapons subsidiary in importance to the surveillance and sensor function.

An illustration of the assumed process is given at Figure 2, which suggests that sensor needs will dominate as firepower-based system considerations decline.

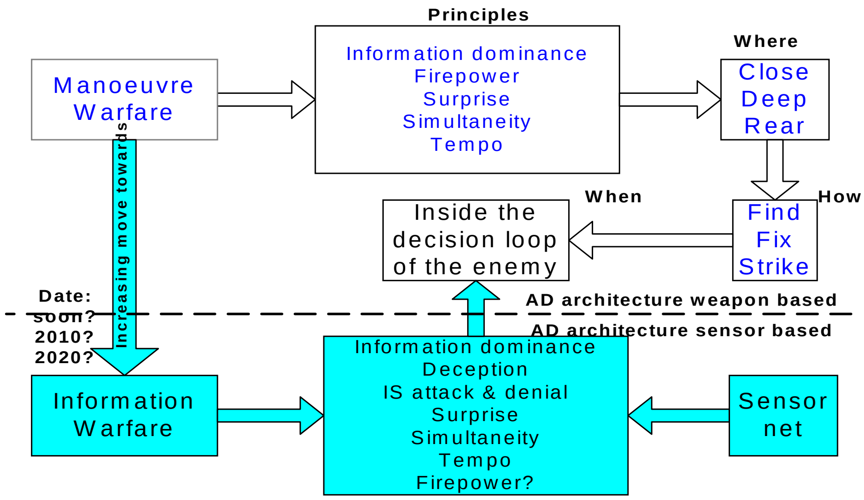

Figure 2: Assumed doctrine development

Information itself may supplant some aspects of firepower, although an effective kill mechanism will remain an essential part of the overall system. Sensors are likely to become more generic and less tied to AD weapon platforms. Political control will be an increasingly-important factor in all military operational planning, and there is already an emphasis on the avoidance of casualties, particularly of civilians and neutrals. Commitment of forces is likely to involve a stated or assumed moral dimension. In particular the avoidance of civilian and neutral casualties will outweigh any operational risks incurred by following this policy, at least until action is joined and the first casualties taken. This trend is already apparent in NATO rules of engagement which suggest that no target should be engaged unless it has been observed committing a hostile act or has been declared hostile.

This projected future is illustrated by the influence diagram at Figure 3. Lines indicate influences on actions, with plus signs indicating a positive relationship, and minus signs the inverse.

The evaluation represented here suggests that all influences in a non-warfighting situation will tend to exacerbate the current requirement for severely-restrictive weapon controls. In the future, this may manifest itself as restrictively high identification thresholds from the identification data fusion process.

Only if enemy action occurs, and casualties are suffered, will the moral imperatives diminish and the need for more effective GBAD act as a counterweight to the restrictions on operations. The need to maintain control in the battlespace, and the continuing political imperatives to avoid friendly and neutral casualties will increase the importance of obtaining air target identification information to assist this process. This additional data may be used to segment the target set so that priorities and comparative risk assessment can allow relaxation in weapon control status, or in identification threshold levels. This will allow the increasing proportion of the target set which is unmanned to be engaged without increasing the fratricide risk for manned platforms.

The operational environment

It is assumed that the aim of future ground-based air defence will remain “to prevent interference from the air with the conduct of ground operations while contributing to the counter-air battle”. For ship-based air defence, the aim is to prevent interference with naval operations, where the wartime coalition littoral operational environment presents the most challenging requirement to be satisfied. Changes in the World Order, emphasis on manoeuvre warfare, and the potentially wide threat spectrum require development of a framework which goes beyond the linear battlefield conditions which were in place during the Cold War.

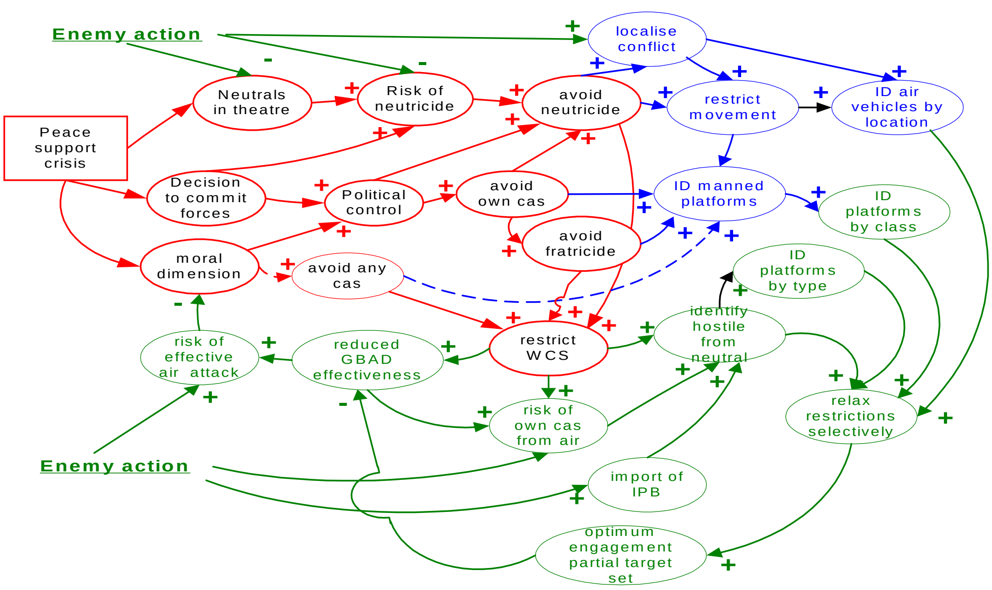

Figure 3: Some influences on the ATI requirement

Warfighting scenarios tend to be relatively well understood, but a crisis reaction scenario implies an operation of an expeditionary nature with a number of potential primary intentions, amongst which might be to: deter, prevent, enforce or restore. Peace support operations may involve peacekeeping, peace enforcement or peace making or a combination of all three. Similarly, the prime posture of engaged forces may vary from policing through coercion to full warfighting. Information requirements may vary from the need to monitor potential aggressors, through identifying targets for selective engagement, to providing "evidence" of transgression. Evidence is also likely to be required to justify the need for force to international investigative bodies after any resort to armed action, even in self-defence.

A large number of major factors are at work in any battlefield AD situation. The geometry of the potential battlefield will depend upon the scenario, plus the force levels committed, and the capabilities and intentions of the hostile forces. This set of basics, together with the potential number and combination of air targets, plus the number and scope of potentially vulnerable assets needing to be defended on differing parts of this battlefield, make a set of variables which is too large to be modelled and assessed.

The "Zone concept" – a focusing framework

However, some of these combinations may be mutually exclusive, or at best highly unlikely. To help maintain a balanced view of all the factors, a focusing framework has been developed with the main factors illustrated in Figure 4. The resultant "Zone concept" is based upon the principle that the air threat to ground-based forces will tend to be a function of the nature of the ground-based asset itself, which will, *inter alia*, depend on its function and importance, its location on the battlefield, the time or stage of the battle, and perhaps most importantly, the ease of targeting - which includes consideration of its "visibility" to electronic and visual systems, its mobility and the "five S's"s (size, shadow, shape, shine, silhouette). Other factors include the value and level of protection of the target. The former will depend upon its inherent battlewinning performance, or political sensitivity, relative scarcity and the time/stage of the battle, whereas the latter will tend to depend on its mobility, "hardness", size/layout and posture, location on the battlefield, terrain, and signature. Finally, the vulnerability, survivability, numbers, technological sophistication, level of training, culture etc., etc., of the attacker must be taken into account.

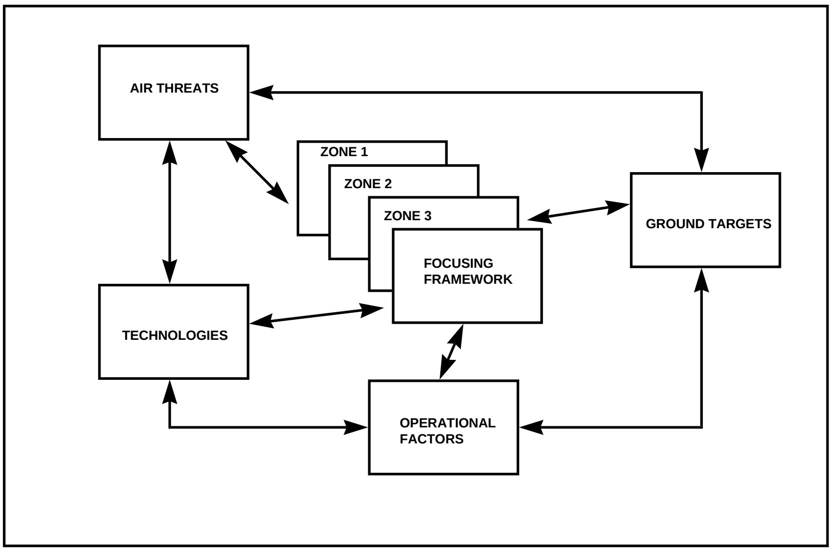

Figure 4: Zone concept as a focusing framework

The vulnerability relationship of the defended asset itself may be complex, especially for manoeuvre elements, as illustrated in Table 1. This shows the inherent vulnerability of combat elements to attack, the least vulnerable being on the right. Although for completeness the defended asset characteristics shown in Table 1 are based upon a conventional armoured formation, and implicitly at divisional level or above, they could also apply at lower levels of force commitment and of equipment capability. A broad summary of the most likely targets to be seen over the battlefield is given at Table 2, which attempts to "Zone" categories of hostile air targets by broadly relating these to targets to be defended by friendly AD.

Main Factor	Element	Greater <	<	<	< Less
Ease of targeting	Location	Mapped	Static	Semi-static	Mobile
	Movement	convoy	x-country	stopped	deployed
	Posture	concentrated	tight	dispersed	widely dispersed
	Physical	big/hot	mid-size/cool		small/cold
	Camouflage	scrimmed	draped	visual	full/thermal
	EMCON	4	3	2	1
	Visibility	line of sight	occulting/obscured		non line of sight
	Contact	static FLOT	fluid	confused	melée
Protection	Armour	soft	semi-hard	hard	defensive aids
	Digging	in open	under cover	dug in	full o/h protection
	AD	none	AAAD	CAD	fully layered AD

Table 1: Combat asset vulnerability

Zone	Grouping by air target type	Air target density	Characteristics of defended asset
1 **Combat elements**	FW - CAS Attack helicopter Hovering helicopter with SOW UAV (tactical) TASM (TGSM)	✈ ✈ ✈	Mobile/manoeuvring Protected – unprotected Dispersed Up-to-minute location fix needed Some relatively small static targets Tactically valuable
2 **Combat support elements**	Subsonic cruise missile TASM UAV (tactical & operational) FW - BAI & SEAD (ARM) RW/tpt aircraft (désant)	✈ ✈	Relatively immobile Static or slow-moving Medium size Location by map fix or surveillance Operationally valuable
3 **Politico-strategic assets**	Super/subsonic cruse missile, TASM Stealth aircraft FW - AI & SEAD UAV (strategic, HALE)	✈	Static Medium/large size Location known Strategically or politically valuable

Table 2: Target and asset distribution

The degree to which an enemy might possess capability in all these threat categories would depend on the individual scenario. The descriptor "Zone concept" does not imply a linear battlefield, but recognises the fact that combat assets tend to group together, and strategic level assets tend to be located relatively far from the combat zone, although this is by no means always the case, especially in peace support operations where "enclaves" may be a major characteristic.

Analysis of asset deployment over time has suggested that the broad groupings indicated in Table 2 overleaf will remain broadly valid over a wide range of scenarios. With minor changes, these groupings have been the basis for all future systems studies.

The design drivers for AD weapon systems are likely to change largely as a result of the characteristics of the targets to be defended and the factors already stated. The characteristics of an AD system for defence of manoeuvre units in contact will be notably different from that for defence of an operational level asset such as a Sea or Air Port of Disembarkation (SPOD, APOD).

In this focussing framework it is the characteristics of the *assets* to be defended that define the requirements for AD, and there are likely to be considerable overlaps between Zones. A summary of the Zone Concept is provided by the illustration at Figure 5. Zone 3, which is the vital area defence of assets of strategic or political importance, where the decision to defend is not made on military grounds, and where the consequences of failure are of greatest significance, is not shown. The Zone 3 threat is only included in Table 2 for completeness as the strategic/political threat, as already highlighted, is beyond the scope of organic short-range GBAD.

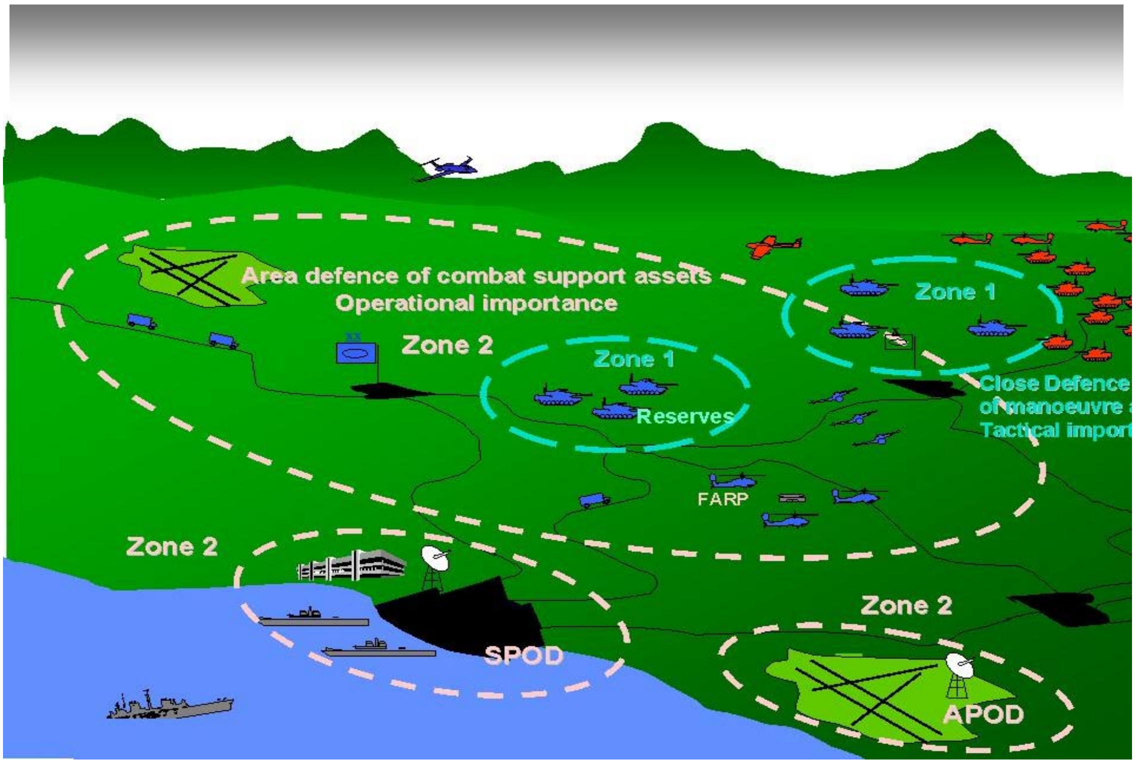

Figure 5: Zone concept

The characteristics of the derived threat are critical drivers and technical analysis of likely developments indicate a complex pattern. Although it is reasonable to group air threat platforms into generic representative classes for analysis, the factors which affect their characteristics all need to be taken into account. Some of the factors applicable to fixed wing aircraft are illustrated in Figure 6, which indicates a number of possible trends. Although the effect of each factor will be largely scenario-dependent and the shape of each factor may be debatable - for example, whether the application of low-observable technology is likely to follow a stepped upgrade pattern as indicated – the overall trends can normally be agreed.

Analysis of the air targets considered to be a priority in Zones 1 and 2 suggests that these are likely to change over time, as shown in the summary in Table 3, where the targets are shown in order of assumed importance for the mid and far timescales. The table indicates the growing threat from the attack helicopter (AH) and small target set, and the relative decline in the importance of the fixed wing aircraft (FW) target. Such analysis also confirms the dangers of an asymmetric degradation of operational capability if the fratricide danger to manned aircraft is allowed to drive overly restrictive weapon control status.

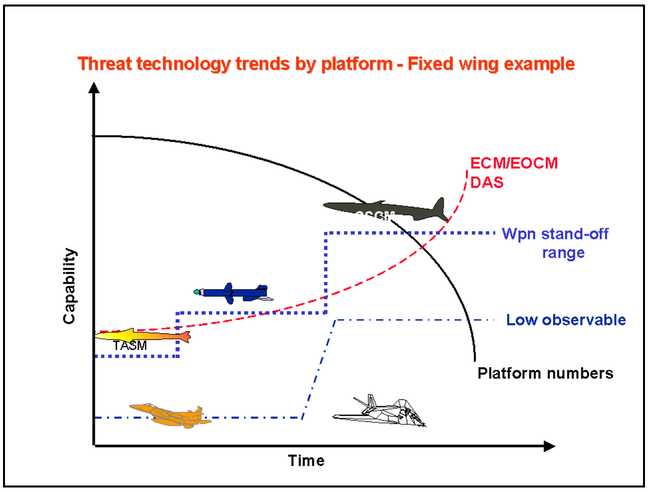

Figure 6: Illustrative threat factors for a single platform type

<table>
<tr><th></th><th>Mid term ~2010</th><th>Far term ~ 2020 onwards</th></tr>
<tr><td>Zone 1</td><td>AH
Tactical UAV
FW
TASM
CM</td><td>TASM
AH
Battlefield UAV
CM
(FW)</td></tr>
<tr><td>Zone 2</td><td>FW
CM
Tactical level UAV
SSCM
Operational level UAV</td><td>TASM
UCAV
SSCM
CM
Operational level UAV</td></tr>
</table>

Table 3: Target priorities in Zones 1 & 2 over time

Emergent AD concept drivers

It is mainly operational issues which delineate the Zone 1 requirements from those of Zone 2, which are broadly threat driven. The Zone 1 AD element has to be able to provide air defence for highly mobile operations on a dispersed battlefield, whilst surviving and maintaining operational security. As the all-weather and through-cloud threat increases this will create a requirement for active systems that will compromise security and survivability. The greatest threat in the latter context is artillery, so active systems must have low probability of intercept and their concept of operations must be difficult to template. A crossing target capability against the Zone 1 threat stream is necessary to free the AD system concept from the need to collocate with defended assets and to enhance security. The advantages of being able to separate the sensor function and weapon functions so as to be able to optimise each without compromising the other, and to exploit the geometry of the battlefield to allow more survivable deployments, becomes very attractive. Such distributed system concepts also allow more radical approaches to the support of moving assets than allowed by concepts which depend on weapon systems collocated with sensors. The greatest technical threat in this Zone is the non-line-of-sight (NLOS) helicopter. The greatest system drivers are this NLOS requirement and the short timelines associated with late-unmasking targets, coupled with the need to be able to satisfy the engagement criteria without the restrictions implied by a requirement for the visual recognition of targets.

Zone 2 is characterised by the most technologically sophisticated and diverse threat with the main drivers being the stealthy small target and the steeply-diving TASM, coupled with a need to be able to match the arrival rate of a multiple and multi-directional threat. Situational awareness, with its implicit benefits for air target identification, and the maintenance of an efficient sensor net in the presence of the most severe countermeasures, are also fundamental to timely and effective engagement.

An all-pervasive driver which is particularly important in a crisis reaction force context, is the need for adequate air target information which will allow effective engagement of the more stressing target set whilst holding fratricide risk, particularly of manned platforms, to an acceptably low level.

An assessment of the most important AD drivers derived from this process is shown in Table 4.

Zone 1 **Defence of manoeuvre forces**	**Zone 2** **Defence of support elements and formations not in contact**
• Mobile operations • Protection • Operational security • NLOS helicopters launching SOW • Increasing numbers of small targets (especially UAV) • Increasing above cloud threat • Need to be able to engage beyond visual identification range • Crossing target coverage • Robustness against self-protection measures	• Low-observable cruise missiles • High-speed steep diving TASM • System survivability • Proliferation of low-cost missiles. • Increasingly accurate all-weather threat. • Supersonic cruise missiles for stand-off attack of fixed assets • Maintenance of Situational awareness • Resistance to C2W

Table 4: Emergent AD concept drivers

Technology alternatives and architectures

The areas within which it is necessary to consider technology alternatives to populate system and sub-system architecture proposals, consist of weapons, sensors and C^3I. Within these areas there will be other considerations such as multi-function possibilities and fusion of information at various levels. The linkage of technology alternatives with the discussion of emergent AD concept drivers is through a general statement of requirements as exemplified in Table 5. The broad requirements have been stated without reference to Zone and there will be detailed trade-offs between system requirements, capabilities and implementation when the operational aspects of Zones are considered. The driving aim, however, is to keep in mind the potential for modularity at the architecture, technology and functional levels to achieve a robust AD system to meet the operational requirements identified through the Zone concept focusing framework.

Required broad AD system characteristics
• All-weather capability • Good performance against physically small and low-observable targets • Good performance against low attitude targets • Good performance against fast crossing targets • Capability against NLOS helicopters • Maintenance of performance in a countermeasures environment • Provision of simultaneous channels of fire from a single equipment • Minimum vulnerability to Defence Suppression and asset fingerprinting • Capability to operate with C3I integration and autonomously • Modularity

Table 5: Required broad AD system characteristics

Whereas many features of Table 5 can be identified as germane to current AD missile systems, results from Operational Analysis and lethality studies have shown that for a future AD system:

- the forecast threat will require a significant increase in lethality compared to current systems;
- a capability against air-launched missiles will be essential;
- engagement ranges, against agile and fast crossing targets, greater than 7-8 km are highly desirable to minimise the regime where neither threat launch platform nor threat munitions can be engaged. It should be noted that the most up to date, authoritative reference on engagement range requirements is extant in the latest NATO Staff Requirement for VSHORADS/SHORADS ;
- the most demanding target detection requirements are set by those targets which operate at very low altitude, by missiles with high, terminal dive angles, and by the very fast LO missile target;
- a capability to provide multiple, simultaneous fire channels from a single equipment will greatly improve resistance to saturation attack from stand-off missiles;
- a NLOS capability will be essential for the defeat of attack helicopters, and improved system effectiveness against both missile and fixed wing threats;
- the ability to site sensors and launchers remotely from each other can enhance system performance, particularly against small cross section targets at very low altitude, and confer other benefits of operational security, survivability and flexibility.

Weapon level architecture options

Initial weapon studies examined potential kill mechanisms based on conventional missiles and novel weapons exploiting Directed Energy Technology (DET) using lasers or RF techniques. It was concluded, and this remains the assessment, that, for the timeframe of interest, novel weapon techniques would be very unlikely to supplant missile-based weapons as the prime kill mechanism. On the other hand, a number of laser-based concepts were assessed as possible and attractive in the context of threat platform sensor dazzle and damage capability. Such soft kill concepts could form the basis of a complementary, adjunct, sub-system in a predominantly missile-based AD system.

Early work on future AD missile-based technologies and concepts focused on a thrust towards physically small missiles. This implies a small warhead, high agility matched to an increasingly rich unmanned target set, but demands small miss distances for high terminal lethality. The thrust was predicated on:

- factors imposed by the User to minimise equipment weight and size;
- threat factors of diversity and “smartness” encompassing increased agility, speed and co-ordination of attack, longer stand-off ranges with an ultimate need to engage the launched ordnance plus intensive use of ECM/EOCM.

Work addressed, and continues to address, the combination of sub-system technologies which could lead to reduced miss distance, the practical limits for miss distance reduction against small manoeuvring targets, and the implications for overall missile design. The crux of the philosophy is linked to achieving a sub-metre miss distance with a small missile and warhead, and this leads to guidance methods based on terminal homing.

The use of terminal homing guidance also potentially confers a number of major system benefits in relation to the discussion on operational factors. These include:

- decoupling of ground sensors from launchers to achieve flexible, distributed sensor and weapon architectures. Important operational benefits are reduced fingerprinting of defended assets, reduction of deployment constraints on engagement coverage, and tolerance to battle damage;
- inherent potential for multi-target engagement capability;
- inherent potential for good crossing cover at high target speeds;
- inherent NLOS helicopter engagement potential.

A full assessment of the spectrum of missile guidance techniques and architectures is beyond the scope of the paper; however, in the context of the indicated focus on terminal homing and seeker options, some limited comparison of options against perceived requirements can be made. Such a comparison is shown in Table 6. Corresponding composite, weapon level examples of architectures are illustrated in Figures 6 and 7. These are not exhaustive, but do illustrate possibilities for sensor options to support weapon delivery from surveillance to kill assessment.

Guidance	**Surveillance and tracking sensors**		**Principal system limitations or vulnerability**
	Active surveillance & tracking	Passive surveillance & tracking	
Command to Offset Line of Sight (COLOS) to intercept	Phased array radar, or, LPI surveillance radar + Differential radar tracker	IRST / passive millimetric alerting Laser rangefinder	Line of sight engagements only Expensive radar requirements Range dependency of miss distance Target illumination throughout flyout
Radar Information Field (RIF) guidance to intercept or for mid course with terminal seeker	LPI surveillance radar RIF projector / tracking radar	IRST / passive millimetric alerting Laser rangefinder	Line of sight engagements only Limited crossing target capability Target illumination throughout flyout
Semi-active RF or RF/IIR seeker (with or without command mid course fly out)	LPI surveillance radar RF illuminator / tracker or, Phased array radar	IRST / passive millimetric alerting Laser rangefinder	Line of sight engagements unless airborne illuminator used Target illumination throughout flyout if semi-active all the way Expensive radar requirements
Laser Information Field (LIF) guidance	LPI radar	IRST / passive millimetric alerting Laser rangefinder / LIF projector	Weather limitation on engagement range Line of sight engagements only Limited crossing target capability
PN mid course command guidance and multi-spectral seeker	LPI surveillance radar (track while scan), or, low cost phased array radar	IRST / passive millimetric alerting Laser rangefinder	Necessity to contain missile costs

Table 6: Some candidate AD weapon system architectures and comparative assessment of key limitations

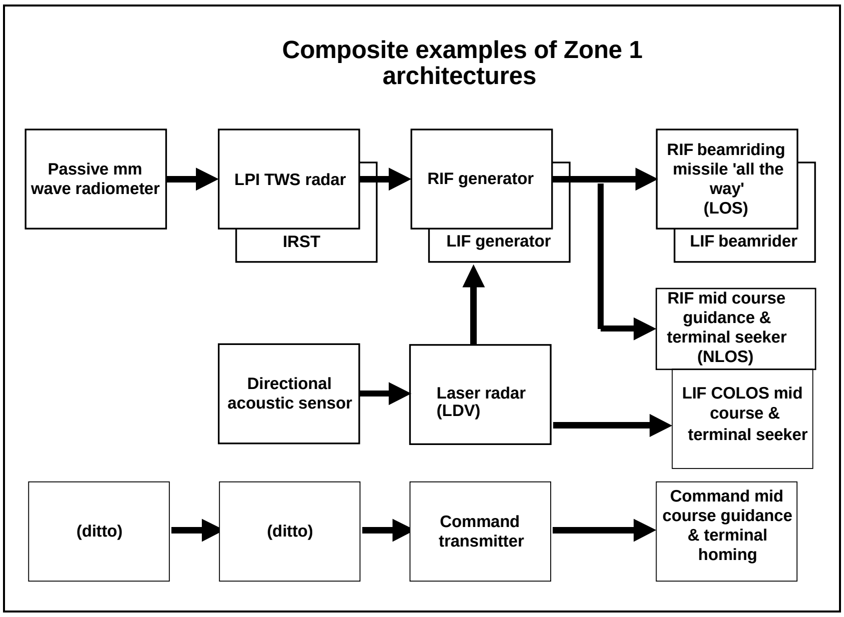

Figure 6: Illustrative Zone 1 options

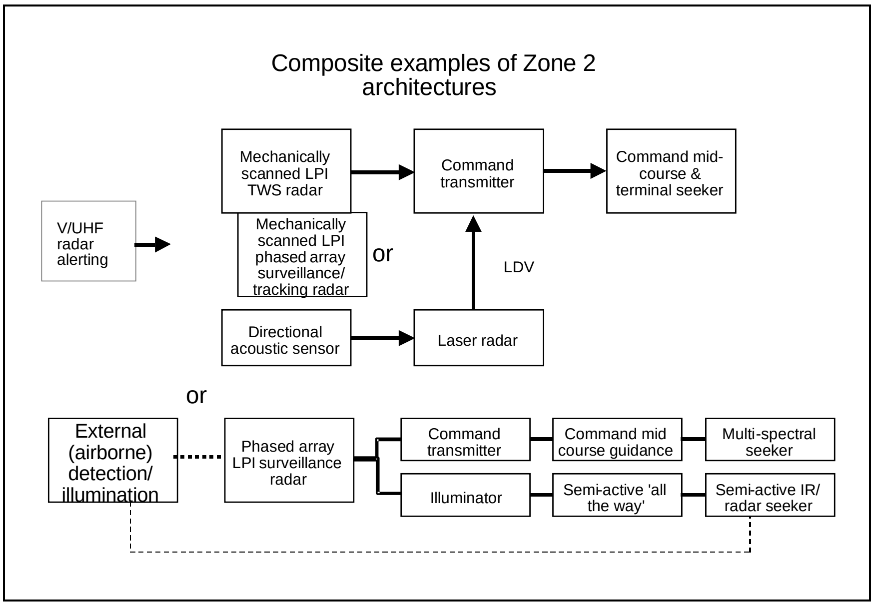

Figure 7: Illustrative Zone 2 options

Surveillance sensors

The illustrative architecture diagrams reference (non-exhaustively) a number of sensor technology options spanning radar in various wavebands, infrared search and track (IRST), passive millimetric radiometry, laser and acoustic. UK-specific studies and joint, collaborative studies within NATO RTO SCI032 have addressed surveillance sensor technologies to support future missile systems. SCI032 derived a Technology Matrix (TM), which illustrates qualitatively the performance attributes of surveillance sensor techniques across the electromagnetic spectrum. This is shown in Table 7 overleaf which consists of columns which address salient attributes of desired sensor performance characteristics, and rows which address generic methods of target discrimination (against clutter, ECM, etc.). The TM entities refer to specific technologies which exploit the physical means of target discrimination. A combination of objective and subjective analyses led to grading of the specific technologies in terms of perceived credibility and performance within the future timeframe. It is to be noted that Table 7 introduces air target recognition and identification characteristics of technology solutions.

Desired Sensor Performance Characteristics

Target discriminants	SHORAD Rdetect Day/Night	SHORAD Rdetect All Weather	SHORAD Rdetect All Climates	Good Accuracy, Resolution	Covert	Recognition and identification	Multiple target capability (system)	NLOS partially masked (helo)	NLOS fully masked	Robustness against Counter measures
Reflection Coef (Radar)	D E	D **E**	D *E*	(i) *D(ii) D(iii)* E	*D(i)* **D(ii) D(iii)** E	*D E*	D(i) D(ii) *D(iii)* E	*D E*	**D(iii)**	*D E*
Temp (emissive)	A B		*A B*	A B	A B	*A B*	A **B**	*A B*		A B
Temp (reflective)	C **H**	C	C *H*	C H	C H	**C** H	*C* **H**	*C H*		*C H*
Polarization	B D	D	B D	D(i) *D(ii) D(iii)* B	**D(i) D(ii) D(iii)**	B *D*	B D	BD	**D(iii)**	B D
Effluent (chemical)	E(iii) B		E(iii) B	E(iii) B	E(iii) B	E(iii) B	E(iii) B	E(iii) B		E(iii) B
Turbulence (Helo)	*E(iii)*		**E(iii)**	E(iii)	E(iii)	**E(iii)**	*E(iii)*	*E(iii)* **B**	*E(iii)* **B**	E(iii)
Sound	*G E(iv)*	**G**	*G E(iv)*	**G** E(iv)	G E(iv)	*G E(iv)*	**G E(iv)**	G E(iv)	G E(iv)	G
Emitter (Intermittent)	*F*	*F*	*F*	*F*	F	***F***	*F*	*F*	*F*	F
Emitter (Cooperative)	I	I	I	*I*	**I**	I	I	*I*		**I(i)** I(ii)

Table 7: Sensor technology matrix

Symbol	Technology
A	IRST(Infrared Search and Track) i – Hyperspectral ii – Broadband
B	IIR (Imaging Infrared)
C	PMMW (Passive Millimetre Wave)
D	RADAR i– mm ii– cm iii – m and lower
E	LASER i – designator ii – rangefinder iii – Laser Doppler Velocimetry (LDV) iv – Laser microphone v – Laser vibrometry
F	ESM
G	Acoustic
H	Visual
I	IFF i – Mk XII (STANAG 4193) ii – SIFF (Successor IFF, STANAG 4162)

Table 8: Legend for Table 7

The assessments in this respect refer to the potential for Non Co-operative Target Recognition (NCTR) with radar, electro-optic, acoustic technologies and with co-operative techniques such as ESM and IFF systems.

Table 8 provides the legend for the TM. It should be noted that the symbol convention is on a (relative) 3-point scale of projected credibility/performance, running from **bold** (worst case) through *italic* to <u>underlined</u> (best case).

The TM shows a wide spread in projected capabilities and limitations of individual sensor technologies. It emphasises:

- the contrast between the use of active and passive technologies against the criteria of realistic range performance in poor weather, covertness, and countermeasures resistance, and the difficulty of finding a robust single sensor solution without compromise to essential performance characteristics;
- the difficulty of finding a robust single sensor solution to the ground-based detection of NLOS helicopters, especially when fully masked by terrain;
- the continuing problems in finding a robust solution to air target recognition and identification;
- the need to research new technologies which may have high pay-off in the areas of counter-stealth, survivability, NLOS target detection. Current indications are that such technologies, embracing new radar frequency bands, atmospheric turbulence, high resolution techniques for NCTR, etc., will be best used in concert with other sensors.

The fundamental message is the need to consider sensor fusion techniques in the context of synergy to close performance gaps without significant operational penalties. This constituted the remit of SCI032, which has completed the largely qualitative Phase 1 assessment and is moving towards quantitative evaluation of promising options in the current Phase 2, under the aegis of SCI069. During Phase 1, it was necessary to postulate a "reference AD system" which could provide good potential capability against the wide threat spectrum, and which constitutes the baseline from which to examine and evaluate enhancements through sensor fusion. The derivation of the reference AD system followed a similar methodology to that undertaken by specific UK studies, *q.v.*, Figure 1, and, in general, reached similar initial conclusions.

AD system architecture building blocks

Figure 8 shows a schematic of the reference AD system which emerged from the SCI032 work, and which has also been derived in UK-specific studies for Zone 2 application. The reference system should be viewed as an autonomous building block with which to explore modular enhancements and alternatives, including fusion schemes to improve air picture spatial and identification integrity both in a local (collocated) and a wider, more global (fully distributed) context.

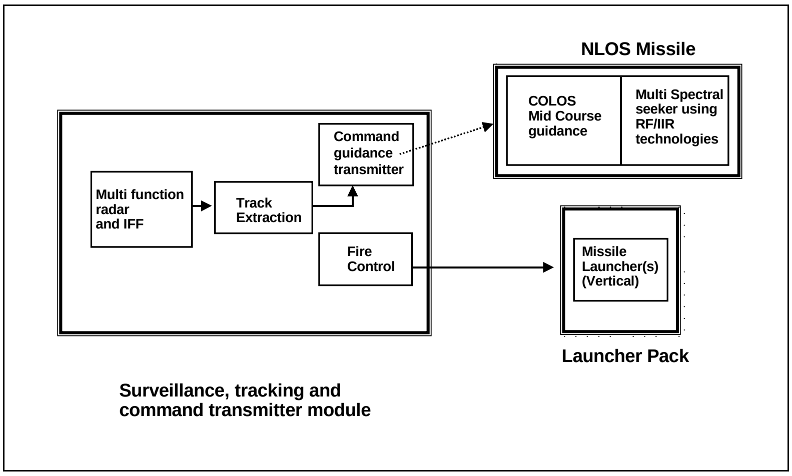

Figure 8: Reference (autonomous) system

The reference building block incorporates a terminal homing missile (hence an NLOS capability) using a multi-spectral RF/IIR seeker whose mid course guidance is provided through a command transmitter using track data from a multi-function radar (MFR).

The latter provides initial surveillance, with integrated IFF and a potential capability for non co-operative target recognition through high range resolution profiling. It is also possible to consider an integral ESM interferometer sensor to support establishing emitter identification when available. A collocated or remote weapon pack with vertical launch of missiles completes the system. Essentially, the reference system provides an intrinsically powerful autonomous kill capability through use of the dual mode seeker employing complementary spectral band attributes, including within-seeker fusion when appropriate.

Integrated system architectures

The performance of the reference system concept against the future target set comprising fixed wing, helicopters, UAV, TASM, cruise missiles will vary considerably with target class, profile, signature. Although the autonomous building block provides a good fundamental capability against elements of the threat stream, it has inevitable limitations of robustness within the complete operational environment discussed previously. A broad appreciation of limitations is:

- the radar emission signature may be unacceptable in Zone 1 applications;
- the radar will suffer terrain masking problems against very low level targets and has no capability against NLOS helicopters;
- the radar will be limited in range performance against highly stealthed targets within the full search volume;
- the combination of low and high level target profiles with low observable targets provides problems for MFR resource management;
- overall situational awareness will be poor, and, in particular, air target classification and identification is likely to be far from robust enough to permit autonomous engagement decisions in difficult operational environments;
- although the missile with multi-spectral seeker provides a cost - effective kill mechanism against manned platforms and missile targets, engagements against relatively cheap targets raise concerns.

The critical limitations apply to surveillance and identification prior to missile launch. SCI032 took the approach of considering two broad categories of multi-sensor and sensor fusion enhancement to these aspects of the reference system functionality. These are:

- the addition of collocated, complementary sensors to the MFR;
- embedding the reference system in a distributed sensor architecture.

Reference system with multiple collocated sensors

The following multi-sensor concepts have been proposed to fill the perceived capability gaps of the reference system by introducing:

- a passive sensor suite to provide covert surveillance, cueing, and fusion with radar plot and identification data;
- a low frequency radar to provide a capability against low (conventional radar) observables, surveillance cover against high altitude targets, and, to use this information to cue primary surveillance for efficient management of the scanned aperture;
- a sensor suite which can provide detection, location and identification of masked helicopters;
- a laser sensor damage adjunct to provide an alternative target defeat mechanism.

The reference system with multiple sensor options and DET adjunct is illustrated in Figure 9. This postulates, for NLOS target acquisition, concurrent airborne and ground-based sensor options although cost considerations, *inter alia*, might dictate choice of a single module. In addition, the cost and operational implications of a dedicated low frequency radar are likely to preclude use on a one-on-one basis. In this respect it may be more appropriate to consider distributed, shared operation of such a facility on the basis of a wider, combined local air picture (LAP).

Figure 9 is intended to illustrate a functionally enhanced autonomous building block with a framework of modularity. A number of possibilities exist for complementary passive surveillance including IRST with spatial and temporal-based NCTR modes, and there is significant effort being expended in NATO nations on plot and track level fusion of IR and radar outputs. NLOS detection and identification techniques could incorporate, for example, sensors in tethered and UAV platforms, ground-based directional acoustic arrays and laser doppler velocimetry.

Integrated distributed system architectures

Although the concepts illustrated in Figure 9 offer the promise of a robust, autonomous capability against the wide threat stream, further enhancement can be postulated by pooling air target track and identification data from other organic surveillance units and from other sources originating from other Commands.

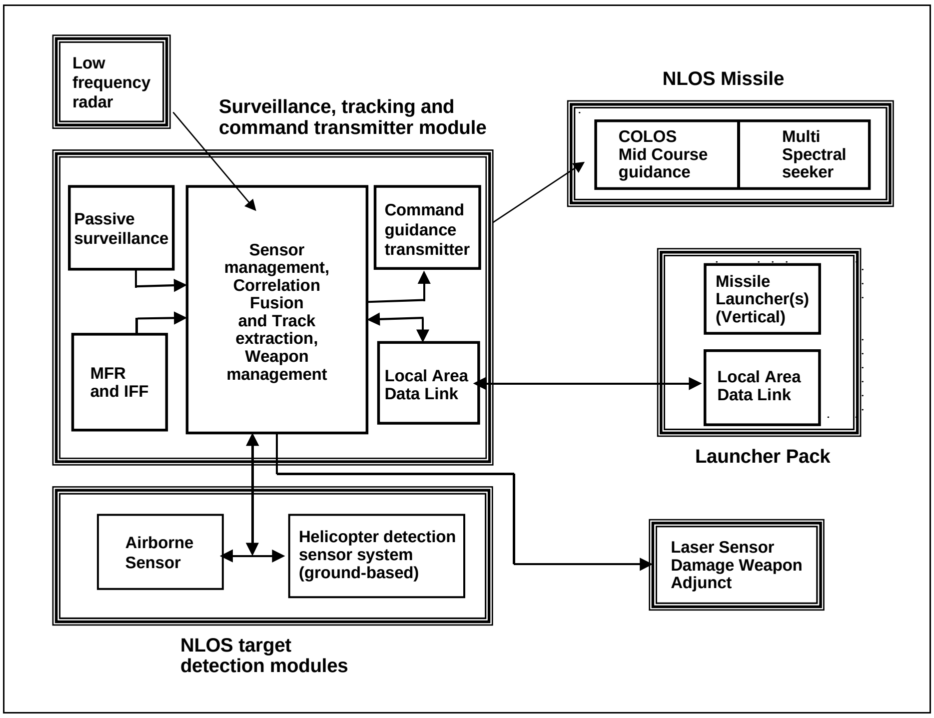

Figure 9: Multiple collocated sensors, DET adjunct

The principles at issue are the widest possible Situational Awareness and interoperability in a Joint environment.

These considerations lead to the concept of embedding configured, modular building blocks exemplified by Figure 9 in a distributed architecture with links to additional sources of air picture data. This is illustrated in Figure 10, which, although is not meant to imply a particular C3I architecture, introduces the concept of a picture compilation and weapon assignment node. The node is postulated as a focal point for fusing external data from other nodes and from sources such as Recognised Air Picture (RAP) and ISTAR platforms / ground stations distributed over wide area data links.

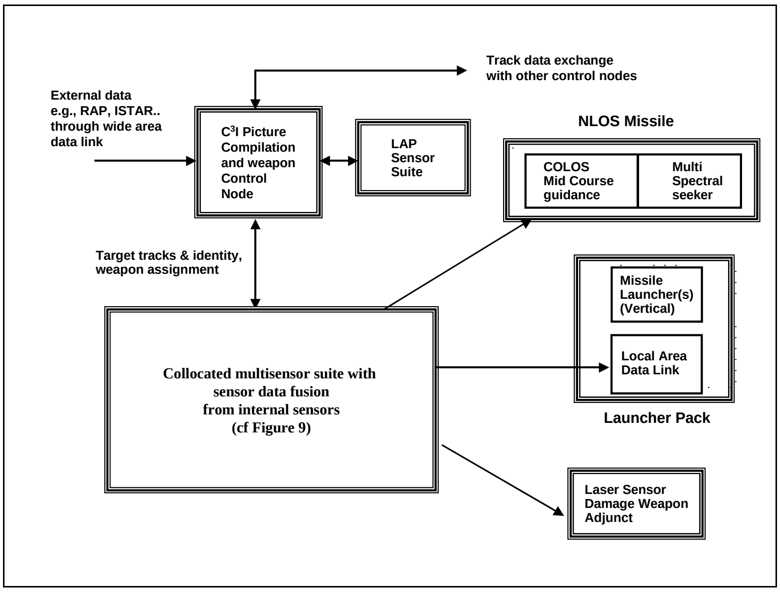

Figure 10: Integrated distributed system

Qualitative assessment of architectures

Phase 1 of the SCI032 work completed with a qualitative assessment of the benefits of moving through the concepts illustrated by Figures 8 to 10. The assessment is condensed into a Performance Improvement Matrix where a number of performance categories are examined in relation to a particular air target class and assessed on a three point scale from "poor" (P) through "good" (G) to "very good" (VG). The results are shown in Table 9 overleaf where each element of the matrix is divided into three cells with the first cell applying to the reference system, the second to local sensor fusion, and the third to a complete system of local and wide area fusion. Cells containing a cross denote no applicability/capability.

The major points arising from the reference system scoring are:

- the missile, based on a multi-spectral seeker, is very capable against small, highly manoeuvring targets, and has an NLOS capability against fully-masked targets, providing it can be cued by the surveillance system;
- the surveillance building block, the MFR, has good performance against fixed wing targets but is limited against helicopters and provides no capability when these targets are fully masked;
- the MFR is limited in provision of timely update data over the required large surveillance volume forced by all threat trajectories, and this is compounded by the most stressing threats being masked by terrain for at least part of the detection / track initiation / track maintenance process;
- whereas some target classification / recognition capability can be incorporated in the MFR using NCTR techniques, and IFF can be integrated, the overall capability for high integrity identification data is limited.

Scoring of schemes using multiple collocated sensors reflects greater robustness across the threat stream. In particular, the addition of NLOS helicopter sensors and a low frequency radar fill in significant gaps in MFR performance capability. The addition of passive surveillance sensors provides for covertness where scenarios dictate such a need. Fusion of spatial and identification data across the active and passive sensor suite promises the establishment of a Local Air Picture with enhanced integrity.

Finally, the scoring of combined local and wide area sensor and C^3I data, in a fully distributed architecture, reflects the goals of widest possible Situational Awareness and interoperability. The scoring assumes that future communications and processing technology will enable these goals to be achieved.

Modularity and operational flexibility

With that proviso, it is possible to iterate the modular reference system to provide a fair-weather Zone 1 variant. This uses the information provided by the sensor net to create the conditions mandated at the operational level for successful engagement.

Function	THREAT	Fixed wing	Helicopter		Cruise missile		TASM		UAV	
	SCENARIO	Combat support	Transit (LOS)	Attack (NLOS)	High altitude terminal dive	Very low altitude	High altitude terminal dive	Low altitude	Recce	Attack
Surveillance and ID										
Detection		G VG VG	P G VG	X P VG	P VG VG	G VG VG	P VG VG	G VG VG	P G VG	G VG VG
Track initiation		G VG VG	P G VG	X P VG	P VG VG	P VG VG	P VG VG	P VG VG	P G VG	P VG VG
Kinematics										
Position		G VG VG	P VG VG	X P VG	P VG VG	G VG VG	G VG VG	G VG VG	P VG VG	G VG VG
Identification										
Classification		P VG VG	P G VG	X G VG	P VG VG	G VG VG	P VG VG	G VG VG	P VG VG	G VG VG
Recognition		P VG VG	P G G	X G VG	X X X	X X X	P G G	P G G	P VG VG	P G G
Allegiance		P G VG	P G VG	X G VG	X X X	X X X	X X X	X X X	P VG VG	P VG VG
Situation assessment		G VG VG	P G VG	X P VG	P VG VG	P VG VG	P VG VG	P VG VG	P G VG	P VG VG
Threat assessment		P G VG	P G VG	X P VG	P VG VG	G VG VG	P G G	P G G	P G VG	P G VG
Weapon assessment		X X G	X X G	X X G	X X G	X X G	X X G	X X G	X X G	X X G
Threat engagement		G VG VG	G VG VG	X P VG	P VG VG	G VG VG	P VG VG	P VG VG	P G VG	P G VG
Kill assessment		P G VG	P G VG	X P VG	P VG VG	P G VG	P VG VG	P G VG	P G VG	P G VG

Table 9: Performance improvement matrix

Similarly, if the concept is considered to be a distributed modular system *ab initio*, a number of possible quasi-autonomous variants, based on specific operational requirements, become possible. The advantage is that this may be achieved without the need to create specialised fully-integrated vehicular systems. The important characteristic in this case is to be able to match or exceed the manoeuvre capability of the supported forces. An example might be a fair- or all-weather Zone 1 fire unit mounted on an armoured chassis for a particular type of operation, and a similar set of modules reconfigured onto a number of highly-mobile all-terrain platforms for another.

A modular distributed system would also allow the development of additional concepts. For example, it may be necessary to be able to deploy into sites which are inaccessible to anything other than troops on foot, especially where helicopter support is not forthcoming. In this case, a man- or crew-portable target engagement element, which could access the full latent power of the distributed system, might provide an elegant, and effective, solution.

A concept of operations (CONOPS) for a distributed modular system in the future timeframe has been developed in support of the concept described. Analysis has confirmed the substantial performance advantages, as well the more obvious benefits in tactical and operational terms. Sensors which can be elevated sufficiently to operate clear of close screening can be shown to provide the most flexibility, security and survivability in system terms. This effect is most marked, perhaps unsurprisingly, in Zone 1. Given the combination of advantages conferred by the concept – the deployability and high engagement rate conferred by a multiple vertical-launch missile pack, and near-circular coverage in the end-game conferred by capable high-speed homing missiles - the weapon system becomes broadly only limited by the capabilities of the sensor net and the timeliness and bandwidth of the communications system.

Separation of the weapon element from the sensor element allows both to be optimized separately. This has major tactical advantages over collocated systems in the defence of mobile operations, as sensor siting and movement are not hamstrung by the demands of conventional mutual support. Similarly, as long as it remains within useable sensor coverage, the centre of the weapon system footprint may be placed where it is really wanted – to defend the target – even to the extent of being sited amongst the forward troops. Operational benefits in terms of robustness, survivablity and capability against the most stressing threats may also be seen reflected in Zone 2 deployments.

In information dominance terms, the concept, as outlined, fits more closely the developing doctrine. For crisis reaction forces, the emphasis on sensor networks allows greater flexibility in planning and employment in non-warfighting situations without compromising the ability to match any subsequent escalation. It is also not difficult to envisage the advantages of distributed systems in such conditions as peace support deployments for isolated enclaves, especially as the weapon element may be kept non-provocatively covert and passive, up to the moment of engagement.

Within the basic principles of war, which have not substantially changed since Sun Tzu’s time, distributed modular systems would allow many of the conventional employment and deployment rules to be re-written. This concept would help provide a broadly effective answer to what has hitherto always been, and increasingly will become, a series of intractable problems for the AD of ground forces.

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An Architecture for Effects Based Course of Action Development

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Summary: A prototype system to assist in developing Courses of Action and evaluating them with respect to the effects they are expected to achieve has been developed and is called CAESAR II/EB. The key components of the system are an influence net modeler and an executable model generator and simulator. The executable model is exercised using the plan that is derived from the selected Course of Action and the probabilities of achieving the desired effects are calculated. The architecture of CAESAR II/EB is presented and an illustrative example is used to show its operation.

INTRODUCTION

Since Desert Storm, the concept of integrated Planning and Execution is becoming accepted and systems and procedures are being implemented to achieve it (e.g., concepts are being tested in Advanced Warfighting Experiments by the Services). Integrated Planning and Execution enables dynamic battle control, (sometimes referred to as dynamic planning). Bosnia and especially operation Allied Force in Kosovo, have focused broad attention on effects-based planning and effects assessment (see Washington Post, Sept. 20-22, 1999). This leads to closer interaction of intelligence and planning: intelligence is not only an input to the process, but a key component of the effects assessment feedback loop. Given the potential complexity of future situations and the many consequences of the responses, an approach is needed that (a) relates actions to events and events to effects; (b) allows for the critical time phasing of counter-actions for maximum effect, and (c) provides in a timely manner the ability to carry out in near real time trade-off analyses of alternative COAs. Such an approach, based on research and development carried out over the last five years, is now feasible. The approach is described in this paper.

The first step is to develop and select a *Course of Action* that will lead to a desired outcome. A Course of Action is composed of a timed sequence of *actionable events* that are expected to cause the desired effects. In current practice, probabilistic models that relate causes to effects are used to identify the set of actionable events that yield the greatest likelihood of achieving the desired outcomes and effects. Note that these models do not include timing information. The selected set of actionable events is provided to planners who use experience to select, assign, and schedule resources to perform tasks that will cause the actionable events to occur. The schedule of tasks with the assigned resources constitutes a plan. Outcomes, in terms of effects, are critically dependent on the timing of the actionable events.

APPROACH

The problem requires the synthesis of a number of approaches that have been emerging in the last few years from basic research efforts by DOD and industry. Indeed, the rapid improvement in computational capability and the availability of design tools have made the process of going from an idea to a proof of principle much more rapid.

The process diagram in Figure 1 identifies four principal functions of Effects Based Operations and three feedback mechanisms that enable these functions to be accomplished. This conceptualization expands the conventional C2 process to include not only the traditional Battle Damage Assessment (BDA) feedback loop, referred to here as Action Assessment, but also two other feedback loops: Dynamic Battle Control and Effects Assessment. There is also a fourth loop not considered here, the real time shooter assessment loop, often referred to as Execution Control. The distinction between Execution Control and Dynamic Battle Control is that the latter involves the controllers and sometimes the planners. The Dynamic Battle Control loop allows for changes in the plans after the plan has been disseminated, while the longer loop involves assessment on how

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well the actions being taken are achieving the desired effects or how well the goals are being met. Each one of these loops precipitates different responses. The Dynamic Battle Control loop affects the execution of the plan by doing real and near real time retasking of assets. The Action Assessment loop affects the development of the next days plan. The Effect Assessment loop leads to the reconsideration of the Course of Action being followed and possibly to the selection of an alternative COA to meet the changing circumstances.

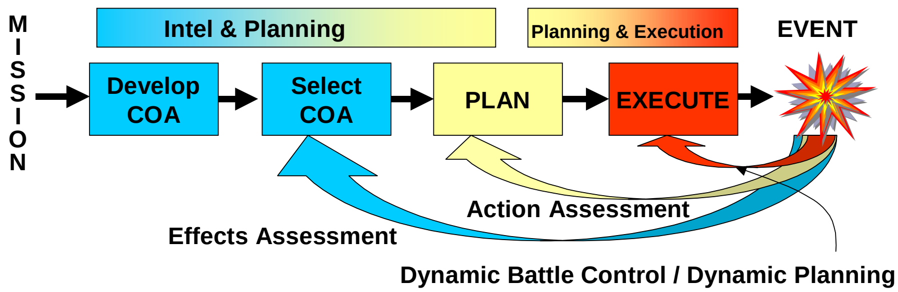

Figure 1 Block Diagram of Process for Dynamic Effects Based Command and Control

More specifically, the forward process includes COA development. COA selection, Planning, and Execution. As Fig. 1 shows, the first three stages require the close interaction of Intelligence and Planning, while the last two require the integration of Planning and Execution. The latter is already occurring in the case of air operations, while the former is beginning to take form.

Once the forward process has been completed, the execution of the resultant plan induces the feedback process. Once we begin to take actions and other events occur, the process and tools must track our progress in achieving the desired effects. Measures (triggers) must be developed for changing COAs. The tools and the process must facilitate the ability to make changes to plans in a dynamic manner, while the plans are being executed. The actionable events are specific; the first feedback loop, dynamic battle control/dynamic planning, involves local adjustments to the specific actions of resources as they perform planned tasks. The assessment is conducted by operational controllers attempting to ensure that the tasks and actionable events occur according to the plan. The second feedback loop, action assessment, addresses the measurement and evaluation of whether the actionable event occurred and to what extent. For example, in conventional air warfare, this would be equivalent to measuring whether the bombs hit their targets and the extent of damage they have inflicted. Adjustments are made to future plans to account for actionable events that were scheduled but did not occur or observations about the immediate impact of the actionable events The third feedback loop assesses progress toward the overall desired effects. Given that the actionable events have occurred, have the effects been achieved? Given that the blue forces have achieved a planned level of bomb damage through the air campaign, have they forced the adversary to change his policies? Changing the policy is a desired effect. If events are not unfolding as originally envisioned, it may be necessary to change or adapt the COA. Ultimately, this feedback is used to assess whether the goal has been met when certain effects have been achieved.

The first observation is that the internal loop, if it is fast enough, permits dynamic planning. The latter forces the integration of planning and execution, since the concept of dynamic planning breaks down the paradigm of a fixed plan to which ad hoc changes are being made. Implementation of dynamic planning results in a fluid, evolving integrated plan that is being modified as it is being executed.

The presence of the two outside feedback loops in Fig. 1 distinguishes traditional planning and execution from Dynamic Effects Based Command and Control (DEBC2). In the same way that dynamic planning integrates planning and execution, DEBC2 integrates intelligence with planning. The establishment of cause – effect relationships between actionable events and effects, or in the reverse direction, the inferencing of the occurrence of events from the observation of effects, is an activity that is carried out by intelligence analysts. By closing the two loops, the paradigm requires intelligence to become an integral part of the dynamics of the planning process, rather than only providing inputs to it.

This process can now be expressed in terms of specific activities that need to be performed and the tools and techniques that support them. This is illustrated in Fig. 2 using the IDEF0 formalism. The first activity is the analysis of the situation using several modeling techniques. This activity is carried out by situation analysts who are usually intelligence analysts. The second activity is the development and selection of alternative courses of action. In the case of DEBC2, the proposed system should be capable of being used to generate a variety of contingency COAs and plans and also be used (with scenarios) to evaluate these COAs and plans in terms of their likelihood of achieving desired effects. It should also be capable to be used in generating plans in near real time for unanticipated circumstances. The third activity is to generate plans for the alternative Courses of Action. The approved plan is disseminated to the units that carry out the tasks in the plan and to operational controllers who monitor the execution. In the fourth activity, the execution of the plan is controlled using the capability to exercise all three feedback loops shown in Figure 1.

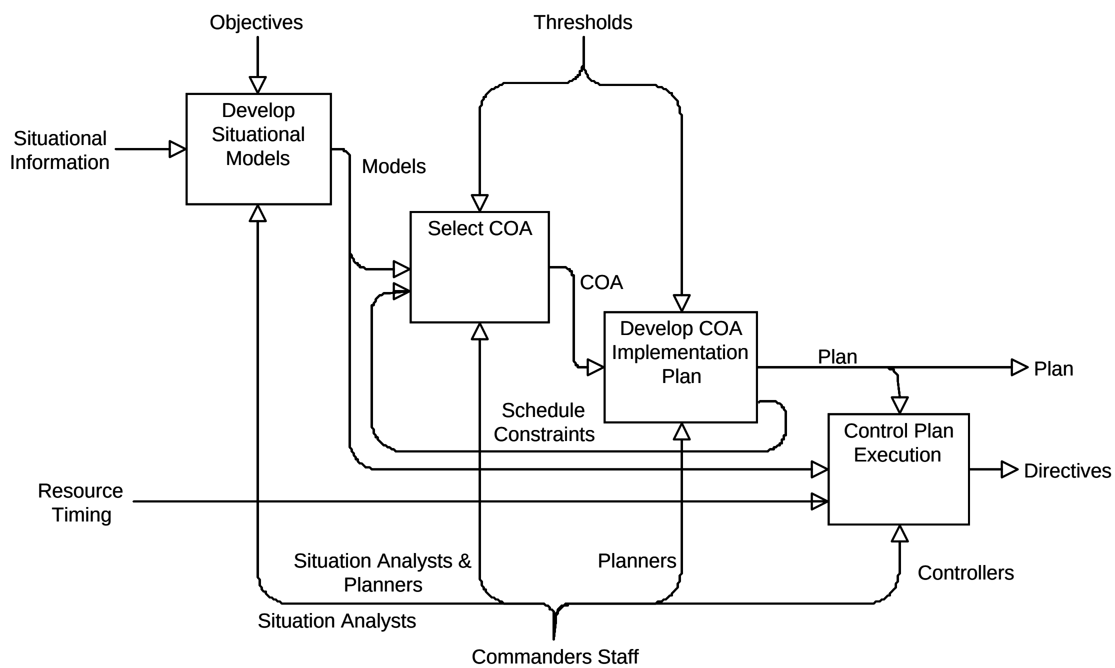

Figure 2 IDEF0 Process Model for Dynamic Effects Based Command and Control

The first activity produces a set of models that are at the heart of providing the capability for dynamic effects based command and control. The development of the first of these models starts with the process shown schematically in Fig. 3. The goals are set by the National Command Authority at the strategic level and by the Commander for the operational level. It is then determined that, to reach the goals, certain effects must be achieved. This determination can be accomplished using probabilistic modeling tools (e.g., Influence net modeling) such as SIAM,[1] as shown in Fig. 4. An influence net model allows the intelligence analyst to build complex models of probabilistic influences between causes and effects and effects and actionable events. This is shown in Fig. 5 which also implies the existence of a library of models that can be used as modules to create new influence models that are appropriate for the specific situation.

[1] SIAM is a COTS product developed by SAIC (Rosen and Smith, 1996) to support the intelligence community and is used as a module in the CAESAR II suite of tools. Other probabilistic modeling tools such as Hugin, Analytica, and the Effects Based Campaign Planning and Assessment Tool (CAT) under development at AFRL/IF can support the modeling of actionable events and effects.

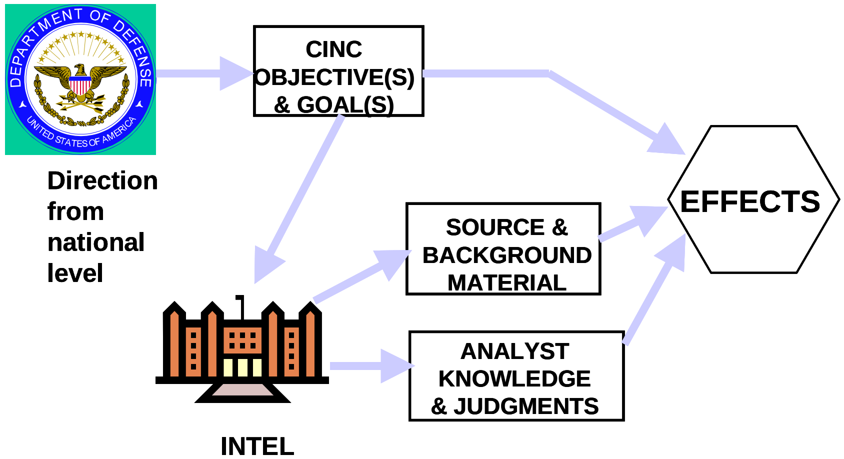

Figure 3 Effects determination in Dynamic Effects Based C2

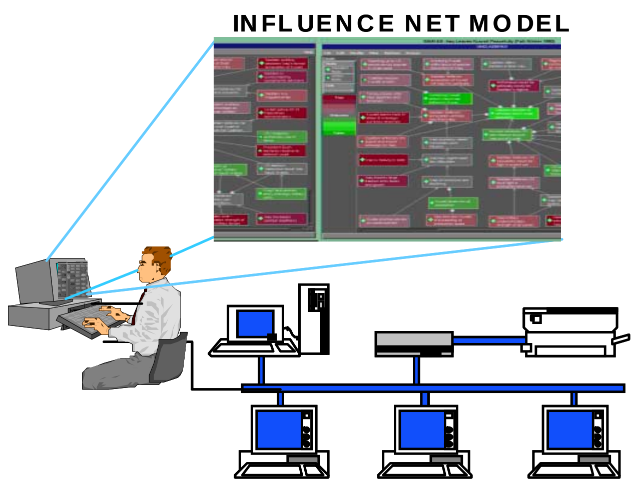

Figure 4 An intelligence analyst developing an Influence net model relating goals to effects and to actionable events. The network implies access to diverse data sources (e.g., through the Joint Battlespace Infosphere or any other network-centric architecture)

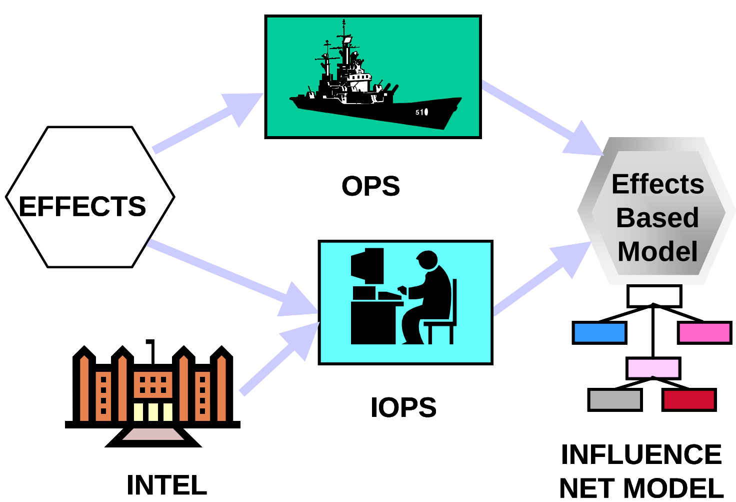

Figure 5 Development of the Influence net model

The Influence net model is then used to carry out sensitivity analyses to determine which actionable events, alone and in combination, appear to produce the desired effects. It should be noted that Influence nets are static probabilistic models; they do not take into account temporal aspects in relating causes and effects. However, they serve an effective role in relating actions to events and in winnowing out the large number of possible combinations. The result of this exercise is the determination of a number of actionable events that appear to produce the desired effects and give an estimate of the extent to which the goal can be achieved.

Once the influence net of the situation has been developed, the situation analyst converts it into an executable model that allows the introduction of temporal aspects (Fig. 6). An automatic algorithm that performs this conversion has been developed, tested, and demonstrated. A Colored Petri Net model is developed using the structural and probabilistic information (the influences) contained in the Influence net model. (Wagenhals et al., 1998) The current probabilistic equilibrium models (Influence nets) used for situation assessment contain a great deal of information in the form of beliefs about the relationships between events and the ultimate outcome or effect. They have an underlying rigorous mathematical model that supports analysis. They provide only a single probability value for a given set of actionable events. They do not capture the effect of the sequence or timing of the actionable events. Additional information needs to be inserted to account for temporal and logical sequencing of actionable events. A particular sequence of actionable events represents an alternative Course of Action. Note that in a threat environment proper sequencing is critical; reversal of two operations can endanger lives and affect critical operations. Consider a trivial example: wear protective equipment then step in hazardous environment vs. step in hazardous environment and then put on protective equipment. While this is obvious, such reversals are not easily observed in a complex scenario with many concurrent tasks. The executable model brings these issues to the fore.

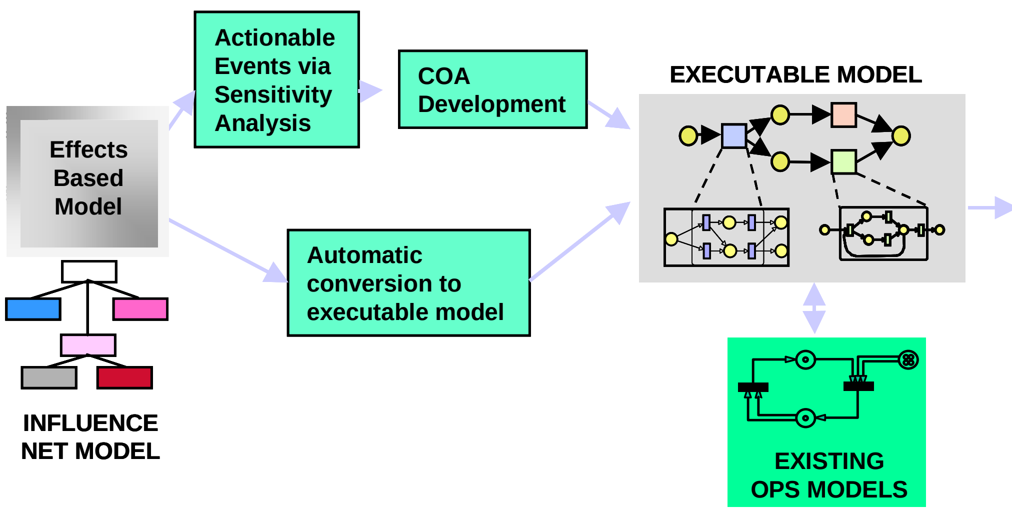

Figure 6 Development of executable model

Recent research by the GMU System Architectures Laboratory has shown that it is possible to enhance these models so that the impact of timing of the inputs on the outcomes/effects can be determined. This impact can be represented by the timed sequence of changes in the likelihood of the outcomes/effects determined by the timing of the actionable events. The sequence of changes in probability is called the *probability profile*. It is a key measure of the effectiveness of a COA that can be used to evaluate COAs during their development and to determine when and how to change the COA during execution.

The executable model, when properly initialized with a scenario, can be used in simulation mode to test the various COAs to determine their effectiveness by generating the timed probability profile for the particular COA. (Fig. 7) The problem and the assumptions can be shown on the future Display Wall at the Joint Task Force level in which the situation is presented (say, the relevant Common Operating Picture) along with alternative Courses of Action and their assessment. A Commander can then make an informed choice and direct the planning staff to prepare the detailed plan for the chosen COA.

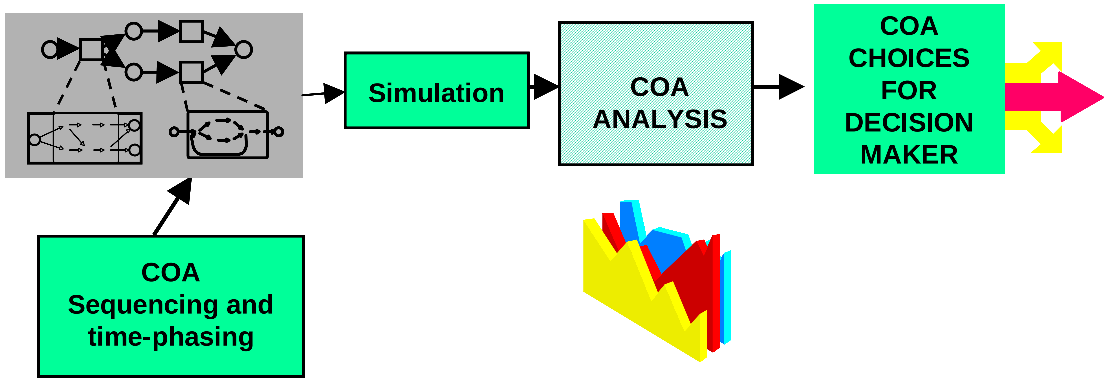

Figure 7 Analysis of Alternative COAs

Carrying out simulations using the executable model is not the only way in which COA analysis and evaluation can be conducted. State Space Analysis of the Colored Petri net model of the influence net can be conducted to reveal all of the probability sequences that can be generated by any timed sequence of actionable events. The result of the state space analysis is a State Transition Diagram that is mathematically a lattice. This state transition diagram can be easily converted to a plot showing the range of probability values that can exist at each step in any probability profile. This technique allows the analysts to see, at a glance, all of the potential effects that timing of the actionable events can have. The analyst can then select the profile that gives the best results. Once the untimed profile has been selected, procedures using a temporal logic application called TEMPER 2, (Zaidi and Levis, 1997) can be used to determine the temporal relationships between the actionable events that will generate the selected probability profile. The set of model composed of the influence net, the Colored Petri Net, Timed Point Graphs from the Temporal Logic formulation, and the State Transition Diagram are called the Common Planning Problem. It is these models created in the first activity that can enable the forward and feedback Dynamic Effects Based Command and Control process illustrated in Figures 1.

In the second activity of the process, the operational planners and the situation analysts use the models of the common planning problem to select candidate COAs. The concept for this procedure is shown in Fig. 8. The analyst uses the State Transition Diagram to construct the plot of the untimed probability profiles. He selects candidate profiles using a set of metrics and determines the temporal relationships of the actionable events that will generate these sequences using the temporal logic algorithms. These COAs are run in the executable model to generate the timed probability profile for final selection. In the example of Figure 9, COA 1 is preferred of COA 2 because it has the higher probability values at all time points and reaches the highest probability the fastest.

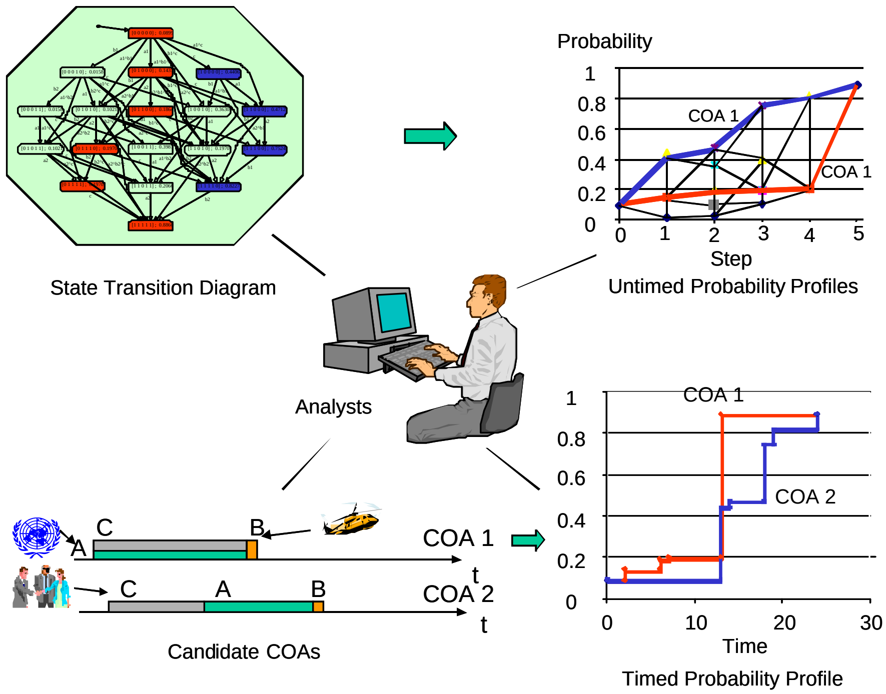

Figure 8 Decision support for COA selection

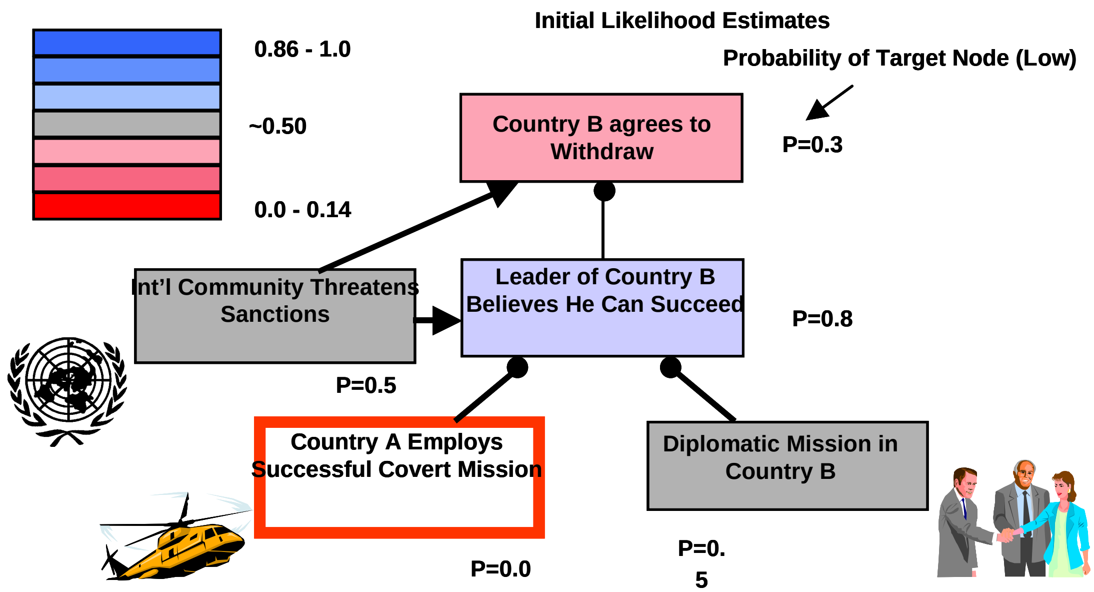

Figure 9 Influence net of example

Having selected a COA, a detailed executable plan is developed in the third activity of Figure 2. The existence of the executable model (structured in an object oriented manner so that it can be instantiated at different levels of abstraction) gives the opportunity to test the plans in simulation mode and *also to monitor their execution by inserting actual event as they occur*. This is a required capability for dynamic planning; the state of the system must be known in order to insert new tasks, eliminate existing ones, or redirect ongoing ones.

The fourth activity involves the continual assessment of the execution of the actionable events, the assessment of their effects and the impact they have on achieving the goal. The three loops correspond, very approximately, to measures of performance, measures of Effectiveness, and Measures of Force Effectiveness. The models of the Common Planning Problem can be used in the assessments associated with each feedback loop. During the execution of a plan, there are two major factors that can impact the expected effectiveness of that plan. First, the timing of the actionable events may change as the resources perform the tasks in the plan. The impact of these timing changes in terms of the timed probability profile can be quickly examined using the executable model of the Common Planning Problem. If anticipated timing changes have an adverse effect on the probability profile, adjustments to the timing can be determined that will bring the profile within acceptable levels. The second type of changes involves the occurrence or non-occurrence of anticipated events in the influence net. In the planning mode, events were assumed to occur with some probability; in the assessment mode, events occur with probability one or zero – depending on whether they occurred or not. This changes substantially the computational model incorporated in the Colored Petri Net but not the structure of the model. The impact of these observations on the timed probability profiles can be observed by updating the elements of the Common Planning Problem.

All parts of this process have been prototyped and executed using the suite of tools called CAESAR (Computer Aided Evaluation of System Architectures.) Several case studies have been run and demonstrated, ranging from a small influence net that illustrates the concepts, to a large influence net (about 100 nodes) representing a complex situation. The next section contains the a description of the small illustrative example.

EXAMPLE

The operation of CAESAR II/EB is illustrated through a hypothetical "day in the life" of such a system. Assume that a crisis emerges. Country B has invaded a neighboring country and a key issue is whether the leader of the country believes that he can succeed in this undertaking. The crisis action team is constituted and begins to evaluate the situation and consider options. An existing influence net that describes the decision making process of Country B is retrieved from the library of models and the analyst modifies it directly to reflect the specifics of the crisis. There are many actionable events ranging from diplomatic efforts by country A all the way to declaring war by a coalition of nations. The analyst carries out a sensitivity analysis of these alternative actionable events and determines that three particular actionable events may be sufficient at this stage, namely, diplomatic mission by country A to country B; sanctions by the international community (through the United Nations) and a covert mission by country A that causes severe damage to the leader's arsenal. The influence net with initial values of probability of occurrence of the actionable events 0.5, 0.5, and 0.0, respectively is shown in Fig. 9. The result of the analysis, the probability that country B will withdraw is only 0.3. However, if all three actions take place with probability 1, then the probability of the outcome rises to 0.9, which is the highest value that can be attained in this influence net.

The influence net is then converted automatically by CAESAR II/EB into a Colored Petri net, as shown in Fig. 10. However, temporal information must be entered. This information is of two types: First, the temporal characteristics of the system as represented by the influence net such as communication delays, procedural delays, etc. The second type is the time sequencing of the actionable events. Even though there are only three events here, there is a large number of alternatives since we allow concurrency of events. Using the analyst's and planner's experience, the number of event sequences can be reduced substantially. Given that the outcome of the sensitivity analysis was to carry out all three actions and given that the covert action should follow the diplomatic efforts, two sequences were chosen as the alternative courses of action: (a) the incremental approach: first country A's diplomatic mission; then the international sanctions, and finally the covert action; and (b) the forceful approach: concurrent diplomatic efforts followed by covert action if diplomacy is not successful.

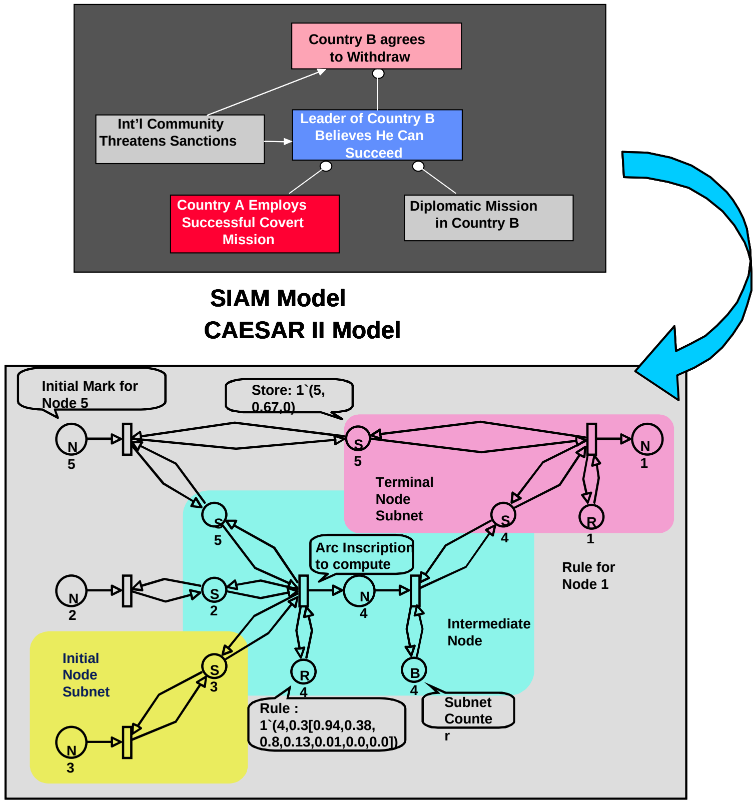

Figure 10 Influence net to Petrinet conversion

The Colored Petri net (Fig. 11) is used in the simulation mode to produce the two probability profiles shown in Fig. 12. Clearly, approach (b) is preferable; it shows a substantially higher probability of achieving the goal without ever resorting to the covert mission.

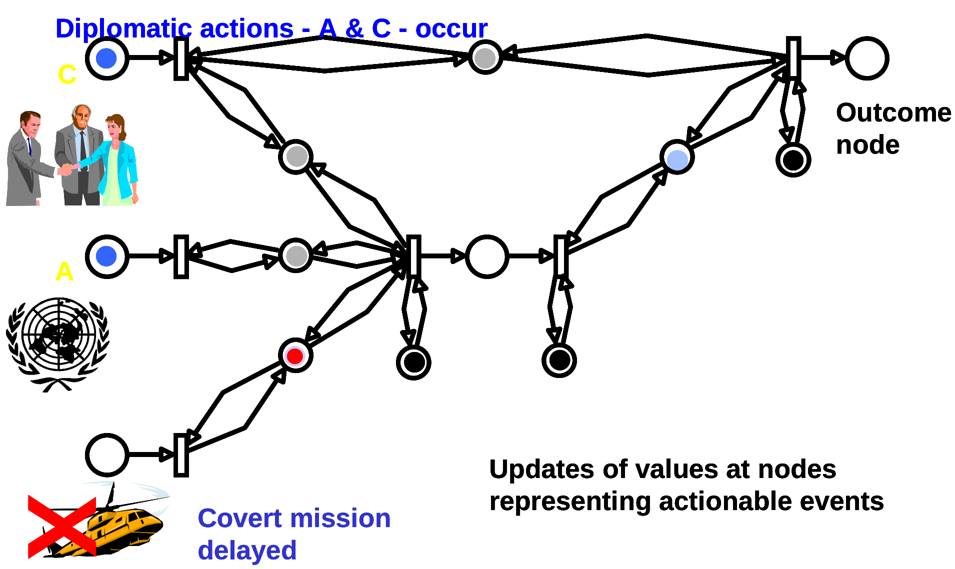

Figure 11 Petri net execution

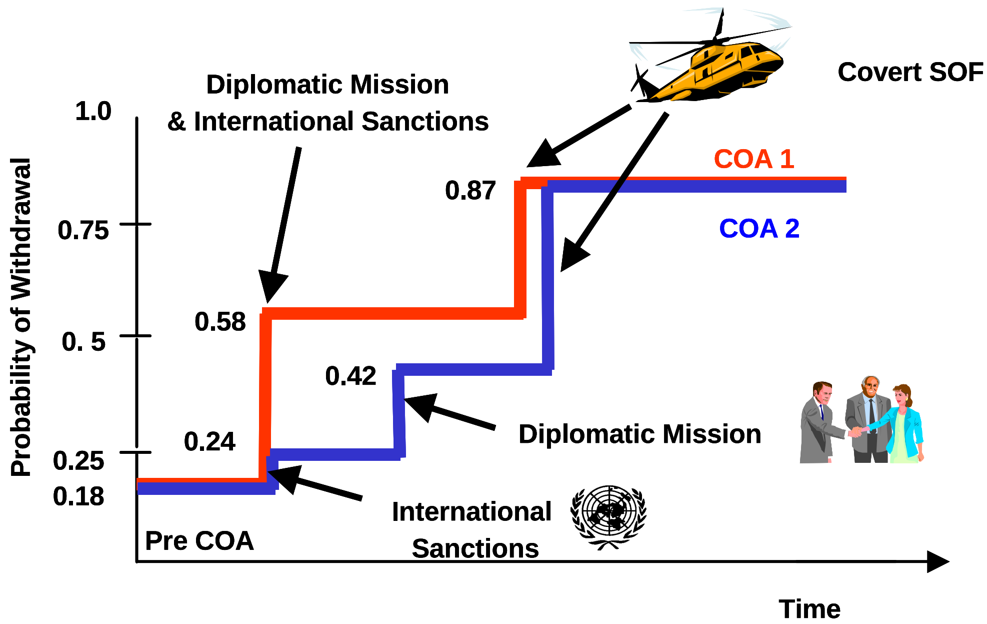

Figure 12 Comparison of COAs

CONCLUSION

An approach to Course of Action development and selection for effect based operations has been described and CAESAR II/EB, a decision support tool prototype, has been described and an example has been used to illustrate the operation.

ACKNOWLEDGEMENT

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On Modularity in (V)Shorad Air Defense

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Summary

This paper addresses the concept of modularity in the context of (V)Shorads Air Defence.

Modularity is a technical concept that provides improved operational flexibility to (V)Shorad systems. Such improved flexibility is specifically relevant to mobile crisis reaction forces.

The discussion is largely qualitative and descriptive, given the premature state of modular technology in defence. The discussion is also largely applicable beyond air defence systems.

In this paper, it will be argued that modularity as a concept indeed addresses many of the problems facing mobile air defence today.

It will also be made clear that there are serious restrictions and drawbacks to modularity.

Further, it will be made credible that modularity is not a binary characteristic but a gradual one. This immediately raises the question how much modularity is required for what application.

Thus, the paper will provide fundamental insight into the use of modularity in mobile air defence.

Background

Air defence of (Multinational) Mobile Crisis Reaction Forces puts forth several specific requirements to the associated air defence systems.

Among other demands, it requires VShorads and Shorad air defence systems that are lightweight to allow both tactical and strategic mobility. It requires a traction system capable of traversing a diversity of terrain at good speed. It also requires that the air defence system can be used in a joint and/or combined environment. This will encourage a reasonable size of the overall international air defence deployment while minimising individual national contributions in the build-up of a multi-national crisis reaction force.

It will not be argued that these requirements compromise effectiveness and fighting efficiency of such systems as a result of engineering complications. Specifically, low weight incurs vulnerability to ballistics and structural integrity. High mobility restricts the choice of components because of size and requires additional ruggedness of systems. A joint-combined capability may require a plethora of communication, data and processing systems.

The obvious challenge for the air defence community is to devise an air defence concept that combines effectiveness with suitability for Crisis Reaction operations.

Paper presented at the RTO SCI Symposium on "System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces", held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

The solution to this challenge lies in *flexibility***.** Flexibility in this respect denotes the use of a system that combines Shorads and VShorads and that does not have a fixed architecture or system composition. In a technical sense, flexibility is realised by the concept of *modularity*.

Modularity has been the subject of earlier studies, such as the NATO JPG-28/30 International Feasibility Study on Future VShorads and Future Shorads and several non-defence studies. In addition, the author has performed in-house research and discussions with Royal Netherlands Army and Air Force, resulting in the underlying paper.

This paper will first present the concept of modularity in general. Then, this concept will be applied to air defence systems, stating advantages and challenges. Finally, conclusions round up the discussion.

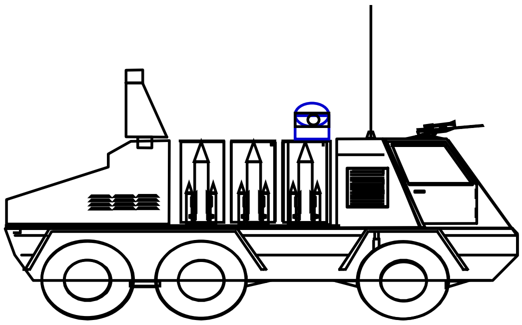

Figure 1. Representation of an integrated (V)Shorads air defence system, capable of autonomous operation. Picture taken [Ref.1].

Modularity as a concept

Any definition describing what modularity is can be a matter of debate. The following definition will serve its purpose for this paper.

Modularity is the concept in which a number of components of any system architecture, in this case a (V)Shorad system, can be combined repeatedly and relatively easy, to result in a large number of operational variants of a system, depending on the need as dictated by user, use and circumstances.

A few insights can be drawn from this definition.

First, this definition provides a hint towards benefits of modularity, namely the possibility to have more than one variant of a system.

Further, the definition also points out that modularity may be applicable to any number of components within a system. This implies that modularity is a gradual characteristic; a system is not either modular or non-modular.

Finally, the definition states that a modular system can be re-configured repeatedly and relatively easy, raising the question how ‘relatively easy’ is defined.

In order to be able to apply these considerations to (V)Shorads air defence, it is necessary to understand how a modular system is devised. The next section will provide this understanding.

The Architecture of modular systems

A system architecture can be thought of as having two at least two aspects of interpretation:

- A physical breakdown;
- A functional breakdown.

The physical breakdown is purely a technical matter dealing with subassemblies, production techniques materials, design, and ‘nuts and bolts’.

The functional breakdown is a schematic indicating what functionalities are present in the system and how they interrelate.

The key issue to embed modularity in a system, is to maximise the similarity between the functional and physical breakdowns of a system.

For example, a very non-modular design is the wing of an aircraft. Physically, it is one entity, since although constructed from smaller parts, it cannot be taken apart sensibly. However, the wing performs multiple functions simultaneously: it lifts the aircraft, contains fuel, often suspends engines, contains control surfaces etc. etc.

By contrast, an example of a very modular product is LEGO, the building-blocks children’s toys.

A number of significant advantages of the concept of modularity can be identified to improve future (V)Shorads if modularity is considered from the outset.

Operational advantages of modularity

Modularity provides the potential for two major benefits for the operational user:

- Construction of variants;
- Enhanced growth potential;

Likely areas of interests for a (V)Shorads air defence system are the following.

<u>Operational variants</u> are compositions of a modular system that have been tailored to a specific air defence mission, terrain environment, meteorological conditions, threat assessment and other operational issues.

Some examples to clarify are the following.

Example 1
An air defence mission in hilly or mountainous terrain may require an elevated sensor, in addition to vehicles’ autonomous sensors. This could easily be a stand-alone jacked or tethered sensor. Of prime concern is only the interoperability in terms of organisation and information. This example represents modularity with modules on a relatively high level in the functional system hierarchy.

Example 2
A mission in areas of regularly poor weather may prefer a dual engagement capability, in terms of both IR and RF guidance. To incorporate both an IR and RF seeker into one missile may prove to be technically feasible but costly at the same time. A modular solution would feature a missile with a changeable seeker head and circuitry. A requirement would be that relatively poorly skilled operational personnel could do this routinely, within minutes. This example represents modularity on a level relatively low in the functional architecture.

Example 3
Assume that in a certain conflict, an NBC threat is anticipated. Continuation of operations then requires an NBC-proof air defence system. Or, an NBC-proof variant of a modular air defence system. NBC-proofing requires several measures in the system: NBC-proof crew compartment (pressurised), EM-hardened electronic equipment, blast protection and add-on decontamination/cleaning facility.

These are technical solutions, some of which can be applied by isolated modular building-blocks. If the crew compartment is stand-alone, it can exist in two variants. A cleaning facility is not necessarily physically integrated in the system, and blast protection can possibly be realised by add-on blast shields. This example represents a technically more challenging use for modularity.

Similarly, national variants may reflect national preferences such as a specific brand of vehicle, a gun/missile weapon mix, and rather important, a certain effective range for the sensor/weapon combination.

On a lower level, force variants may see specific preferences with respect to tactical mobility, interoperability standards, and support requirement.

The second major benefit is growth potential. Contemporary procedure for (V)Shorads equipment is to perform a Mid-Life Upgrade (MLU) after considerable service time, and numerous minor updates throughout the service life.

A key issue is that modularity in a system should allow replacement of modules without having to replace a higher-level or neighbouring module.

Modularity also provides the potential to:

- Incorporate new capabilities and technologies into the system;
- Incorporate technologies that are an improvement over the technologies already in the system;
- Replace components that have passed their service lives.

Other advantages of modularity include improved interoperability, enhanced potential for (physically) distributed operations, graceful degradation, smooth migration from legacy systems, common Human-Machine Interface and improved training, and maintenance and logistics. These will not be elaborated in this paper.

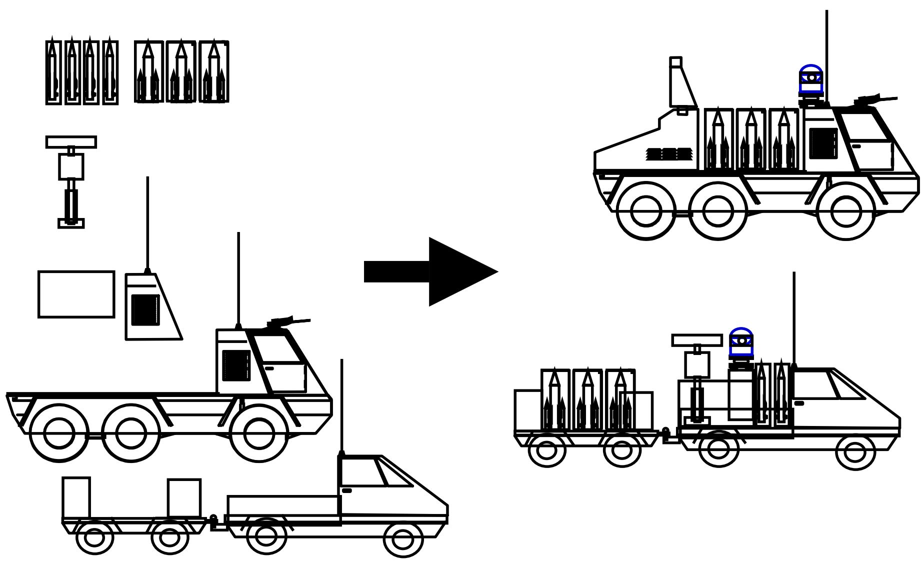

Figure 2. A loose set of modules is used to construct different operations, national or force variants, depending on mission need or specific user preferences. Picture taken [Ref.1].

Technical modularity

According to the previous sections, modularity is a promising concept. This section will elaborate on the realisation of the concept: technical modularity.

Technical modularity is the physical design that must make operational modularity possible.

First, consider two fundamentally opposite design principles:

Specialisation is initiated by the need to a improve a system's performance by optimising certain components and their interaction. This is often realised by for example combining functions (missile launch tube is also missile storage), removing redundancies, and dedicating and finetuning components to their specific function.

Standardisation is the opposite. It is aimed at broadening the scope of a components' applicability. It is often realised by incorporating redundancies, over-capacity and compromises.

Modularity is neither only specialisation nor only standardisation. Modularity combines the two. It allows specialisation by using standardised elements, called modules.

Technical modularity provides many advantages and disadvantages to industry.

Advantages include economies of scale, easier verification and testing, greater product line, reduced order lead time etc.

Disadvantages include [Ref. 2] a static product architecture, restricted product optimisation, ease of reverse engineering, increased unit variable cost, excessive product similarity and physical interface imposed design restrictions in terms of size, weight and shape.

For example, a modular missile launcher should be able to launch a multitude of missile types. This will either be a very large launcher to hold the largest of the missiles, or the missiles may not be larger than the tube. One way or the other, performance is compromised.

Further, interfacing is of crucial interest. An open architecture is required to accommodate a plethora of modules to be connected. It has been stated that whereas a modular system theoretically has an infinite service life, obsolescence of the interface is actually a firm show stopper to life extension.

A first step to realise interfacing that is suitable for a modular air defence system is a very well-defined functional and physical hierarchy. This requires exact knowledge of which elements, functions or capabilities are required to be modular. Interfaces also need to be highly standardised if multiple parties (nations, industries) are involved. Such interface specifications do not exist at present. Contemporary STANAGS are, in the view of the author, open to relatively wide interpretation.

Concluding, technical modularity is an enabler of operational modularity. It provides several technical challenges to be addressed.

Technical modularity also leads to sub-optimal component performance, and thus compromises operational effectiveness. Costs play a crucial role and will be discussed in the next section.

Cost consequences

Life Cycle Cost analysis is a delicate topic for any system. For modularity, the topic is even more difficult. How is the life cycle of a modular system defined? Theoretically, there is no end to the life cycle, since any worn module can be easily replaced without touching the remaining part of the system.

Further, primarily a cost comparison with non-modular systems is relevant at the present stage. But on what basis is the comparison made? With a non-modular system of the same effectiveness, with the same acquisition cost, or compared to any in-inventory system that is of national interest. Obviously, quantitative analysis is beyond the scope of this paper.

Some qualitative effects can be observed. Both cost savings and penalties result from modularity.

In a technical sense, economies of scale, greater production efficiency and greater product variety contribute to reduced acquisition costs. However, also increased unit variable costs apply and are a primary contributor to cost of modularity.

In an operational sense, growth potential reduces replacement costs, and is a long term effect. LCC of a modular system is also strongly dependent on acquisition strategy, ranging from a custom-made set (i.e. an integrated (V)Shorads based on a modular design) to a loose set of modules procured over time (first a basic set to complement legacy systems, then additional modules such as sensors, warheads and others).

One single contractor, supplying to many different nations from a single pool of modules represents the absolute ideal situation, taking all the benefits whilst maximising cost savings.

It is very unlikely however, that such an international process can be substantiated at present, given the limited economic, industrial and political integration in Europe.

A solid conclusion can not be drawn, other than to state that perhaps contradictory to expectations, it is definitely not guaranteed that a modular (V)Shorads air defence system has reduced Life Cycle Costs.

Before setting out on a LCC comparison, it is recommended to devise a proper comparison methodology first.

On the amount of modularity

This paper so far addressed the operational benefit, the technical realisation and the cost consequences of modularity. These sections implicitly addressed both totally modular versus totally non-modular systems. However, it has already been stated that modularity is not a binary characteristic, but a gradual one.

Consider a system consisting of larger components (sensors, weapons), minor construction elements (computer memory chips) and anything in between. Now consider that any of these can be theoretically denoted as module.

Appointing any element as a module leads to additional specifications for that element. For example, the earlier example of dual interchangeable missile seekers requires that the two seeker are of the same (external) size and shape. It is also required that they are within man-portable weight limits. Such additional requirements are needed to ensure seamless integration of the module into the system.

Obviously, the higher the relative number of modules, the more modular the system will be.

The amount of modularity is therefore a variable scale with two extremes.

On the high end of the scale, an integrated (V)Shorad system can be considered as one single module. This can be a quite capable system.

On the lower end of the scale, a seemingly irrational collection of bolts, nuts, chemicals and other ground materials is a very, very modular system. This obviously will not make a very effective air defence system.

The obvious conclusion is that increasing the number of modules and thus the degree of modularity is not necessarily a good thing. Careful selection and optimisation are in place.

Such an optimisation has not been carried out on behalf of this paper. However, from discussions and expert opinions, there seems to be agreement that modularity should be applied at a fairly high functional level, in order to be technically feasible and operationally useful.

For example, the (V)Shorads major functional breakdown into four functions as follows may be a suitable level for applying modularity to:

- Surveillance;
- Tracking;
- Shooting;
- Moving.

It would be worthwhile to investigate the technical feasibility of modularity on this level. A next step would be to explore modularity one level down the hierarchy.

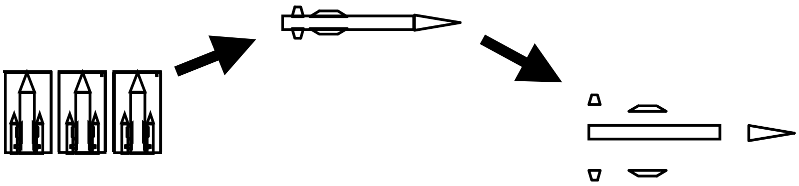

Figure 3. Modularity on a low level in the system architecture, such as applying a varying set of control vanes to a missile, is unlikely to give overall benefit. Increased element variable costs resulting from over-specification is paramount. Picture taken [Ref.1].

Control

A final issue to consider is the party having control over modularity. For example, it may be desirable that the user, i.e. the man in the field, can control his system. For low-level modularity such as changing seeker heads according to variations in threat or weather, it is undesirable to have to ship the system back to industry. The operational capability would be compromised immediately and a force planners' job would become impossibly difficult.

On the other hand, it is extremely undesirable that front line air defence troops are required to physically integrate an additional sensor into a system.

This issue has not been addressed in any other source on modularity in defence. Since it has a major impact on operations, it deserves proper attention.

Conclusions

The following conclusions can be drawn from the preceding sections.

1. Modularity is a technical solution to provide operational flexibility of (V)Shorad air defence systems.
2. Modularity is applied to a system by appointing selected elements as modules. This will lead to additional interfacing requirements for that element.
3. Accordingly, isolated element cost is likely to increase and isolated element performance may decrease. Technical complications and increased acquisition cost are likely.
4. However, the long-term net effect may be a reduction in Life Cycle Cost, improved growth potential and improved overall performance over wide range of threats and circumstances.

Recommendations

For continued research into modularity, two recommendations have been made and are repeated below.

1. For Life Cycle Cost studies, it is recommended to first devise a suitable methodology for comparing LCC between modular and non-modular air defence systems.
2. For establishing the optimum amount of modularity for an air defence system, a top-down approach is recommended, starting with modularity at a high functional level.

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ESM-Sensors for Tactical Information in Air Defence Systems

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Abstract

The main purpose of this paper is to inspire investigation efforts in clarifying whether ESM-sensors can become components of a cost-effective Integrated Air Defence System for an International Reaction Force, as we think that the potential of ESM-sensors in air defence is not yet fully recognized and analysed. The planning and conducting of air attacks with today's and tomorrow's technology seem to increasingly make use of electromagnetic emissions from airborne platforms. ESM-sensors can pick up these emissions; such sensors are likely to become more available due to the current technical development. The paper tries to enlighten the applicability of ESM-sensors in Air Defence Systems by presenting and discussing the different types of information they supply. An analysis of position accuracy is presented. Some principles for integrating ESM-sensors in a radar-based Air Defence System are suggested.

1. Introduction

ESM-sensors (Electronic Support Measures) may be seen as tactical versions of ELINT-sensors (Electronic Intelligence) (1) being one part of modern electronic warfare (2). ESM-sensors are currently not regarded as significant and cost-effective suppliers of tactical information in air defence, possibly caused by their type of information, their relative high price, and the fact that they depend on signal-emissions from an unpredictable adversary. This rationale is challenged by the ongoing technical development, likely relevant for an International Reaction Force.

True enough, ESM-sensors depend on emitted electromagnetic signals from the adversary. However, an increasing number of possible threats to an International Reaction Force normally emit signals, as indicated in section 2. Most of the platforms and emitters could be in the inventory of a potential future adversary. Proper ESM-sensors may supply valuable tactical information from these emitters. Also, if knowing the presence of the ESM-sensors, the adversary may restrict himself beneficially for the Reaction Force.

The current technical development of small and relatively cheap microwave components, signal processing devices and computers are likely to make ESM-sensors more available and their information more easily transformed to useful tactical information. ESM-sensors exhibit a quite wide spectrum of capabilities, as indicated in section 3, and improvements are likely. Their more salient features in this context are to detect objects in a complementary way and to characterize the detected signals enabling an identification of the emitters and platforms. By combining bearings, elevations, and time arrivals from different ESM-sensors, the position can be obtained.

Tactical useful information from the ESM-sensors include detection and verification for alerting, identification of the threat, possibly with a coarse position, or ultimately positioning and tracking of the emitter, as described in section 4. The position information from the ESM-sensors is important for associating the ESM-information with tracks from radars, which still are the basic information source in air defence in the foreseeable future. The position accuracy of ESM-sensors highly depends on the characteristics of the emissions, the measurements, the number of sensors and their geometry, as shown in the analysis of section 5. ESM-sensors use only the direct signals from the emitter to the sensor, but other passive sensor concepts are demonstrated, see section 5.

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The data from ESM-sensors have to be integrated into the radar-based Air Defence System to fully utilize their tactical information. This may involve a central Multi Sensor Tracker (MST) integrating different types of sensors. However, we suggest that this is done by "graphical integration" after a first "preprocessing" in an ESM-system. These and some other aspects of Data Fusion are discussed in section 6.

Section 7 makes a summary of important pros et cons of ESM-sensors and discusses critical issues of their applicability for the air defence of an International Reaction Force. ESM-sensors may be worthwhile to integrate in such a system, but a conclusion requires a lot more investigations.

2. Unclear and Diverse Air Defence Threats to a Reaction Force - Many Emitters Involved?

An International Reaction Force may be employed in a wide range of situations where the threats are quite unclear and diverse. Specifying relevant scenarios is therefore almost impossible. This section rather gives a brief outline of various general air defence threats and the use of emitters in association with such attacks. The purpose is not to predict the likely nature of an attack and participating platforms, but to point out that a large spectrum of conceivable threats emit electromagnetic signals. Figure 1 shows a number of platforms that may be present in a scenario and a number of different classes of emitters.

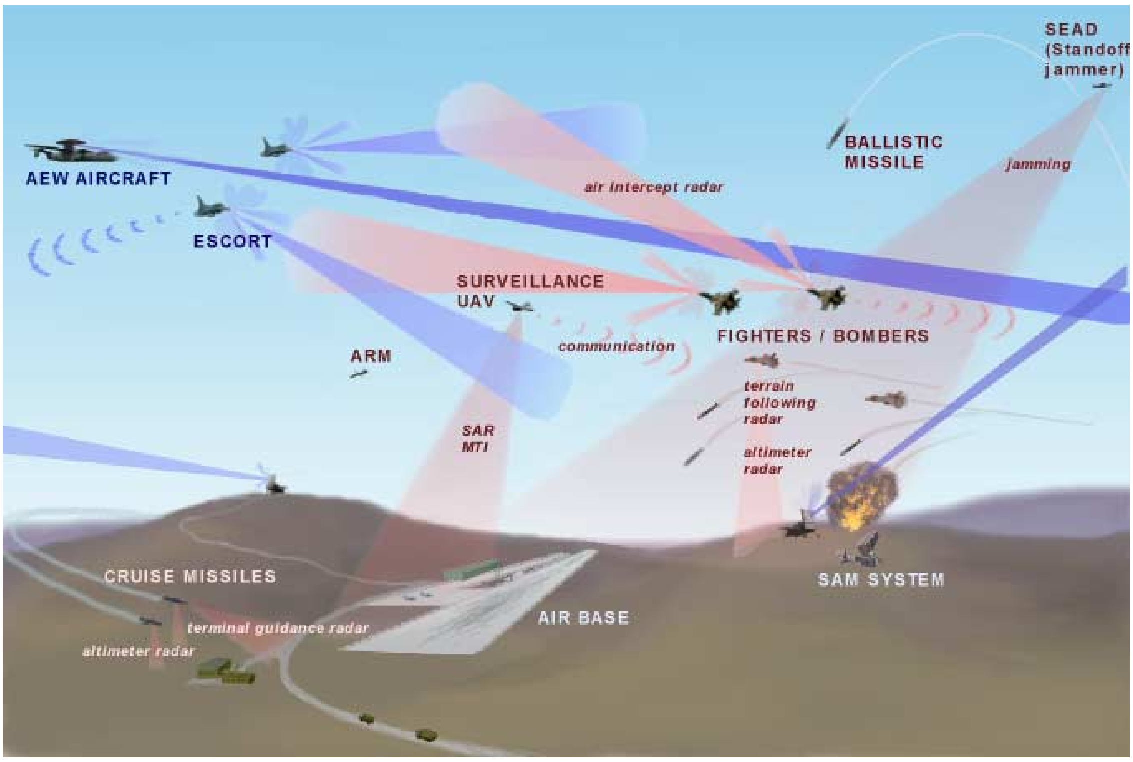

Figure 1 Examples of threats with emitted signals (red) and some threats that do not emit

Today the threats facing an International Reaction Force are unlikely to include the more sophisticated weapon systems. However, one can not rule out the possibility of a technically advanced adversary in a future conflict, at least possession of some new technology. As referenced in the US Space Command's Long Range Plan of 1999: "Advanced technology can make third-class powers into first-class threats." (Dick Cheney, former Secretary of Defence). The aerospace is an increasingly important part of the battlefield. The following observations regarding the development and proliferation of the different weapon categories can be pointed out:

- Fighters and attack aircraft are used by an increasing number of countries. In the near future conceivable adversaries would presumably use fighter-bombers carrying unguided bombs. Among the major military powers there is a trend towards the use of precision-guided munitions (PGMs) delivered from longer ranges.
- Up to now sophisticated land attack cruise missiles have not been widely proliferated, but the technology needed to produce UAVs is readily available. Armed UAVs and technically simple cruise missiles constitute a future threat.
- Tactical ballistic missiles (TBMs) is an increasing threat.
- UAVs for ground surveillance and targeting are likely to be available for potential adversaries in the future.

Many of these threats emit signals. The effectiveness of aircraft and weapon systems seems more and more to rely on advanced electronic equipment, including a variety of electromagnetic emitters. The following emitters might be important:

- Air intercept (AI) radars (powerful emitters used by fighter aircraft)
- Navigation- and terrain-following radars (might be incorporated as modes in AI-radars)
- Altimeters (relatively low-powered emitters used by aircraft and cruise missiles)
- Radars for ground surveillance, i.e. SAR and Ground MTI (carried by UAVs or special aircraft or incorporated as modes in AI-radars)
- Communication links
- Jammers

An International Reaction Force has to pursuit information superiority. This might be particularly important in scenarios with a heterogeneous Reaction Force and diverse and unclear threats. Emitted signals from airborne platforms can tell a lot about the tactical situations and ESM-sensors may therefore constitute a valuable information source for the Reaction Force.

3. A Sketch of Current and Future ESM-sensor Capabilities

ESM-sensors have been around since Word War II to detect and characterize electromagnetic emissions (radar, link, voice etc.). They are used on land, at sea, in the air and in space, and therefore come in a lot of different configurations (technology, quality, size and price).

ESM-sensors have to cover a very wide frequency range, traditionally 1/2 to 18 GHz, and in the future even higher. To achieve a high probability of intercept (POI) for these emissions, each frequency within the range should ultimately be continuously covered. However, covering a wide frequency range is often contradictory to other ESM requirements like the ability to detect, sort, and measure parameters of the radar signals (2).

ESM-receivers based on a number of different principles and technologies have been developed. The most popular receiver type has been the so-called Instantaneous Frequency Measurement (IFM) which coarsely measures parameters of the radar pulses over a wide frequency range. The main drawbacks of this receiver are its relative low sensitivity and instantaneous handling of only one signal. Some ESM systems use an additional high sensitive narrowband (superhetrodyne) receiver for precision measurement of signals of special interest.

It has long been acknowledged that having a number of narrowband receivers in parallel, a channelized receiver, would be the best solution since it combines high POI with high sensitivity and multiple emission capability. The disadvantages of the channelized receiver have been its complexity, resulting in high cost, power consumption and large size. The last five years developments in microwave components and packaging technologies have made the channelized receiver a more attractive solution and development of such receiver are going on.

Another important and fast evolving technology that will improve future ESM-sensors is the increased speed in sampling and digital processing of signals (3). Signal bandwidths of a few hundred megahertz can be sampled and digitally processed. Today the major limitations are dynamic range of the analogue-to-digital converters and the speed of the signal processors. There are a number of advantages by using digital signal processing: More accurate information can be extracted from both single pulses and from pulse trains. The same hardware can perform different signal processing by use of specialized software, which will be important for detection of Low Probability of Intercept (LPI) radars.

The antennas determine the spatial coverage of the ESM-sensor, which is normally 360° in azimuth and typically 20° in elevation (but depends on the application). The antenna configuration also contributes to the direction finding capability, i.e. the angle-of-arrival (AOA) measurements. Omni-directional antennas give 360° coverage and therefore 100% POI with respect to direction, but they have low gain, which gives low system sensitivity, and no AOA. A 100% POI can also be obtained with a number of directional antennas arranged in a circle (often 6 to 8). This leads to higher antenna gain, and AOA can be calculated from the signal differences between two adjacent antennas. A third principle is to use a highly directive spinning antenna with high gain, but with a lower POI. One ESM-sensor may use several antennas to improve its performance.

As a general summary one may state that the parameters characterising ESM-sensors generally span a wide range (2) (3) (4); POI (<1% to 100%), sensitivity (-40 to -110dBmi), antenna gain (-5 to +25dBi), accuracy of frequency-of-arrival (FOA) (50Hz to 10MHz), time-of-arrival (TOA) (1ns to 1ms), AOA (0,1° to 10°), pulse density (100k to 10Mpulses/s). Other signal characteristics may be measured for pulse sorting and emitter identification, the latter requires an emitter library. In addition to the techniques used in the ESM-sensor, the performance also depends on the actual emissions. An ESM-sensor instantly (100% POI) measuring the parameters with the best performance available would be very costly and therefore tradeoffs have to be accepted. One solution is to use a high POI solution for signal detection, and additional specialized hardware for precision measurements. Since the actual solution highly depends on the operational requirements, a further discussion is outside the scope of this paper.

Selecting appropriate sensor capabilities for use in Air Defence of an International Reaction Force is not an easy task. The blend of emitters likely to observe, their tactical use, and the resulting price of the ESM-system have to be taken into account. As a starting point for an accuracy analysis we choose the following nominal values for the measurement uncertainty (1σ):

Bearing:	1.0°
Elevation:	1.5°
Time arrival:	70 ns
Frequency:	100 Hz

The values applies to a single sensor, and by assuming independent errors between pair of sensors a TDOA gets an accuracy of 100 ns, and FDOA an accuracy of 140 Hz (resulting from a square sum of the two components).

4. Tactical Contributions from ESM-Sensors in Air Defence

The ESM-sensors may produce different types of tactical information to an Air Defence System. This depends on the operational situation and the choice of ESM sensor capabilities - a choice within a quite wide spectrum, as indicated in the previous section.

An example of a valuable piece of information is a record of detected signals as evidence of what happened in a specific situation. However, this is not “tactical information” if it can not be used in the situation itself. A piece of tactical information is the very first detection of a hostile platform by an ESM-sensor. Since the ESM-sensors constitutes a complementary “sense” of the Air Defence System, it might well supply the very first warning. The value of such a contribution highly depends on the gained alerting time and on the gained understanding of the tactical situation by the supplied information. Even if the ESM-detection did not happen to be the first, it may confirm a detected threat and supply complementary information for a better understanding of the situation.

The ability to deduce identification information from the signals detected, is the more valuable benefit of ESM-sensors. Different levels of identification might be obtained according to the accuracy of the parameters measured, the prior data gathered in an emitter library, and the applied methods and interpretation-software. One level is to determine the class of emitter (AI-radar, altimeter etc.); another is to identify the type (product name) of the emitter. In some cases individual emitters might be distinguished and recognized by specific signatures of their signals (“fingerprints”). The number of emitters might be deduced fairly independent of the identification level. The type of hostile platform may be deduced when the library contains emitter-platform associations.

Radars are unquestionably the core sensors in air defence. Identifying the tracked objects by radars may be possible, but it is difficult. The association of ESM-identifications to radar-tracks would be of great importance. This would reduce the weapon engagement time and avoid engagements of friendly platforms (“blue on blue”). Such track-identification might be possible without positional information from the ESM-detections due to the situation and prior tactical knowledge. However, the association normally requires positional information to decide which among several tracks the identified signals come from. In dense situations this might mean independent ESM-system tracking. In other situations a medium accurate bearing of the identified signal might be sufficient.

As indicated in the next section, ESM-tracks may be quite accurate, even compared to radar tracks. This might be used to improve the radar track accuracy, either by track-track correlation or by using a Multi Sensor Tracker. This is especially useful in situations where the radars do not function at their best like in heavy clutter or jamming. Theoretically, the ESM-tracks can be based on the jamming signals degrading the radars. In such a situation the ESM-system will truly be a complementary element to the radars.

In cases where the airborne platforms constantly use detectable emitters, a fairly complete air picture can be generated from the ESM-sensor data. ESM-system tracking opens for weapon firing and guidance. The next section makes a position accuracy analysis of ESM-sensors that is relevant for the question of tracking.

5. Position Information in Combined ESM-Sensor Measurements

As indicated in the previous section, the position-information is tactically important for several reasons. The geometry-related position accuracy of ESM-sensors seems not to be well known, and is therefore treated in some detail here. Interested readers can hopefully expand the results to other parameter-settings and geometries.

Here we only treat position estimation by the direct signals from the emitter to the sensors when bearing, elevation, and TDOA (Time Difference Of Arrival) can be measured. The reader should be aware of other methods of passive sensor positioning. One is a bistatic radar “hitchhiking” on a rotating search radar (5).

Other may use the bistatic principle with additional Doppler-measurements using commercial FM-radio and TV-stations as the emitters (6) (7). A third is to use terrain-reflections from a wide-band jammer (8).

As stated, measurements from two or more ESM-sensors have to be combined in order to estimate the position of the emitter. The regarded ideal measurements expressed in a Cartesian coordinate system are:

$$\varphi_{i,j} = \arctan\ [(x_j - x_i)/(y_j - y_i)]\theta_{i,j} = \arctan\ [(z_j - z_i)/\sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}\,]$$

$$\Delta\tau_{i1,i2,j} = (1/c)\ (r_{i1,j} - r_{i2,j})\ ,$$

$$r_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}$$

where

$\varphi_{i,j}$	bearing of emitter *j* from sensor *i*
$\theta_{i,j}$	elevation of emitter *j* from sensor *i*
$\Delta\tau_{i1,i2,j}$	time difference of a signal from emitter *j* to the sensors *i*1 and *i*2
(x_j, y_j, z_j)	position of emitter *j*
(x_i, y_i, z_i)	position of sensor *i*
$r_{i,j}$	length of $[(x_i, y_i, z_i) - (x_j, y_j, z_j)]$
c	the speed of light

A bearing measurement theoretically restricts the position of the emitter to a vertical plane through the sensor and emitter. An elevation restricts the position to the surface of a cone. A TDOA restricts the position to a hyperboloid through the emitter having the two sensor- positions in the focal points. Combining several measurements may theoretically restrict the position to a point. Each type of measurement has an accuracy depending on the measurement principle, the technical solution and the signal to noise ratio. Geometrically, the measurement uncertainty adds a “thickness” to each of the three types of surfaces. Figure 2 illustrates the three types of measurements with their uncertainty from two out of a four sensor-configuration used throughout this paper: three sensors in a regular triangle 20 km from a central forth sensor.

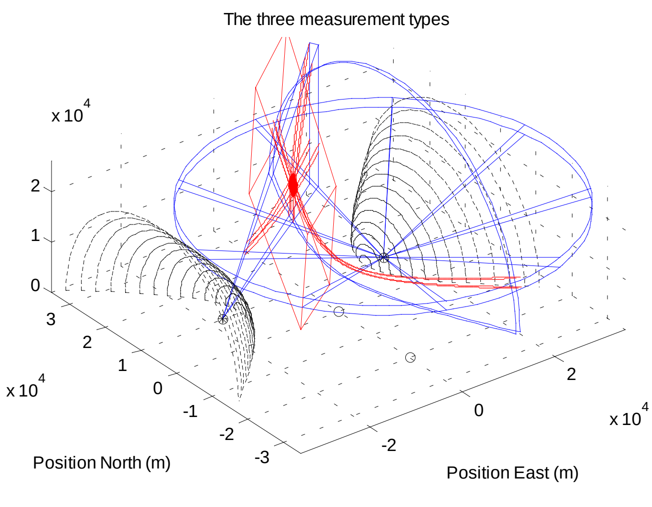

Figure 2 Three types of “measurement volumes” (blue) and their intersections (red)

The “volumes” are from a bearing, an elevation, and a TDOA with measurement uncertainty of 1.0°, 1.5°, and 10x100ns respectively. The three “pair intersections” (red curves) make a “box” around the object which is enlarged 15 times. The box corresponds to the position uncertainty; it increases with distance and poor intersection geometry. (The two other sensors in the four- sensor example of the paper are indicated.)

The accuracy of the calculated position depends on the local "surface thickness" and the intersection geometry of the surfaces defined by the measurements; the more orthogonal, the better. The following formulas can be used for calculating the "surface thickness" for a coarse analysis of a specific geometry:

$$ds_\varphi = 2r_{i,j} \sin \sigma_\varphi$$
$$ds_\theta = 2r_{i,j} \sin \sigma_\theta$$
$$ds_{\Delta\tau} = \frac{\sqrt{2}\ c}{\sin \frac{\alpha_{i_1,i_2,j}}{2}}\ \sigma_{\Delta\tau}$$

where

ds_m	$m = \varphi, \theta, \Delta\tau$, the local "measurement surface thickness"
$r_{i,j}$	length of $[(x_i, y_i, z_i) - (x_j, y_j, z_j)]$
σ_m	$m = \varphi, \theta, \Delta\tau$, the measurement uncertainty
$\alpha_{i1,i2,j}$	the angle between the lines from the emitter *j* to each of the sensors *i*1 and *i*2

The uncertainties used in Figure 2 are 1°, 1.5°, and 1μs, the latter 10 times the nominal value for illustration purpose. The ranges to the emitter (x=14 km, y=31 km, h=6 km) are 38 km and 22 km, the angle between the lines-of-sight to the sensors are 64°, giving the approx. "surface thickness" of 1.3 km (bearing), 1.1 km (elevation), and 0.6 km (TDOA). Figure 2 also shows the intersection between all three "thick surfaces" making up a "box" corresponding to the position uncertainty of the three measurements. The shape and size of the "box" change according to the 3-D position of the emitter even if the measurement uncertainties do not change. Here the intersection geometry is fairly favourable, but other positions may skew and stretch the remaining "box" to a considerable size. The reader hopefully gets a "feeling" of the mechanism of position uncertainty shaping by the measurement uncertainties and the geometry.

Figure 3 is included to give a better understanding for the use of TDOA for position estimation. The topic here is the geometry of the intersections of hyperboloids (the measurement uncertainty now disregarded). The sensors in Figure 3 are three out of the four regularly positioned sensors. Two families of hyperboloids are indicated; each hyperboloid is made up of points having the same TDOA with respect to the sensors in the hyperboloid focal points. The red curves are the intersection of two hyperboloids, one from each of the families. All the points on a single red curve have the same TDOA with respect to both pair of sensors. (Using the hyperboloids from the third pair of the three sensors, results in the same intersection curves.) Notice that all curves intersect the horizontal plane perpendicularly, and that the curves are close to horizontal near the extensions of the lines connecting any two sensors (the base-lines).

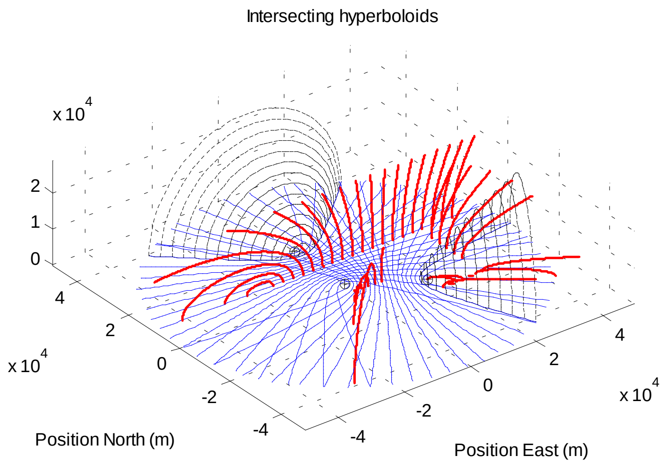

Figure 3   Hyperboloid families (black/blue) from three sensors with intersections (red)

One hyperboloid of each family is shown (black) with intersections of the horizontal plane (blue). Hyperboloid intersections (red) start on four different lines parallell to the axes. Starting points near the extension of any base-line make curves turning down again; horizontal parts of the curves are quite close to these extension lines. One region makes intersection curves almost vertical.

Figure 3 shows that TDOA from three sensors are insufficient for calculating the position of the emitter in 3-D. However, with a correct assumption of low altitude compared to the sensor-distances, TDOA is sufficient. An additional elevation measurement from one of the three sensors is sufficient to decide the emitter position in 3-D provided that it is not located on a near horizontal section of the associated intersection curve. Also, a single bearing can do this job provided the emitter is not located near a vertical part of the associated intersection curve. As seen, together with TDOA, an elevation may give position information (North/East) and a bearing may give altitude information. Reference (9) describes a TDOA-system with a geometry similar to that in Figure 3 using altitude readings from the aircraft itself to obtain the position.

A statistical approach for analyzing the position accuracy mechanism indicated in Figure 2 is to calculate the so-called Cramer Rao Lower Bound (CRLB). This is a covariance matrix defining a near achievable, lower bound of a zero mean state estimator. This matrix is the inverse of the so-called Fisher information matrix, and is defined by a simple matrix expression based on some general assumptions. The covariance expression is listed below; interested readers are referred to standard estimation theory for more details, one example is (10).

$$P_{CRLB} = \left[D^T \, P_W^{-1} \, D \right]^{-1}$$

where

P_{CRLB} The Cramer Rao Lower Bound (a covariance matrix)

D The linearized measurement matrix, where the matrix elements are:

$$d_{ml} = \frac{\partial}{\partial x_l} h_m(x), \text{ where } h_m,$$

$m = \varphi, \theta, \Delta\tau$, are the listed measurement expressions , and l is the index of the state vector (generally positions)

P_W The measurement error covariance matrix

When the covariance matrix is known, one can calculate ellipses of constant error probability density assuming a gaussian distribution of the measurement errors. Error ellipses illustrates nicely the uncertainty in a simple situation, but not here with geometries implying a large span of the accuracies. The CEP measure (Circular Error Probable) is therefore used instead. This is the radius of a circle around the true position that statistically contains 50% of the position estimates. The CEP is a function of the lengths of the half axes of the ellipse. In a circular ellipse ($\sigma min/\sigma max=1$), $CEP/\sigma max= 1.18$; in an extremely long ellipse ($\sigma min/\sigma max=0$), $CEP/\sigma max=0.675$. Figure 4 shows the position accuracy of bearing intersections of two sensors. Bearings to five emitters are shown together with samples of error ellipses and the resulting CEP. As seen, the position accuracy is here highly dependent on the geometry, which is the general rule for ESM-sensor positioning.

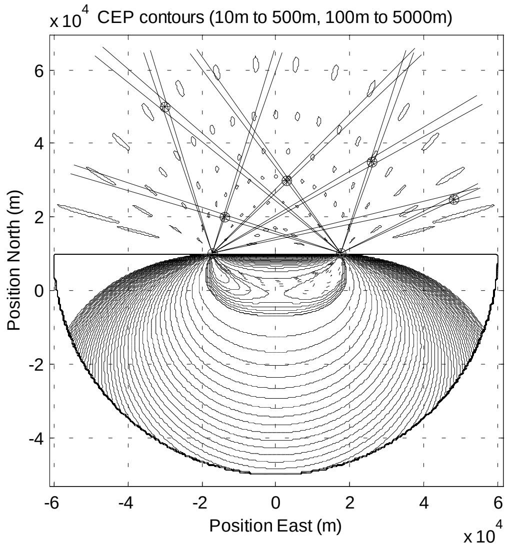

Figure 4 Bearing intersection accuracy by two sensors (five targets present)

Only the bearing uncertainty limits (1.0°, 1σ) are drawn. Corresponding error ellipses (1σ) are shown in positions at fixed distances from the midpoint of the two sensors. The equivalent CEP-values are shown in the (symmetric) lower half plane.

Figure 5 shows examples of the position accuracy obtained by bearings and TDOA from the ESM-sensors forming a regular triangle. The diagram is divided in three equal sectors to show the accuracy of bearings alone, of TDOA alone (assuming known low altitude), and the combination of the two. Each one of the three CEP contours covering 120° is symmetric and representative for the total 360°. As seen, TDOA gives poor position information near the extension of the lines connecting the two sensors (the base-line). The accuracy of combined bearings and TDOA is at least as good as the best accuracy of each of the two. In the central region bearings give approx. 400 m CEP, while TDOA gives approx. 30 m CEP.

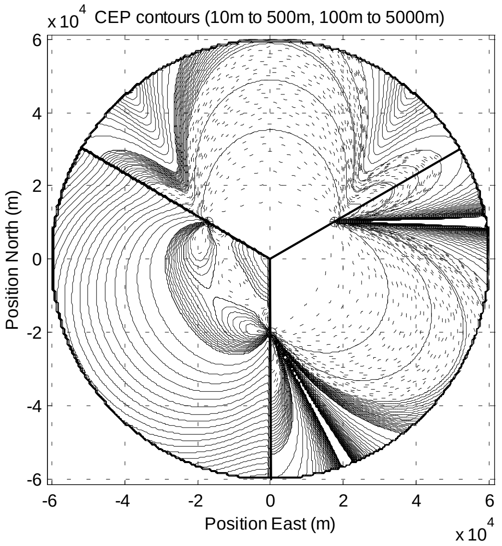

Figure 5 CEP from bearings and TDOA of three sensors forming a regular triangle

Bearings are measured with uncertainty 1° (1σ), time arrivals with 70 ns (1σ). The left 120° sector shows CEP from bearings from the three sensors in a regular triangle. The right sector shows CEP when only TDOA are used, while the upper 120° sector uses both bearings and TDOA giving a CEP at least as good as the best of the two with a single type of measurements.

Figure 6 shows the result when using TDOA only from all four sensors; four are needed to enable a 3-D positioning with TDOA only. This diagram is also divided into sectors that can be duplicated (flipped around the sector borders) to represent the total 360°. The position accuracy is shown in the lower third of the circle, while the rest is altitude accuracy (1σ). This sector of 240° is divided into four slices of 60°, each representing different altitudes. The altitude accuracy highly depends on the altitude of the emitter. It is quite poor at low altitudes, as can be realized from Figure 3 since the intersection curves of hyperboloid pairs intersect at a small angle here. Notice that the altitude uncertainty has local minima somewhat outside the three surrounding sensors, while the position uncertainty does not have such minima. Both the position- and altitude accuracy are best at the centre of the sensor-configuration.

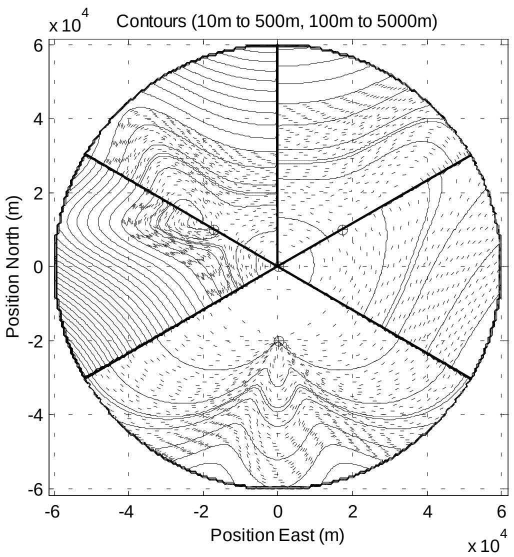

Figure 6 CEP and four altitude RMS of TDOA from four sensors

Time arrivals are measured with uncertainty 70ns (1σ). The lower 120° sector shows CEP at zero altitude. Each of the 60° sectors show the altitude RMS from different altitude levels; from left to right: 2500m, 5000m, 10000m, and 20000m.

Rules to extend the results of Figure 4, 5, and 6 to other parameter values should be mentioned. As seen from the expression of CRLB, the uncertainty is proportional to the measurement uncertainty. As for the linear scale of the geometry, different principles apply to angle measurements (bearing and elevation) and TDOA. When angle measurements are the dominating position source, the position uncertainty is proportional to the scale. This mean that the position uncertainty of a point referred relatively to the sensor configuration is doubled if the scale is doubled. When TDOA is the dominating position source, the uncertainty is independent of the scale. When other sensor configurations are used, the results will not be as easily modified. We then suggest to use the geometric approach mentioned in relation to Figure 2.

As seen from Figures 4, 5, and 6, CEP increases more than proportionally with the range from the centre of the sensor configuration. Figure 4 also indicates that the error ellipses get stretched at long distances, which also happens when TDOA is involved. This means the position information at long distances turns into a direction information governed by the "thickness" of the long ellipse being somewhat less than the involved "measurement surfaces". As seen from the expressions, the "measurement surface thicknesses" are approximately proportional with the distance. At long distances the position information are therefore more appropriately expressed as angle uncertainties.

Some comments should be made regarding tracking since an emitter will be positioned by a tracker algorithm using a sequence of measurements rather than a static position estimator, as analyzed here. Further, accurate frequency measurements may be available, adding to the tracking performance by Doppler information. However, as for the purpose of analyzing the likely tracking accuracy, the CRLB-method can be used. One then has to adjust for the reduced measurement errors by averaging repeated measurements with independent errors. However, systematic errors will not be reduced this way. A reduction factor of 2-4 of the nominal measurement accuracies might be achieved depending on the portion of systematic errors and the measurement update rate. As the target-sensor geometry will not change significantly during a measurement averaging time period in a tracker, the CRLB-analysis should be a valid approach for tracking also.

Frequency measurements may supply Doppler information by calculating the FDOA (Frequency Difference Of Arrival) similarly to the TDOA. FDOA contains information about the velocity of the emitter, but does not add to the position accuracy in the presented static analysis. However, a tracker may use this information for a quicker initial establishment of the emitter velocity, and also for a better tracking of the velocity avoiding additional position errors in case of target manoeuvres. Numeric calculations depend on assumptions about the tracker and target manoeuvres, and are outside the scope of this paper. However, the velocity information from FDOA can be drawn from the CEP of TDOA measurements. This depends on the fact that FDOA is proportional to the time derivative of the TDOA, the scaling factor being the frequency of the emitter signal. The CEP can be interpreted as speed after a proper scaling. The scale factor is the uncertainty of the frequency measurements divided by the product of the uncertainty of the time measurements and the emitter frequency. In this case the scale is close to 1/7 (100 Hz / (70 ns x 10 GHz)). This means an emitter velocity uncertainty of approximately 3 m/s in the central region of Figure 5 and 6. The geometry of FDOA is the same as TDOA meaning that four sensors are necessary to get a 3-D speed vector from FDOA measurements only.

Only the accuracy aspect of position information has been treated here. Sufficient receiver sensitivity and sensor-coverage of the terrain to get the needed detections are assumed, but this may pose a problem. An additional problem is to correctly associate the measurements when several emitters are present in the same area, see Figure 4. This problem is here termed "deghosting", and is briefly mentioned in the next section.

6. Integrating the ESM-Sensors - Data Fusion

As described in the previous section, the ESM-data has to be "fused" in order to obtain an emitter position. To obtain maximum tactical information, a further fusion with the radar data is necessary, as described in section 4. The readers should be aware of the evolving literature on Data Fusion; a search on the Internet might be worthwhile. The framework given by the US DoD Joint Directors of Laboratories (JDL) Data Fusion Group has been dominating in the last decade, and is now subject to adjustment (11).

Figure 4 illustrates a sorting problem in the case several emitters are producing bearings at two or more sensors. Wrong combinations of bearings make up "ghosts", which have to be sorted out. Hopefully, simple signal characteristics or elevation measurements can do the job. If three or more sensors observe the scene, the “ghosts” can also be sorted out by having less crossing bearings than the real ones, or by having improbable speed or speed changes. Some of these techniques are used in a Bayesian framework in (12). In case of simultaneous observations by two or more sensors, time sequence characteristics of signals can be used, or a measured TDOA can verify the position of the intersection. Lastly, if the system can do “fingerprinting”, each individual emitter will be sorted out, and the problem is solved. Some of these methods imply tight sensor coordination and integration. The hyperboloid intersections will also need “deghosting”.

The theoretical aspect of estimation and tracking from combined measurements of radars and ESM-sensors should be well known, but practical experience seem to be rare. The use of a MST-algorithm (Multi Sensor Tracker) may seem an obvious choice at a first glance. However, even if theoretically best, a MST requires lot of work and detailed sensor knowledge. The involved sensors and the integrating MST-software might have to be delivered as a single unit, possibly reducing flexibility and modularity. A simpler and more flexible way to integrate ESM and radars is “graphical integration”, which can be viewed as a first integration level. The “integration” is then performed in the mind of the operator when seeing the two sets of information on top of each other (graphically transparent). Actual ESM-data to present together with radar tracks are bearings, TDOA-hyperbolas, or ultimately ESM-tracks, all with associated uncertainty and hopefully properly identified. The ESM-system should be controlled from an operation level such that high sensitivity antennas can be directed against the positions of radar-tracks for additional track- information, possibly identification.

The suggestions above call for an independent ESM-system being the main coordinator of the ESM-sensors and “preprocessing” their data before a further integration. This obeys the principle “integrate similar sources first”, as stated among other interesting principles in (13). “Preprocessing” should also be done in each sensor to relieve communication bandwidth and the central computing load. This should include averaging of measurements before transmitting in order to reduce the random errors of the measurements and enable the estimation of their characteristics which is important for achieving a near optimal central track estimation.

A relatively low rate communication channel is preferable for operational flexibility, possibly a rate of 64 kbits/s or less. Time synchronization, in case of TDOA, then has to be achieved by accurate local clocks that are externally coordinated, possibly by GPS. ESM-sensors observing some of the emitters of Figure 1 may produce a lot more data than it is possible to transfer through a channel of the suggested capacity. However, the signals normally exhibit some sort of regular patterns. According to a principle in information theory, only the “new” or “surprising” elements in the data need to be transmitted. This calls for a “momentary signal library” characterizing the detected signals to reduce the bandwidth by sending references to the library elements rather than the data itself. Such a library should be seen in relation to the emitter library used to identify the detected emitters. Suggested integration principles and architecture are illustrated in Figure 7.

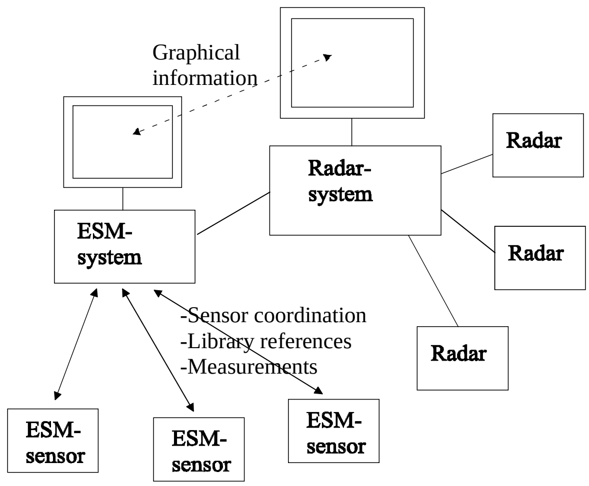

Figure 7 Integration of ESM-sensors in a radar-based Air Defence System

The data from highly coordinated ESM-sensors are first “preprocessed” in an ESM-system which supplies identified bearings, TDOA-hyperbolas, and tracks as graphical overlays on the radar-system screen; graphical info is sent both ways. Cueing of the ESM-antennas from the radar system should be possible.

7. Discussion of the Applicability of ESM-Sensors in Air Defence

There are several arguments for applying ESM-sensors in the air defence of an International Reaction Force, but there are also a number counter-arguments. The following is a discussion of some of the opposing arguments.

An International Reaction Force should pursuit information superiority in its undertakings. ESM-sensors are sources of information adding complementary data for building the general situation picture and good situation awareness. A counter-argument is that the significant sources of this information are the emitters controlled by the opposing adversary. Knowing the presence and possibly the capabilities of our ESM-sensors, he may choose to avoid using the emitters or using them in an unfavourable or misleading way for the Reaction Force. This counter-argument is hard to evaluate without knowing a lot more details. It can be argued, on a general basis, that the adversary by not using his emitters may restrict his abilities in a way that justifies the investment in ESM-sensors, even though they do not supply any information at all.

The stronger point of ESM-sensors compared to radars is identification. ESM-sensors should therefore be an obvious component of an integrated Air Defence System. Even more, electronic warfare jamming degrading the radars might be a valuable information source for the ESM. An important counter-argument is the effort necessary for collecting and updating an emitter-library vital for performing reliable and confident identifications. Such signal intelligence requires collection activity over a substantial time period. Further, collected emitter-data is sensitive information, and the use in an international setting might be difficult. Automatic identification might have to be supported by human decisions in critical situations. This requires manpower and proper education and training. The ESM-information might also be hard to integrate in a radar system, as indicated in section 6.

ESM-sensors are passive, small and relatively cheap compared with radars. Their number, ease of operation and silent presence make them hard to avoid, detect, or destroy by an adversary. They therefore significantly reduce his operational freedom. A counter-argument is that the ESM-sensors add to the cost of the Air Defence System, as they hardly can be used to reduce the number of radars. They will need a communication system, not likely that used by the radars. If some sort of radio communication is required, they might not be that difficult to detect after all. Further, even though the ESM-sensors are cheaper than radars, more sensors are needed to establish the same level of track information. Without very accurate direction measurement and dense sensor deployment, only TDOA-measurements might give a track accuracy near that of radars. Use of TDOA requires simultaneous detections by pairs of sensors, and three sensors have to be involved for obtaining an accurate position even with additional altitude information. Four are needed if the altitude of the object is to be deduced from the TDOA-measurement alone. Signal strength and terrain screening might then pose a problem for the required simultaneous detection in such a system. The accuracy “outside” the sensor area is poor compared to “inside”; this may pose a problem for a favourable deployment of the sensors.

8. Conclusion

The main purpose of this paper has been to present ESM-sensors as candidate sensors in a cost-effective integrated Air Defence System for an International Reaction Force, and to inspire investigations to clarify this question. As sketched, a number of threats normally emit signals that may be valuable sources of information about the situation. The characteristics of available ESM-sensors and those likely to be available on the marked in the near future exhibit a wide range of capabilities and prices. This is both an opportunity and a challenge for the design of a cost-effective system.

ESM-sensors may supply tactical information of different categories and should be seen in conjunction with a radar-based system. Emitter identification is the more important contribution, even if this requires substantial signal intelligence and emitter library handling. A tight coordination of the ESM-sensors improves their information. This includes the pointing and rotation of the ESM-antennas in order to increase simultaneous detections which are useful both for position accuracy and for “deghosting”. We suggest to first integrate the data in an ESM-system before presenting information to a higher level in the Air Defence system by "graphical integration"; the latter being a first level of ESM/radar integration.

ESM-sensors should generally be regarded according to their name "support measures", but an ESM-system can theoretically by itself establish and maintain tracks with a position accuracy better than 100m. The position accuracy highly depends on the type of measurements made, their accuracy, and the sensor geometry. Fundamental principles and numerical results are presented to give a basic understanding and enabling a simple further analysis of this topic. If an adversary does not choose to fully use his airborne emitters, the tactical information support from the ESM-sensors is reduced, but so is the operational freedom of the adversary. The investment in ESM-sensors may also happen to be worthwhile in this case.

We believe that the technical development, both on the side of the defender and the adversary, points toward the use of ESM-sensors in an Air Defence System for an International Reaction Force. We hope this paper will inspire the interest in tactical ESM-sensors and that clarifications of these questions will be seen in the time to come.

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SCI Panel Perspectives on Systems Integration

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SUMMARY

The need to adopt a systems engineering approach throughout the defence acquisition cycle, in order to ensure satisfactory system integration, has been recognised in recent years. In the UK, the 1997 Strategic Defence Review resulted in *Smart Procurement* which has been introduced as a result of a number of factors such as cost over-runs and slippage, increasing complexity and diversity in defence systems, rapidly advancing technologies, and the changing defence industry structure in the USA and UK.

The Smart Procurement lifecycle is being introduced particularly to ease the acquisition of large-scale battlespace systems of systems. Such systems can be perceived to be federations of autonomous or semi-autonomous sub-systems, in implemented operational terms. Nevertheless, throughout system development there has to be a fully-integrated, functionally-based system of systems concept without which a rational approach to the incorporation of legacy systems cannot exist. This fundamental concept has to be fully-integrated yet flexible, since it also forms the basis for successful system evolution to accommodate component obsolescence, technology inserts, etc.

Smart Procurement is being introduce at a time of increasing uncertainty in terms of capability requirements and the rate of technological change. A whole-life systems engineering approach enables the acquisition cycle to become smarter and to control programme costs whilst taking advantage of the evolutionary opportunities for system capability provided by technology inserts. To this end, the primary need is to develop system architectures which can facilitate evolutionary change over the lifecycle of the system.

It is important to recognise that these smart architectures have to be provided at the system concept level. For too long we have tried to use software techniques to compensate for fundamental weaknesses in systems -- this has ‘papered over cracks’ but has not provided a satisfactory long-term solution. In developing satisfactory system architectures, a systems of systems perception should be adopted at all levels in the system, and will impact upon system partitioning for integrated modular architectures.

There is a clear need to develop modelling and analysis capability in order to best configure the architecture of evolving systems in the knowledge that they will have to accommodate evolutionary change. This becomes an important development in improving the defence industry’s capability, as a system integrator, to develop evolving defence systems more affordably.

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Multi-Sensor-Integration Concept for Airborne Surveillance Applications

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1 ABSTRACT

Modern airborne surveillance systems have to cope with an immense number of inputs from real wanted and unwanted ground, maritime and/or airborne targets as well as correlated clutter. This causes significant challenges for tracking, classification, and identification of the detected objects. A state of the art multi-sensor integration (MSI) system calls for real-time integration of all available information pertaining to a real world object, in particular, geometric, kinematic, and signature data. The MSI system provide by DaimlerChrysler Aerospace yields improved tracking quality and performs automatic identification of targets.

The multi-sensor integration system processes data of various sensors, e.g., primary surveillance radar, secondary surveillance radar (IFF), data of passive electronic support measurements (ESM), acoustic sensor systems, crosstold data of Link-11 and Link-16 etc.. Based upon these data, the system will perform two tasks: Multi-sensor tracking and multi-sensor identification.

New tracks will be initiated automatically based upon data input from active or passive sensors, respectively. State of the art multi-model technology is used. It guarantees optimal track stability under various maneuver conditions. In the correlation function, either an improved nearest neighbor algorithm or the advanced multi-hypothesis concepts are applied.. ESM reports from tactical data links and specific sensors are used to perform multi-sensor cooperative passive tracking.

The multi-sensor identification system (MSI) is capable to identify air, surface, and ground tracks. It will operate fully automatically using all available data from all sensors as well as derived and background information depending on the confidence which is associated with the particular source. The system is able to handle various identification schemes in parallel. The automatic identification process will evaluate all available identification information for every MSI track using ‘‘identification indicators’’. The identification indicators will be combined to yield a track identity using an artificial intelligence (AI) supported combination process. Both, the MSI tracking and MSI identification functions can be controlled by mission data which are provided at mission startup or at any time during the mission.

2 THE MULTI-SENSOR INTEGRATION SYSTEM

2.1 MSI System Overview

The ultimate goal of all multi-sensor integration systems is to generate a precise picture of the according real world scenario. The system has to merge all available inputs that pertain to one target to only one object in the picture on the display. This picture must contain only real and no false targets, all correctly identified at the correct locations. This goal can only be achieved by a careful harmonization of the sensor integration software with the high performance of the contributing sensors. The term Multi-Sensor Integration comprises essentially two distinct functions, which are Multi-Sensor Tracking including the correlation function and the Multi-Sensor Identification.

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Our MSI will provide multi sensor tracking and identification functionality. The MSICP (Multi-Sensor Integration Computer Program) will consist of the following parts:

- MSI Tracking
- MSI Identification
- MSI Manager

The MSI Tracking and Identification functions provide the basic operational functionality of the MSICP. The MSI Manager includes functionality mainly in the area of control and monitoring, communication, redundancy support and test and maintenance provisions for the MSICP.

2.2 The Multi-Sensor Tracking System

The Multi-Sensor Tracking has the capability to use sensor inputs from a wide variety of different sensors which are the primary radar, the SSR/IFF sensor, etc., the ESM system and crosstold sensor inputs via the various tactical data links. It is based upon Multi-Model technology which guarantees in the various maneuver conditions optimal track stability and continuity. New tracks will be initiated automatically either based on data inputs from active radars or from passive sensors only. The tracking process has the capability to perform self-triangulation based on passive strobes from onboard sensors. Additionally, ESM reports from tactical data links are used together with reports from onboard sensors to perform multi-sensor cooperative passive tracking. Deghosting is done automatically.

The functions of the Tracking system are grouped in the following categories (see Figure 2):

- Data preprocessing
- Correlation/Association
- Track Update
- Track List Management
- Post processing

The preprocessing comprises functions like ordering of measurement data in a timeline related sequence, performing coordinate system transformation, etc.. In this processing bias compensation is performed for all input sensors.

In the correlation function, either the classical nearest neighbor algorithm or the advanced Multi-Hypothesis concepts are applied. Which concept will be applied is dependent on the actual complexity of the scenario in the vicinity of the current measurement/track position. Adaptive selection of the most suitable correlation algorithm will significantly reduce processor load. In doing so, maximum track continuity will be provided under all target conditions, and hence, track identification will be preserved through complicated target track crossing situations. Furthermore, ESM-based signature data and cross correlation between ESM- and kinematic data will also be used for the final report/track pairing. The operator can at any time either prohibit a selected correlation or enforce a correlation.

The track update function is executed for each track which has been associated to a target report. Depending on the type of the target report either a kinematic and/or a attribute update is performed for every model which is currently applicable to the track. Kinematic updating of active tracks is done by means of a Kalman component filter, whose peculiar feature is that updating of the state vector is performed for each measurement component separately. A major advantage of this Kalman component filter is that even under jammed or distorted conditions all available useful measurement information will be utilized. Attribute updating is performed by keeping record of attribute data of target reports incorporated into the track.

The Track List Management contains functions like track initiation, track deletion, track prediction and bias error estimation. Track initiation is performed on target reports for which no correlation was found. They will be initiated as tracks and labeled as potential track. Initiation of tracks will not only be performed on sensor data from active sensors but also on data from passive sensors. Track deletion will be applied to tracks, whose quality figure recedes below a certain threshold. These deletion thresholds automatically adapt to environment parameters and to the different track states. Track prediction is performed for the time when the next sensor update is expected. The predicted position is input to the correlation function the next time. The bias error estimation function analyzes measurement residuals of each sensor with respect to the system track. In order to maximize overall track quality and accuracy, possible offsets between all sensors are monitored and estimated continuously in background. If necessary, observed offsets are compensated automatically by an adaptive logic.

In the post processing, coordinate system transformations are performed to adapt the tracker to the external system. Finally, data is converted to external data formats.

In summary, the functions performed by the MSI-Tracking are:

- processing of input data from different types of sensors - Primary Radar, IFF, ESM, Links
- merge active and passive tracking (both cooperative and self triangulation) including sophisticated correlation and association logic. This makes use of geometric data and attributes. The correlation and association logic uses rules about identity indications from ID sources
- update each measurement component (Range, AZ, EL, Range Rate) separately, using a special form of Kalman Filter algorithm
- automatically associate of signature and attribute parameters (IFF, ESM, ECM, Link data) to tracks
- update attributes (IFF codes, ESM attributes, ECM attributes)
- compensate ownship motion
- automatic track initiation and track drop
- automatic maneuver detection
- measurement dropout coasting
- automatic detection & compensation of bias (registration) errors
- processing of operator initiated track commands
- determination of target environment (air, ground, surface) based on kinematics data

Upon reception of system control commands issued automatically by the MSI monitoring & control as part of MSI management SW, the tracking adapts its functions automatically to graceful degradation measures in order to prevent uncontrolled program behavior in case of special conditions (e.g. overload). Additionally, the MSI-Tracking function monitors sensor input data for plausibility in order to generate inputs for error logging.

2.3 The Multi-Sensor Identification System

The MSI Identification function has the capability to identify air, surface, and ground tracks. It will operate fully automatic and uses all available data of the available sensors as well as derived information and background information dependent on the confidence which can be given to the information sources. The system can handle different identification schemes in parallel (e.g., suited for either peace, tension, war states, contingency missions etc.). The identification schema is loaded as data during system initialization.

High flexibility in the ID process is achieved by providing the operator with several means to adapt the identification function to mission specific needs. Some of these means are:

- modification of the set of information to be used for identification,
- modification of mission data
- overriding of identification results.

The functions of the multi-sensor identification are based upon artificial intelligence concepts, which use a rule based artificial intelligence system. This rule-based system was developed by DASA ASD with the focus to be used in operational systems and give responses with minimum delay.

The MSI Identification function does provide the capability to assign track identities based on integrated sensor, communications and operator provided data. ID related information as for example conformance of tracks to flight plans, or platform identification by origin (IDBO), which on its own may not provide conclusive ID are combined in order to extract maximal benefit from the available sources of data. Conflict resolution is performed in case of contradictory data. Therefore, the MSI- Identification function will make maximum use of the available information to provide its results.

The MSI Identification function uses the information from different sources to determine the identity of MSI tracks. These sources are:

- 2D-position, altitude, speed and heading, their error values, environment category (air, surface, ground) and time of track update of the targets from MSI Track File
- ID related data from data links
- Mission data

All available information for the MSI Identification process is used in a most effective way to derive a unique target identification and classification for the environment categories air, surface, and ground. The identification is done automatically or by operator input. The manual ID assignment has priority over automatically determined ID. In case of manual ID assignment automatic ID determination will continue and MSI ID will report detected differences between automatic identification based on available information and the manually assigned ID.

The automatic identification process will evaluate all available identification information for every MSI track using “identification indicators”. These identification indicators will be combined into a track identity by an artificial intelligence (AI) supported combination process. Conflicts in the available identification information will be detected. The automatic system will provide conflict resolution functionality. In cases where conflict resolution is not possible operator alerts will be generated automatically. Possible ID conflicts with ID data from the data links are indicated to the operator. In case of detected severe ID-changes (e.g. from FRIEND to HOSTILE or vice versa) a manual ID assignment will be requested.

The MSI Identification function will provide rationale for its results to the operator. The complete MSI Identification process will be controlled in a flexible way by operator changeable “Adaptation Data”.

The incoming (live) sensor and communication data may be mixed with simulated data in order to train operators during real mission flights.

Upon reception of system control commands the MSI Identification adapts its functionality automatically to graceful degradation measures to prevent uncontrolled program behavior in case of special conditions (e.g. overload).

2.4 MSI Manager

The MSI Manager function will integrate the MSI Tracking and Identification functions. It will provide all necessary communication mechanisms for MSI Tracking and MSI Identification based on the Real Time Communication middleware.

The MSICP application software will use the Real Time Communication Layer and MC/MSIC System Software layers and provide CORBA 2.0 compliant interfaces for external communication and communication between major internal software components (cf. Figure 1).

An overall MSICP system control will be provided by the MSI Manager including system startup and shutdown mechanisms as well as the overall control of operational modes of the MSICP. The MSI Manager will also provide an overall system monitoring function. This function will provide all required MSICP system status data in regular manner to the MSICP external interfaces.

The MSICP will be responsible for redundancy support of MSI Tracking and MSI Identification.

The MSI Manager will be responsible for the overall computer load management within the MSICP. It will measure computer load, detect overload situations and activate the load adaptation functionality of the MSI Tracking and Identification function to prevent unpredictable behavior.

Within the MSI Manager and within MSI Tracking and Identification provisions for test functionality will be included, which can be activated by the MSI Software Test Bed. These provisions will be used during system testing and integration and may be used for maintenance activities in the software life cycle. These provisions will support:

- recording of external and internal MSICP interfaces
- logging of MSICP internal data for test and maintenance purposes.

The MSI Software Test Bed will include the functionality to make use of these provisions including the external interfaces.

3 SYSTEM TEST

During Test and Development the MSI Software Test Bed provided by DASA Airborne Systems will include all functionality needed to operate the MSICP in a test environment. It will additionally provide simulations of Mission Computer functionality as needed to run the MSICP in a test bed. The MSI Software Test Bed will simulate interfaces to the MSICP compatible to the MCP real time interfaces. Parts of this MSI Software testbed may also be used for maintenance purposes during the operational usage of the MSICP. Functionality and performance of the MSICP will be verified by a two stage approach. First, testing is performed via computer models. The Test and Development Support software contains a variety of representative scenarios and generates the inputs of all relevant sources. It also considers the sensor behavior that affects detection performance and accuracy of the measurements. The Test and Development Support Software (TADS) will include all features needed to generate the necessary data, and do the analysis of results. Second, the MSICP is tested by using recorded life data. The evaluation of the results is also performed by the TADS.

In the final qualification test run, the configuration data of the multi-sensor tracking and identification function will be optimized during real flight tests. This will finally verify the functions and the performance of the MSICP.

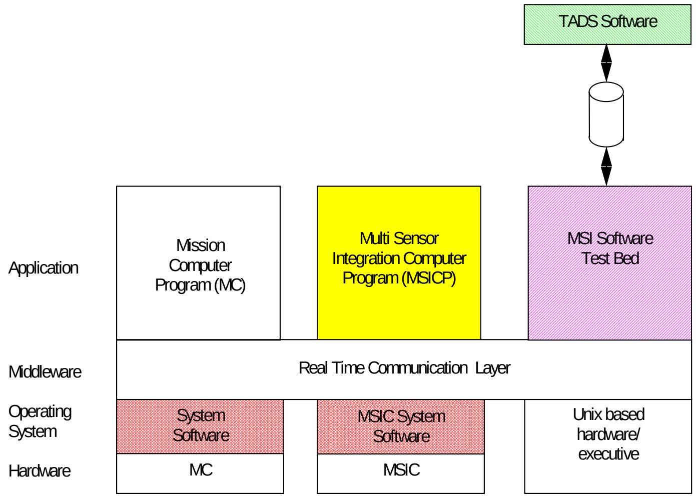

Figure 1: Software Layers (Test Configuration)

4 SUMMARY

In this article we have presented a brief overview of the DaimlerChrysler Multi-Sensor Integration System. It explains the requirements for the new system and its performance drivers as well as the concepts which were applied in the system design in order to match the practical requirements. Especially in the identification function a new dimension of flexibility is implemented to enable operators to cope with the changing real world situation.

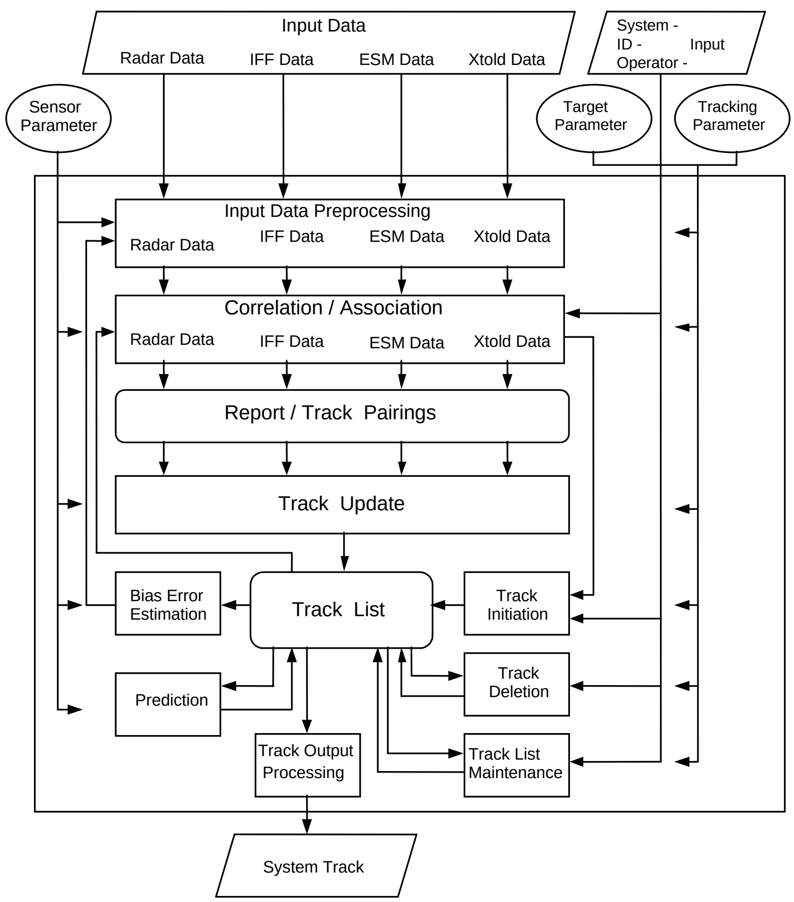

Figure 2: MSI Tracker

OPTIMAL ALLOCATION OF TARGETS FOR THE HAWK AIR DEFENCE MISSILE SYSTEM

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Optronics in Integrated Air Defence

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Introduction

The aim of this paper is to review the use of Optronic sensors in Integrated Air Defence Systems, concentrating mostly on **I**nfra-**R**ed **S**earch and **T**rack (IRST) sensors. Optronic sensors are used today in **V**ery **SHO**rt **R**ange **A**ir **D**efence (VSHORAD) and **SHO**rt **R**ange **A**ir **D**efence (SHORAD) weapon systems. Their operating range is typically 10 km or more, and they are particularly useful against low level targets. Optronic sensors are 'line of sight' sensors whose range performance is dependent upon the signal level emitted by the target (its signature) and the absorption of that signal by the atmosphere between the target and the sensor.

This paper concentrates on sensors which operate in the infra-red waveband between 8 and 12 micrometres in wavelength. Two distinct types of optronic sensor are used today :-

Thermal Imaging (TI) equipments, which are used to produce a picture of the target for classification and engagement purposes. The advantages of TI sensors are that they operate for 24 hours of the day and have the ability to penetrate certain poor visibility conditions, usually producing a picture of the target beyond the visual range to the target. TI sensors are widely accepted as an essential component of modern VSHORAD and SHORAD systems, and are in widespread use today.

Infra-Red Search and Track (IRST) equipments, which are used to search for targets, detect and track them before they are handed over to the weapon operator. IRST equipments have the same advantages as TIs of 24 hour operation and detection beyond visual range. They also have the advantage over the more widely used radar sensors that they are passive. A drawback of IRSTs is that, when used in isolation, they do not provide the range to the target. IRST sensors are not yet in widespread use, although they are expected to become increasingly adopted in future air defence systems. Indeed, ground based IRSTs have a number of benefits when considering the scenarios likely to be encountered by crisis reaction forces.

As well as providing a dedicated and automatic alerting capability for VSHORAD and SHORAD weapons, IRST equipments can also be networked to contribute to the **L**ocal **A**ir **P**icture (LAP). The networking can either be with other IRSTs to provide a fully passive system, or with radars to combine the advantages of both passive and active sensors.

This paper starts by discussing two specific operational areas:-

- The vulnerability of alerting sensors, particularly in relation to experiences gained from recent conflicts.
- The expected performance of IRST sensors against the evolving air threat.

Some results of track fusion experiments are then presented, followed by some suggestions for future developments to IRST sensors which would improve the overall effectiveness of future air defence systems.

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Sensor Vulnerability

Recent conflicts have given an important insight into modern air defence tactics. In the Gulf War and in the Kosovo conflict an essential part of the allied campaigns was the **S**uppression of **E**nemy **A**ir **D**efences, or SEAD. The air defence weapons aimed against the allies depended almost exclusively upon radar sensors for their effectiveness. Without radars these air defence weapons became virtually useless. The vulnerability of these radar sensors can be explained as follows :-

- ***Easily detected***. Since radars are active sensors they emit electro-magnetic radiation which can be easily detected by approaching aircraft.
- ***Provide unique signature***. The characteristics of radars which are used with specific air defence weapons are well known. The attacking pilot can often identify which weapon he is approaching and modify his attack profile to stay outside the engagement envelope.
- ***Vulnerable to Electronic Counter-Measures (ECM).*** Jamming techniques are used to make the radars ineffective, and this usually prevents the launching of the associated air defence weapon.
- ***Vulnerable to Anti-Radiation Missiles (ARM).***
- ***Subject to EMission CONtrol (EMCON).*** Radars which have not been jammed by EMC or attacked by ARM will often be switched off, to preserve them for future action.

IRST sensors are not vulnerable to the problems described above.

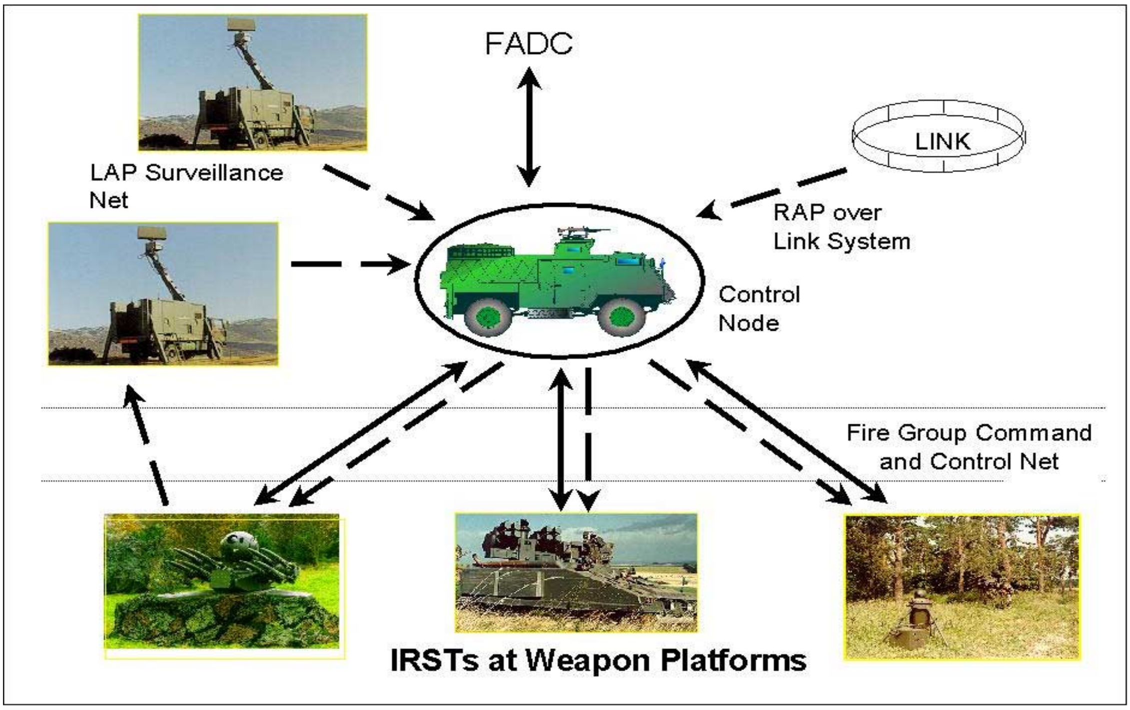
It is, therefore, not surprising that the allied air campaigns in The Gulf and Kosovo concentrated on SEAD, mostly directed against the radars. This was achieved by two main methods :-

- ***The use of ARM***. In the Kosovo campaign last year more than 48 F-16s were deployed with ARMs, and by the end of hostilities more than 300 were fired against radars.
- ***The use of EA-6B Prowler jamming aircraft***. 66 aircraft were in operation in Kosovo, which represented the balance of all of the aircraft available to NATO. The remaining aircraft were deployed on enforcement duties in Iraq. It is now recognised that there is a shortage of jamming aircraft, and plans are being considered to increase their number for the future.

The importance of the SEAD tactic to the NATO campaign in Kosovo can be understood when it is considered that out of the total number of 37,465 air sorties, 14,006 were SEAD missions. Also, every air sortie was accompanied by a Prowler jamming aircraft for protection.

It is clear that air defenders in the future will face significant difficulties if they rely entirely on radar sensors for surveillance. The most robust system will be a combination of radar and IRST sensors connected together in a network to provide C2 information to all firing units. A possible networked arrangement for the future is shown in Fig.1, with the IRST and radar sensor outputs combined at a control node. The shorter range IRST equipments are deployed with the weapons to provide local coverage, including effective detection against helicopters and aircraft using terrain screening. At the same time the IRSTs can also contribute to the LAP. This deployment provides a robust fallback mode in which the IRST sensors will remain fully operational, allowing autonomous weapon operation even if the active sensors and C2 network are lost.

Fig. 1 Future network concepts



The Evolving Threat

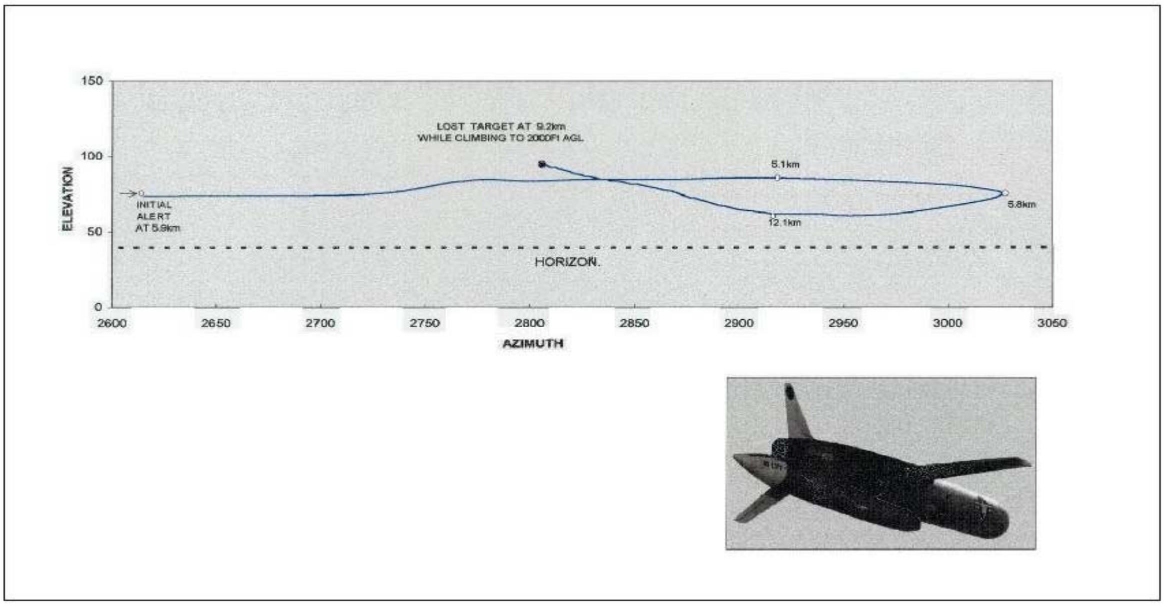
The air threat is continuously evolving. In the past the traditional fixed and rotary winged manned platforms have been most prevalent, but in the future there will be increasing numbers of **U**nmanned **A**erial **V**ehicles (UAV) and cruise missiles. Future air defence systems must deal with these new threats. As well as reducing in size, these future targets will also reduce their signatures (reflections and emissions) by employing stealth technology. These two factors will result in both the radar cross-section and the thermal signature of the targets reducing significantly. The best chance of locating them will be provided by a combination of sensors.

Dramatic reductions can be made in radar cross-section by shaping the outside contours of an aircraft to reduce the reflected signal. Thermal emissions can be reduced by burying the engines inside airframes and minimising the visibility of hot tailpipes. However, IRST equipments operating in the 8 to 12 micrometre waveband have good sensitivity against targets at ambient temperatures and can detect them by the thermal emissions from their skin surface, without the need to see the engines. These emissions are increased as the target speed increases due to the frictional heating of the skin as it passes through the air : a target travelling at high subsonic speeds suffers a temperature increase of more than 30 degrees Centigrade due to friction with the air.

Trials have shown that aircraft which are stealthy to radar can easily be detected by TI and IRST equipments. Indeed, the stealth coatings used on some aircraft seem to slightly increase the frictional heating with the air, and therefore enhance the thermal signature.

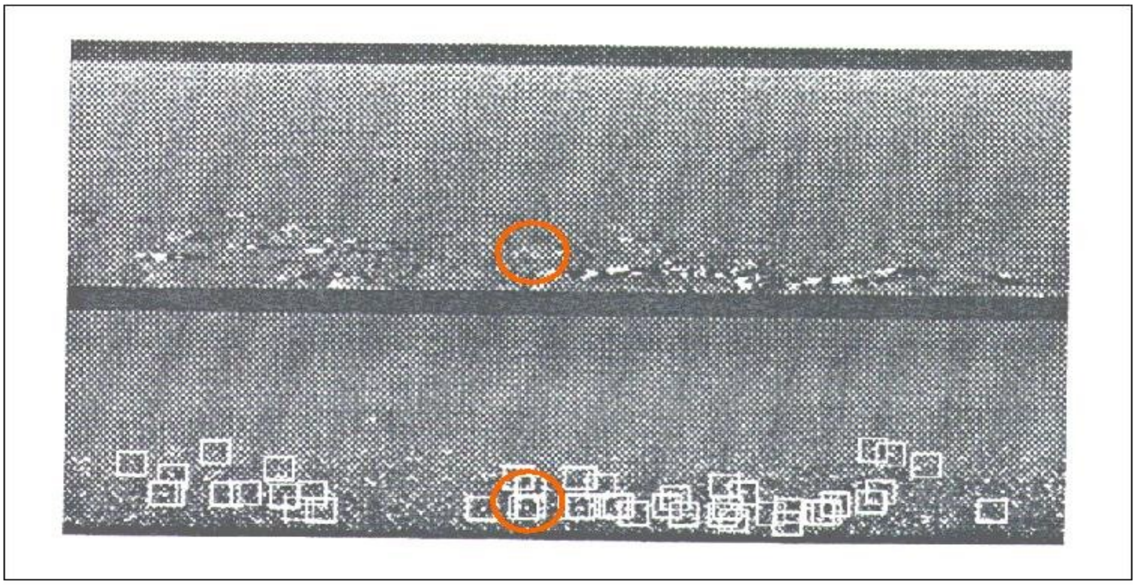
The lower signatures of UAVs and cruise missiles will require greater sensitivity from all sensors in the future, especially if they are to be detected under adverse conditions. However, current generation IRST equipments already have an effective capability against these threats. Fig. 2 shows the track of a BQM-74 drone, which is used to simulate a cruise missile, being detected and tracked by the UK IRST, ADAD (**A**ir **D**efence **A**lerting **D**evice). After being dropped from its carrier aircraft, the BQM-74 was first detected at a range of 5.9 km in good weather conditions, and was continuously tracked while it completed a circuit in front of the test area. It was lost at a range of 9.2 km when it deployed its recovery parachute. At this point it ceased to exhibit aircraft-like characteristics and the software algorithms within the ADAD processor rejected it as a true target.

Fig. 2 ADAD track of BQM-74 target drone



Another problem occurs for air defenders when sensors are attempting to detect low-level targets amongst the clutter arising from objects on the ground. Processing techniques must be sophisticated enough to discriminate real targets within the clutter background in these conditions. Fig. 3 is a frozen frame from the ADAD IRST video showing target detection in a heavy clutter environment. Such a picture was obtained using special test equipment, and is not available to the operator using a standard ADAD. The upper picture is unprocessed ADAD video, and the lower picture is the filtered video complete with detection boxes. The ADAD has detected a helicopter target (position marked by the circle) against a warm ground background which has a high level of clutter in the thermal waveband. The square boxes denote the clutter points detected by the IRST but rejected by the software algorithms because they do not have the characteristics of a real target. The operator is only aware of the real target, which is indicated to him on a separate display unit. As with most IRST alerts, the declaration range is longer than the visual range, and the high resolution thermal camera used to confirm the detection was unable to locate the target until it had approached closer, which was more than 15 seconds after the initial ADAD alert.

Fig. 3 Target detection by ADAD in a heavy clutter environment



Track Fusion

At the moment IRSTs are used as dedicated sensors, operating in association with a specific weapon platform. However, additional benefits can be obtained by fusing the track information from two or more sensors to provide more comprehensive information on the target and to provide a contribution to the LAP. Trials have been carried out fusing the tracks from two IRST sensors, and also fusing the tracks from an IRST and a radar sensor. The IRST/IRST fusion work was carried out by Pilkington Optronics together with the UK **D**efence **E**valuation and **R**esearch **A**gency (DERA), and the IRST/radar fusion work was carried out by Pilkington Optronics, DERA and BAE SYSTEMS.

Fig. 4 shows the results of one of the early IRST/IRST fusion trials on an approaching helicopter target. Special software was used to fuse the two tracks of the same target. These tracks were separately declared by each of the two IRSTs before being fused. It is important to note that the IRSTs were not synchronised in any way, and so the individual detections made by each sensor were at different times, and therefore the target positions were different at the times of the detections. The IRSTs are located at the red spots in Fig. 4 and the fused track is shown by the blue line. The black line shows the target track as recorded by a radar for comparison. It can be seen that a successful fusion has been made from the two separate IRST tracks.

Fig. 4 ADAD / ADAD track fusion - helicopter

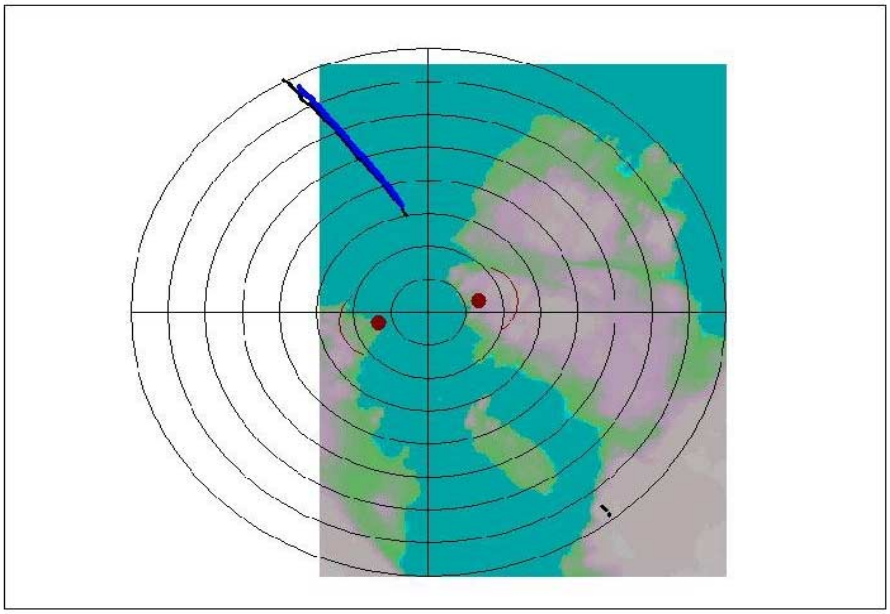
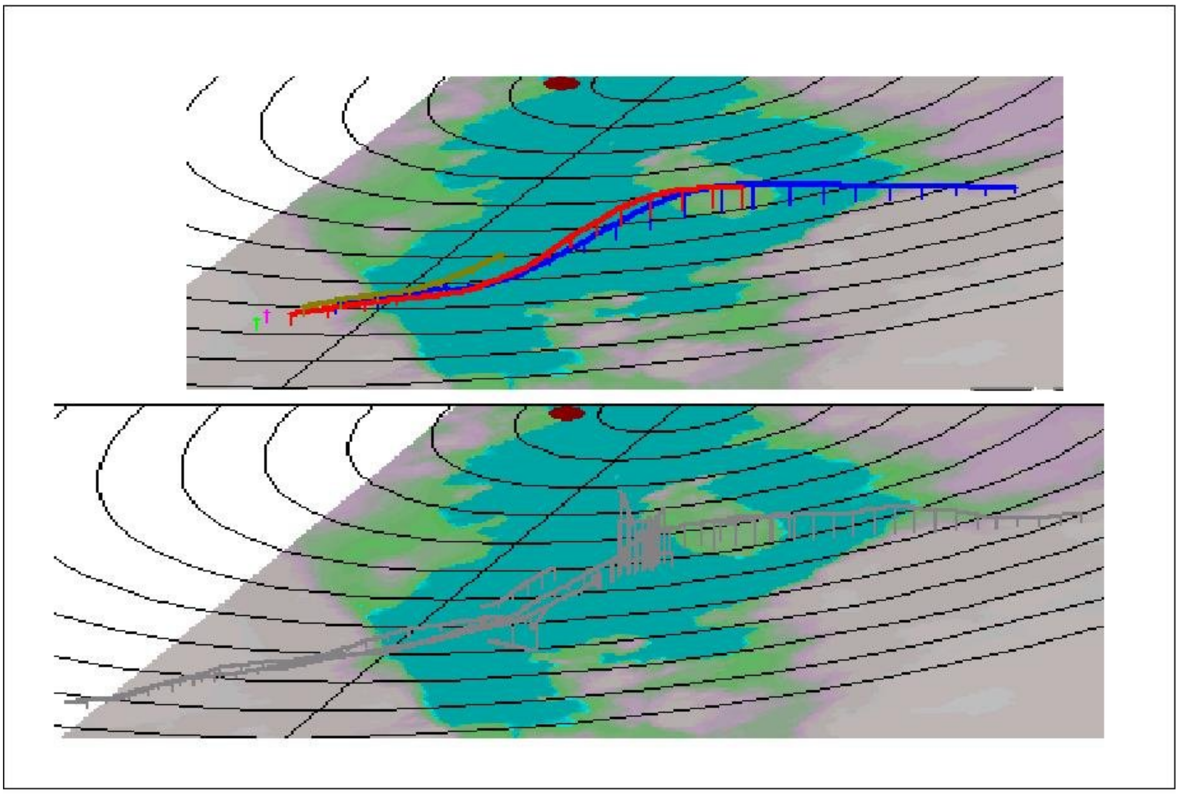


Fig.5 shows a further track fusion experiment with two IRSTs, this time on three aircraft following close behind one another. The picture is an isometric view, and this time the IRST fusion tracks and the radar comparison tracks have been separated into two views for clarity. Once again it can be seen that the IRST fused tracks have produced a true picture of the target tracks. Indeed, the higher resolution of the IRSTs compared with the radar has produced a very smooth and accurate 3-dimensional track of each target.

Fig. 5 ADAD / ADAD track fusion – 3 aircraft



The higher resolution of IRST sensors compared with radar arises from the shorter operating wavelength. This has benefits in addition to the smooth/accurate tracks mentioned above :-

- ***better spatial discrimination*** is provided between targets which are close together, giving earlier warning of a formation attack.
- ***virtual immunity to multi-path transmission*** effects, which means they are not susceptible to spurious detections caused by reflections close to the ground.

The IRST/radar track fusion work is still continuing, but some initial findings can be described here (these results were first presented as part of a paper at the VIIIth European Air Defence Symposium, Ref. 1). Fig. 6 shows the radar only track of a helicopter approaching on a zig-zag track. The solid black line represents the output from the GPS receiver on the target aircraft, which outputs the ground position but does not provide any altitude information. Altitude from the radar is indicated by the vertical bars, their absence indicates missed measurements. A different colour is used when a break occurs in the track and a new track is started. It can be seen that breaks in the tracking caused four separate tracks to occur, and the indicated altitude is quite variable. When the track data from one IRST is combined with the radar (Fig.7) it can be seen that a fully continuous track is achieved with better elevation information. In other words, the track has become more robust and more accurate. In this trial situation the IRST was co-located with the radar, although in a tactical situation the two sensors would be separated by a safe distance to avoid the IRST becoming damaged if the radar should be attacked by an ARM.

Fig. 6 Target track - Radar alone

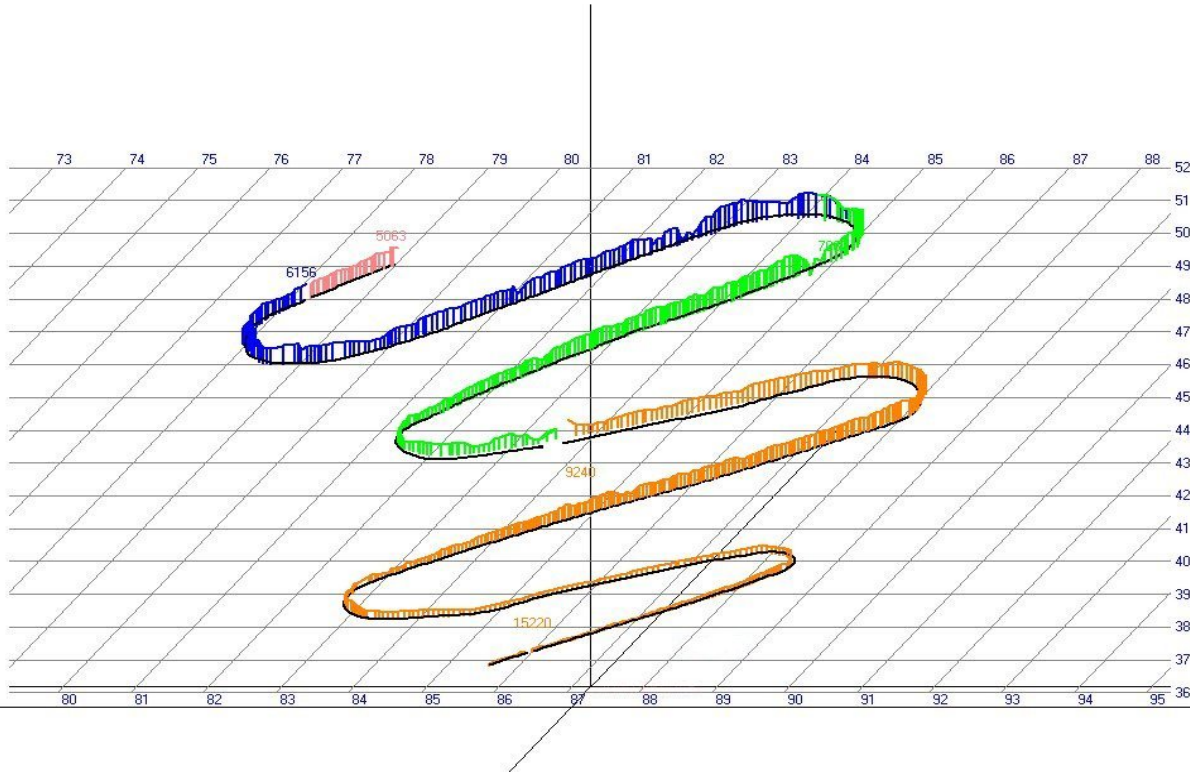


Fig. 7 Target track - Radar and ADAD 1 track fusion

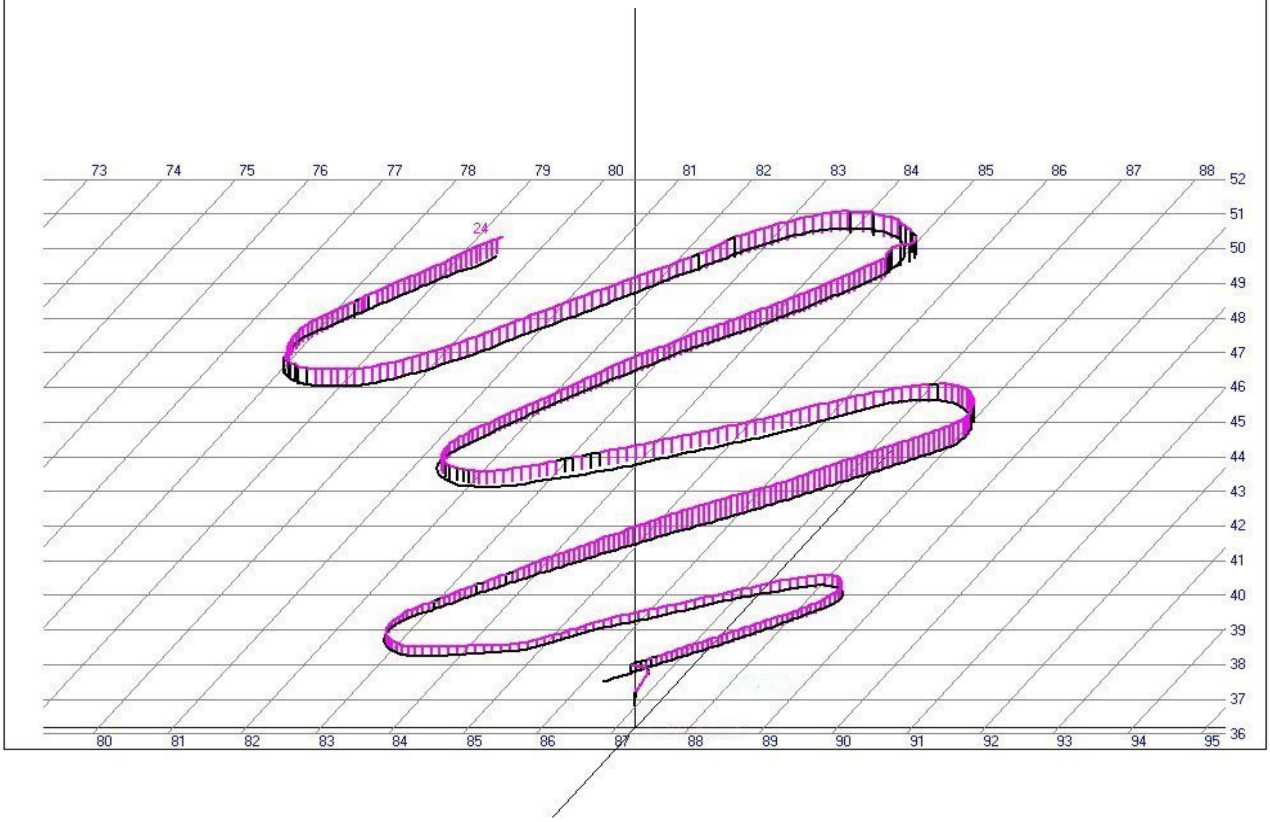
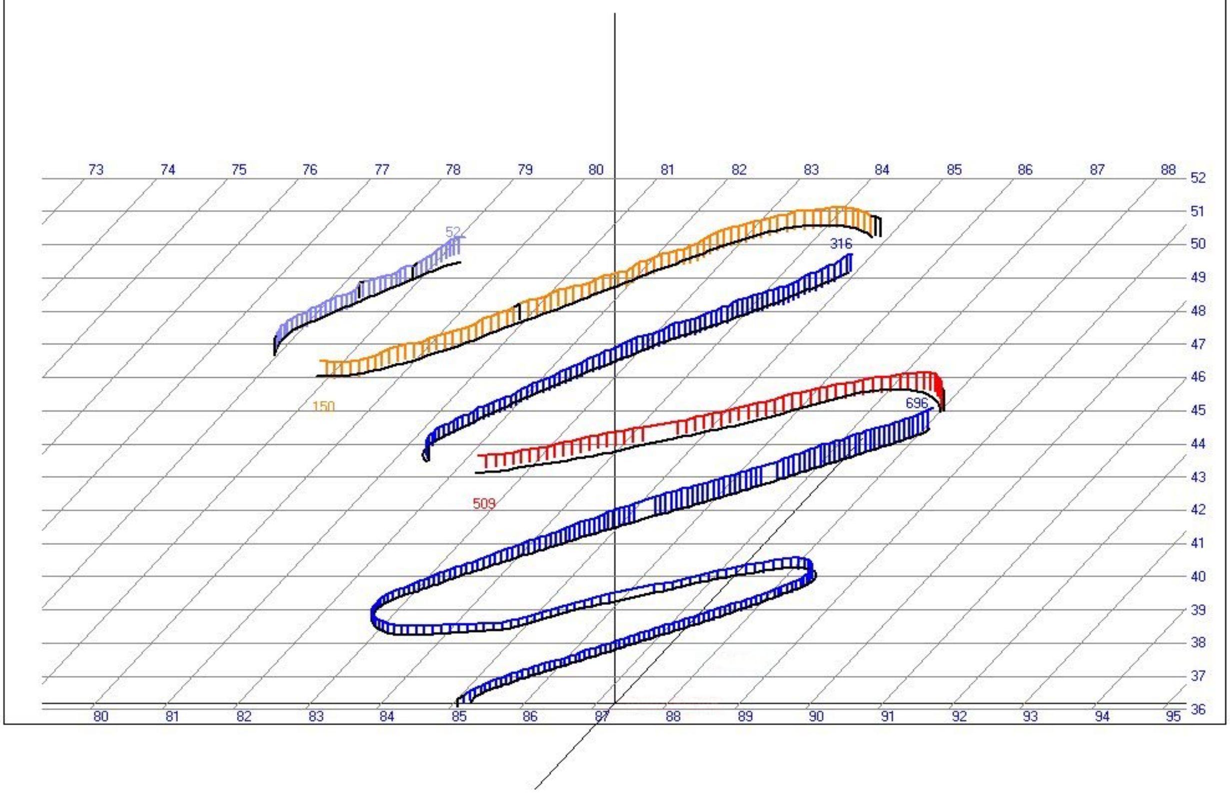


Fig. 8 shows the same mission as recorded by the tracks fused from two IRSTs, without the radar. Good target track information has been produced, although there are some breaks in the track at the turning points. This was caused by one of the IRSTs breaking track on the target for a short time and, although the other IRST was still tracking the target, the current prototype software is only designed to show a track when both are present. In this trial arrangement the two ADADs were only 1.6 km apart, which is not an optimum fusion arrangement because they both viewed very much the same aspect of the target.

Fig. 8 Target track - ADAD 1 and ADAD 2 track



These results show the benefits of networking sensors to produce a LAP. When all of the sensors are operating an accurate and robust air picture is produced, overcoming any minor shortfall in an individual sensor and providing more information than any of the sensors could provide on their own. If one or more sensor fails, useful target information is still produced. If the radar is not available due to the effects of ECM or ARM, the two IRSTs will still produce a high resolution target track in 3-dimensions.

One important conclusion which has come out of the multi-sensor fusion work is the need to know the individual sensor positions very accurately. Initial conclusions are that sensor position must be known with an error of 2 to 5 metres in three dimensions if satisfactory track fusion is to be achieved. Also, accurate time registration of the data is required, with a registration of better than one tenth of a second needed if agile targets are to be tracked successfully. These effects have been investigated by the Pilkington Optronics / DERA / BAE SYSTEMS team (Ref. 2).

The Future

The commitment of air defence forces to IRST equipments for the future is now well established. In the recent JPG 28/30 feasibility study, both consortia of companies concluded that IRSTs would play a prominent role at the weapon platform in future VSHORAD and SHORAD systems. Also, they concluded that networking of sensor data will be required to provide information into the LAP. Also, in the UK studies have just started into the future air defence programme IGBAD, or **I**ntegrated **G**round **B**ased **A**ir **D**efence. It is certain that passive sensors will be a part of IGBAD, and it is expected that the next IRST sensor will either be a modified version of ADAD or a next generation equipment derived from ADAD.

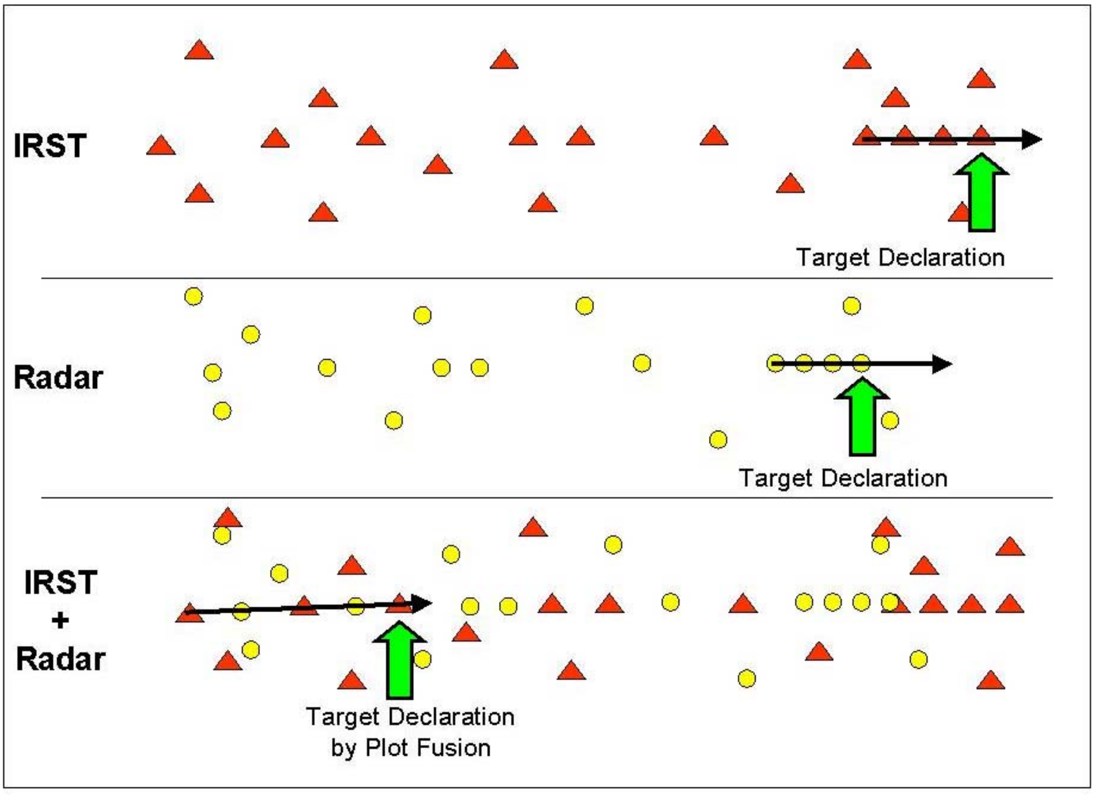
Major evolution areas for the IRST sensor itself are increased sensitivity and operation on-the-move. Increased sensitivity, and possibly increased resolution as well, will be made possible by using future generations of detectors. This will enable targets with lower thermal signatures, e.g. UAVs and cruise missiles, to be detected at longer ranges and in a wider range of weather conditions. In addition, new scanning techniques will allow the possibility of reconfigurable scanning. This will mean that a very wide scanning area can be used to search for a target initially, which could be adjusted according to the perceived threat, e.g. a larger vertical field of view would be used for high attack angle targets such as bombs and some types of missile. After initial detection the scan area could be made smaller to achieve a more accurate track on the target and enable a smooth hand-over to the weapon. A picture output could also be provided to aid identification. All of these techniques are already being implemented in the airborne IRST, called PIRATE, which is currently in development for the EuroFighter Typhoon aircraft.

Operation of future ground-based IRSTs on-the-move will also be possible, so that surveillance can be carried out during mobile operations and during re-deployment. This will probably be an essential requirement for mobile crisis reaction forces. Once again, such techniques are already under development for the EuroFighter Typhoon. However, adaption of this technology for ground use is expected to be particularly demanding because the appearance of fixed clutter points which are ‘streaming’ past the sensor at close range will be similar to the tracks made by targets. New processing techniques and algorithms will need to be developed to ensure that an acceptably low false alarm rate can be achieved.

The benefits of track fusion have already been discussed. The challenge for the future will be to carry out sensor fusion in real time. Also, it will be necessary to establish simple and universal interfaces to achieve a genuine ‘plug and play’ concept, so that sensors can easily be added to or removed from an air defence network

One important area for future research will be to achieve plot (or detection) fusion between two independent surveillance sensors. All sensors create plots of targets before these can be associated into a robust track, which is then classified as a target and declared to the operator. Often, target plots exist within the sensor processor long before a target track can be formed. The fusion work described earlier in this paper has been carried out using target tracks already declared by the sensors. If individual plots could be fused from separate sensors, there is a possibility of creating a coherent target track at a longer range than either of the two separate sensors could achieve on their own (see Fig. 9). Plot fusion also allows the possibility of lowering the detection thresholds of the individual sensors because the better correlation between the sensors will allow better false alarm rejection and clutter rejection. This will allow a further increase in detection range. The recent trials carried out by Pilkington Optronics, DERA and BAE SYSTEMS recorded plot data from the sensors as well as track data. Future analysis work is aimed at fusing this plot data and, hopefully, demonstrating the benefits described above. One word of caution must be mentioned with regard to the fusion of plot data : the data rate and computing requirements are much more demanding than for track fusion. The realisation of plot fusion in the battlefield will require large communication bandwidths and large computing power.

Fig. 9 Plot fusion concept



Conclusions

This paper has described the benefits of optronic equipment for providing effective passive sensor systems for air defence weapons. They can overcome the problems of vulnerability associated with active sensors, and they can also cope with some of the problems of the evolving threat : low signatures, low level operation and high clutter environments.

Initial trials have shown that significant benefits can be obtained by networking passive sensors with other passive sensors, and with active sensors. Future work on plot fusion should enable networked sensors to provide an accurate and robust LAP, with longer ranges than are currently possible with track fusion.

Optronic sensors can clearly offer a major contribution to the safe operation of Mobile Crisis Reaction Forces.

Acknowledgments

The author would like to thank the Priority Pathfinder team from DERA Malvern, BAE SYSTEMS (Land and Sea Systems) and Pilkington Optronics for permission to publish some of the figures and conclusions from their work.

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Distribution of Intelligence in Airborne Air-Defense Mission Systems

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Summary

This paper addresses the distribution of intelligence, knowledge and learning capability among the main system elements. The enabling technologies are briefly introduced and the overall and subsystem structures are presented. In this context functional intelligence is integrated into the weapon system (air-air missile) yielding a considerable level of autonomy. This is complemented by a missile mission unit as part of the mission avionics which intelligently supports the pilot taking into account the new capabilities of the weapon system. Altogether this leads to improved efficiency and efficacy as well as extended functionalities of the air defense system.

The system evolves with the learning capabilities of the intelligent elements starting with initial knowledge and by learning from experience, thus improving automatically. To gain experience in a variety of situations, applications and missions, training can be performed applying advanced embedded simulation and including virtual reality. Of course, also ACMI-type training is possible utilizing new range independent air combat training and debriefing systems.

1 INTRODUCTION

Tactical Systems are implemented as Integrated Mission Systems (IMS) such as air- and space defence systems. Key elements of IMS are platforms with sensors and effectors, ground-based components with communication, command and control etc.

Airborne Air Defense represents a very difficult mission because

- it is so dynamic,
- it depends so heavily on situational awareness, pilot skill and quick decisions,
- multiple sensor information must be tracked,
- communication/IFF must be performed,
- of close proximity to adversary AC and highly dynamic geometry.

Optimization of an intelligent mission system design can only be realised if a common approach is taken to the interpretation, implementation and integration of the weapon system, avionics and cockpit functions, as they are depicted in the very simplified blockdiagram of Fig. 1.

Paper presented at the RTO SCI Symposium on “System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces”, held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

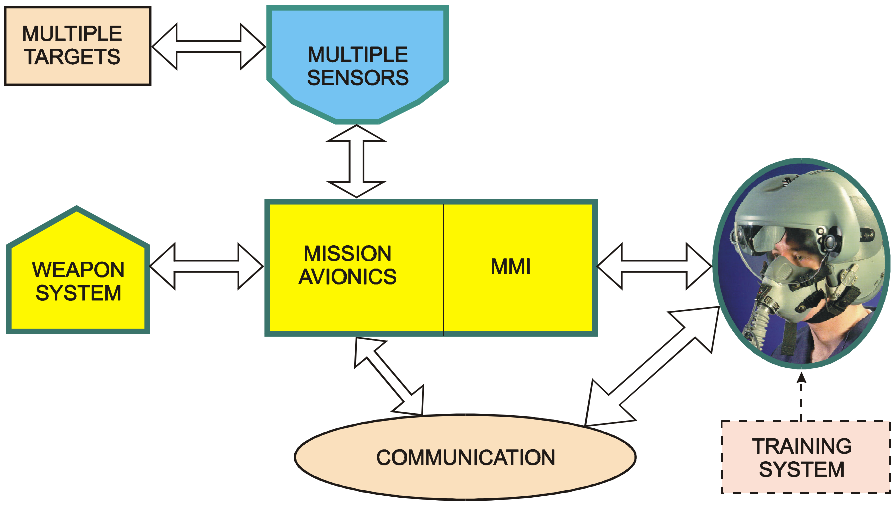

Figure 1: Air defense system block diagram

A structured approach is therefore required to the design of an advanced integrated airborne air-defense mission system that considers the mission avionics hardware, software and human pilot together with the air to air missile weapon system. This is vital if we are to obtain required enhanced mission system performance whilst reducing the overall aircrew workload and simultaneously staying within affordable cost margins.

Structured system design methods and mission and task analysis must therefore be a cohesive part of the corresponding integrated mission system. The design must be based on optimum functional and technical partitioning of the elements

- weapon system
- mission avionics
- man-machine interface
- pilot

2 THE IMPACT OF COMPUTATIONAL AND MACHINE INTELLIGENCE

The development, procurement and utilization of defense system will in future be strongly influenced by the affordability issue as already mentioned before. A considerable potential for future cost reduction is seen in the extended use of artificially intelligent autonomous elements as part of the IMS. Moreover, driven by ever increasing requirements there is a demand for extended and improved decentralized intelligence and autonomy concerning airborne air defense systems. The key notion of “autonomy” is intimately connected with advances in information technology. In this context the following question arises immediately: What is computational, machine or more generally artificial intelligence? In relation to the issues and topics treated here, the following answer shall be given.

- Systems/units have no artificial intelligence if a program/software “injects” them with what they have to do and how they have to react to certain pre-specified situations.
- Systems/units have artificial intelligence if their „creator” has given them a structure - not only a program - allowing them to organize themselves, to learn and to adapt themselves to changing situations.

Thus intelligent structures must be able to comprehend, learn and reason.

The automation of intelligent functions does require methods, techniques, technologies by means of which

- the cognitive abilities of humans for detection, classification, identification, assessment of a situation and of objects in it as well as for goal-oriented behavior can be automated (see Fig. 2).
- a complex problem-solving knowledge (algorithmic, heuristic) for real-time processing can be mapped on (nonlinear) network structures.
- the reflexive and knowledge-based behavior of humans (e.g. perception eye/ear) can be modelled and thus included in an optimum design of the man/machine interface.
- training and instruction systems can be implemented which take into account the specific learnability of the elements of the mission system such that an optimum distribution of intelligence is ensured.

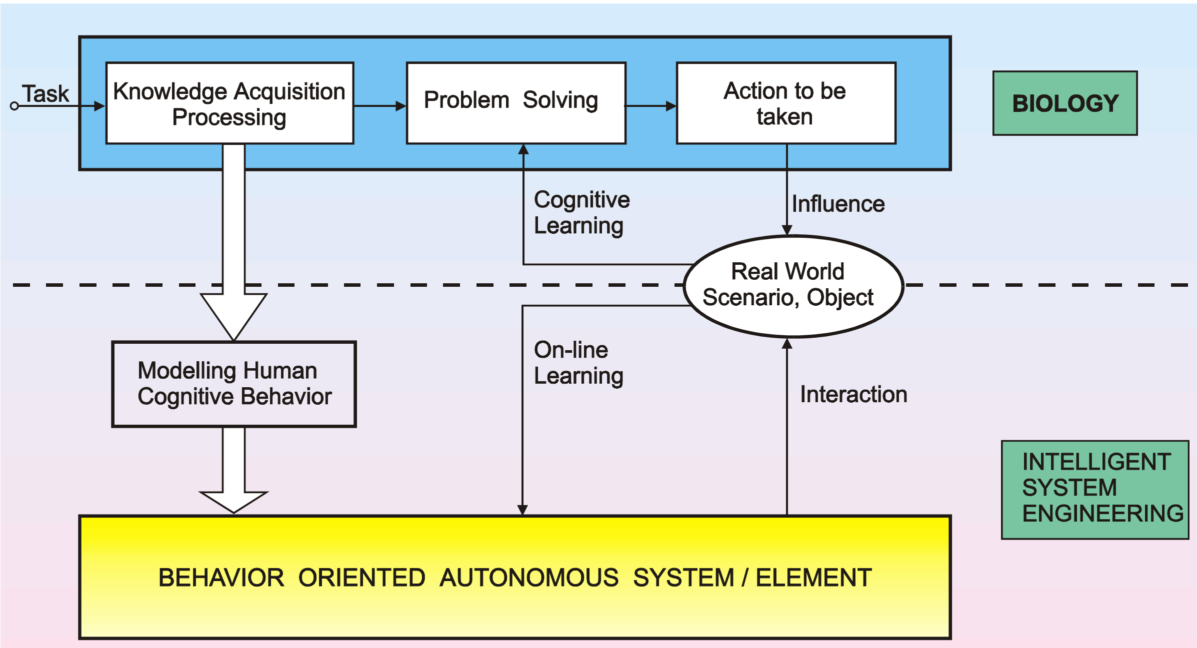

Figure 2: Modeling human cognitive behavior

There is a paradigmatic complementary shift from conventional artificial intelligence, knowledge based (AI/KB) techniques to new so called soft computing technologies, which are based on modelling the conscious, unconscious, cognitive reflexive functions of the biological brain. In contrast to the conventional method, soft computing [1] addresses the pervasive imprecision of the real world. This is obtained by consideration of the tolerances for imprecision, uncertainty and partial truth to achieve tractable, robust and affordable cost solutions for complex problems.

Important related computing methodologies and technologies include among others fuzzy logic, neuro-computing, as well as evolutionary and genetic algorithms which are described very briefly as follows.

- **Neural networks** are derived from the idea of imitating brain cells in silicon and interconnecting them to form networks with self-organization capability. They are modelled on the structures of the unconscious mind.
- By contrast, **fuzzy logic/fuzzy control** has developed an exact mathematical theory for representing and processing fuzzy terms, data and facts which are relevant in our conscious thinking.

- **Genetic algorithms** are based on the mechanism of natural selection and genetic evolution which offer search, optimization and learning behavior.
- A **combination of these techniques** as indicated in Fig. 3 is of particular importance for achieving unprecedented levels of self-organization capability and learnability and thus a new kind of artificial, computational and machine intelligence (CMI) in technical equipment and systems.

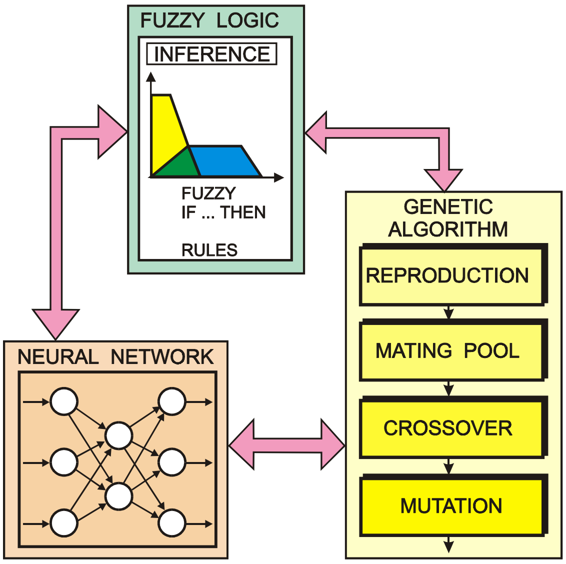

Figure 3: Soft computing techniques

Together with conventional algorithmic processing, classical expert systems, probabilistic reasoning techniques and evolving chaos-theoretic approaches the techniques treated here enable the implementation of knowledge based functions. Genetic and evolutionary algorithms can be applied to generate and optimize appropriate structures and/or parameters to acquire, encode, represent, store, process and recall knowledge. This yields self-learning control structures for dynamic environments that evolve, learn from experience and improve automatically in uncertain situations. Ideally, they can be mechanized by a synergetic complementary integration of fuzzy, neuro and genetic techniques (Fig. 3). Fuzzy logic for decision making and reasoning, neural networks for learning and self-organization and genetic algorithms primarily for task oriented optimization. These soft-computing techniques support the move towards adaptive knowledge based system or system elements which can rely on experience rather than on the ability of experts to describe the dynamic, uncertain world perfectly in order to program (top-down) the system or corresponding element for a predetermined behavior. Thus, soft computing techniques in conjunction with appropriate system architechtures provide the basis for creating behavior oriented systems or elements with appropriately distributed intelligence (Fig. 2). In the following, this will be looked at with respect to an air defense system.

3 SYSTEM-WIDE DISTRIBUTION OF KNOWLEDGE AND INTELLIGENCE

3.1 General remarks

The combined effects of new information technology and telecommunication are leading to whole new developments and IMS structures [2]. While progress made in information technology enables us to cope with tasks which are becoming increasingly complex, telecommunication is eliminating the dependence on distance and time as far as advanced mission management processes are concerned and as highlighted by the following issues:

- Enable full spectrum decision aiding/ automation network ranging from the C^3 environment down to the vehicle on board system level, to allow unprecedented degree of autonomy and decentralized freedom of action, using common consistent decision frame-work/criteria.
- Broad continuous information available to all operational levels together with suggested plans of action and proposals for optimum implementations, produced by machine intelligence, to provide dramatically improved situation awareness which in turn can improve both effectiveness and efficiency of force application.
- Enable distributed, flexible command structures designed by force commander to optimize response and action for any mission, operation or situation.

Related trends can indeed be called revolutionary and there is hardly any other example which confirms the quotation of Le Corbusier more forcefully: “One does not stage a revolution by rebelling, but by delivering the solution!”

In this context and looking at the title of this paper the following question arises immediately: How do we - in a first careful step - distribute knowledge and intelligence among the main elements weapon system, mission avionics, man-machine interface, considering the “given” cognitive capabilities of the pilot, however, also accounting for the human deficiencies and limitations in more demanding scenarios and in the operation of complex, highly integrated systems.

3.2 Weapon system

In order to

- improve the performance (firing zones)
- increase the availability
- reduce the cost of aircraft-missile integration
- increase the autonomy

it is highly recommended, if not to say mandatory, to integrate functional intelligence into the future air-air missile.

Consequently Bodenseewerk started some years ago R.a.D. work to apply neuro, fuzzy, and neuro-fuzzy network techniques for knowledge-based learning guidance and control. A functional blockdiagramm is shown in Fig. 4. The function of the missile guidance and control loop is to determine appropriate controls to produce a flight path such that the mission objective is achieved in the most efficient manner.

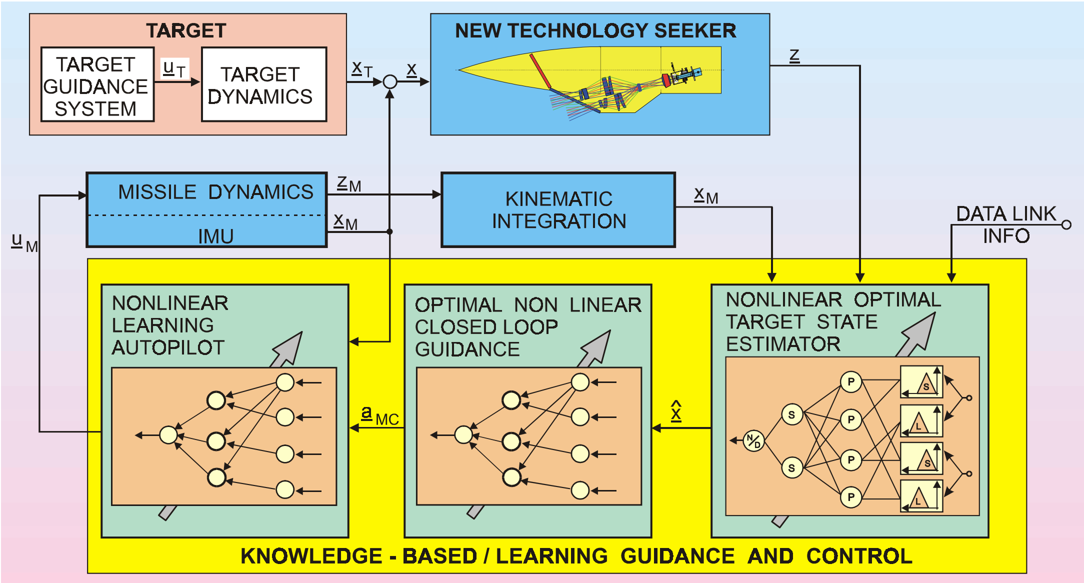

Figure 4: Functional block diagram of the guidance and control loop

Together with an all solid state new technology seeker, where also neuro-fuzzy techniques are applied for sensor processing [3], the knowledge-based learning guidance and control approach provides the following attributes:

- Application of most advanced guidance and control techniques
  - superior guidance and control performance
  - high agility
  - extended flight envelope
  - large operational ranges
  - increased pilot survivability by intercepting near hemishere targets
- Implementation as parallel networks
  - fast computation, high bandwidth
  - inherent redundancy, fault tolerance
- Providing learning, health monitoring, self-repair capability
  - high reliability and mission success probability
  - increased availability
  - compensation of design uncertainties
  - improved cost effectiveness

Altogether this leads to improved efficiency and efficacy as well as extended functionalities. In this context some aspects of the paramount potential of the missile´s learning capability such as the acquisition of expert knowledge and (sub)-systems behavioral knowledge as well as the acquisition of operational knowledge from experienced pilots and last but not least the continued knowledge acquisition during real mission are to be mentioned here.

3.3 Mission Avionics

The general objective is to support new kinds of capabilities (knowledge processing, learnability) of future missiles by a complementary module on the aircraft side in the mission avionics, thus further increasing the functionality and effectiveness of the missiles and their utilization, which leads to a decisive improvement of their performance and availability.

The extended functionality allows the pilot´s workload to be reduced through introduction of a Missile Mission Unit (MMU) as pilot support element, thus achieving a decisive reduction of the time constants in the so-called “recognize-act-cycle” of the missile utilization.

The “recognize-act-cycle” comprises functions for sensor fusion, situation assessment and awareness, reasoning and decision making as well as fire control, trajectory generation and weapon release.

For future support systems a degree of artificial intelligence is required, such that in the expected highly dynamic scenario a considerable portion of these functions can be removed from the pilots workload. Fig. 5 shows the structure of the recognize act cycle with the air-to-air scenario, the aircraft and missile sensors for situation measurements, the MMU with dedicated functions and last but not least with the pilot in the loop as final decision element regarding the goal directed interactions with the real scenario.

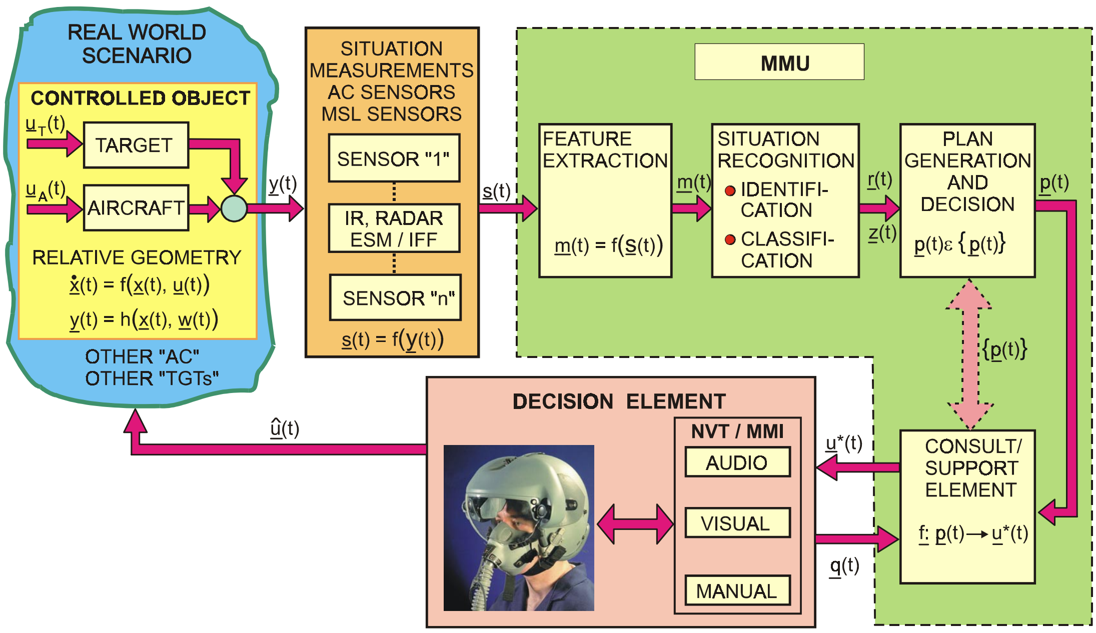

Figure 5: Recognize-act-cycle structure with MMU functions

The functions performed by the MMU are summarized in Fig. 6, which also shows in a much simplified way the integration of the MMU with the aircraft and missiles.

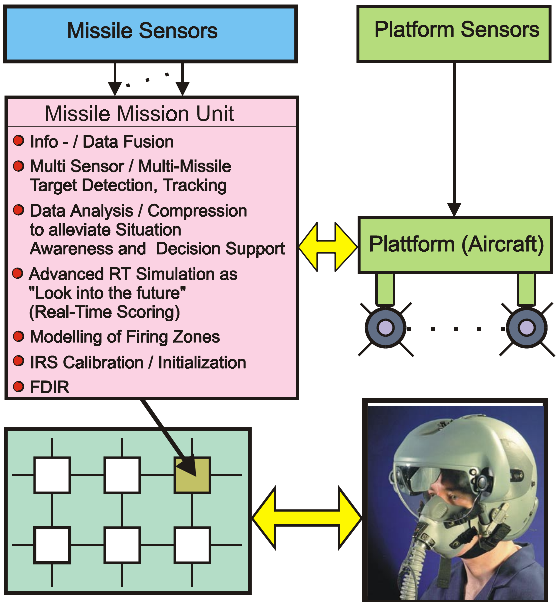

Figure 6: MMU function and integration with the aircraft and missile

Applying CMI techniques as introduced in chapter 2 and implemented in hardware and/or software, the MMU will be integrated into a future modular avionics computational network structure. This way of distributed processing in networks with standard interfaces (photonic in future) supports and complements the concept of distributed intelligence with cooperative behavior.

Finally, it is worth mentioning, that the neuro-fuzzy failure detection, identification and reconfiguration function greatly enhances the availability of the missile system.

3.4 Man-Machine Interaction

This is a very specific subject and shall be covered here only by a few remarks. CMI tools, implemented in intelligent machines or system modules will help the human brain to have better ideas, generate better solutions and respond faster in complex dynamic situations.

Life science research will discover new ways to move forward the limits of human mental and related physical capabilities and to model the human brain by brainlike structures implemented in technical constructs, for the interaction of the human with intelligent machines, applying new visualisation techniques (NVT) such as e.g. virtual interface technology [4].

The useware needed for this interaction is of ever increasing importance. Under the notion useware all software and hardware components serving the use of a complex technical system are accomodated.

There is a need for human centered control concepts, which is a challenge for both engineers and cognitive scientists. Within this context work is required in two main areas:

- Direct interfacial mechanisms to improve modes of interaction, e.g. speech.
- Overall system design to make the system/machine more like a human, i.e. accepting high level instructions and understanding operators needs and intentions.

Intelligent useware should give the human operator so much control as he or she wants and can use, and intelligently fill in the remaining required functions. Software/hard-ware that can think and learn will be part of it to e.g. analyse the behavior of the operator and account for it when generating recom-mended interactions.

4 CONCLUSIONS

The concepts described in this paper represent a step towards distributed intelligence with cooperative behavior in airborne air defense systems requiring enabling technologies and techniques available today. A more future oriented approach based on a so called holonic system with subsumption (behavioristic) architecture is dealt with in [2].

The knowledge-based intelligent subsystems or modules as treated here offer learning capability. They are not only programmed in the conventional way. Starting from initial knowledge the CMI elements evolve by learning from experience and thus improving automatically. Like practice in engineering it is an indispensable prerequisite, that systems with the said new functionalities and features as described here must be designed, built, trained and utilized according to an adapted dedicated new strict methodical approach.

Based on a suitable training (learning) strategy the system acquires some of its knowledge during a training phase. Training can be performed applying simulation including virtual reality. Within this context environments can be used that are much more changeable than the real ones. Fig. 7 depicts the use of embedded simulation [4] to support a variety of applications as well as situations and incorporating both real and simulated mission (weapon) systems, which are linked together by communication to conduct combat exercises and training.

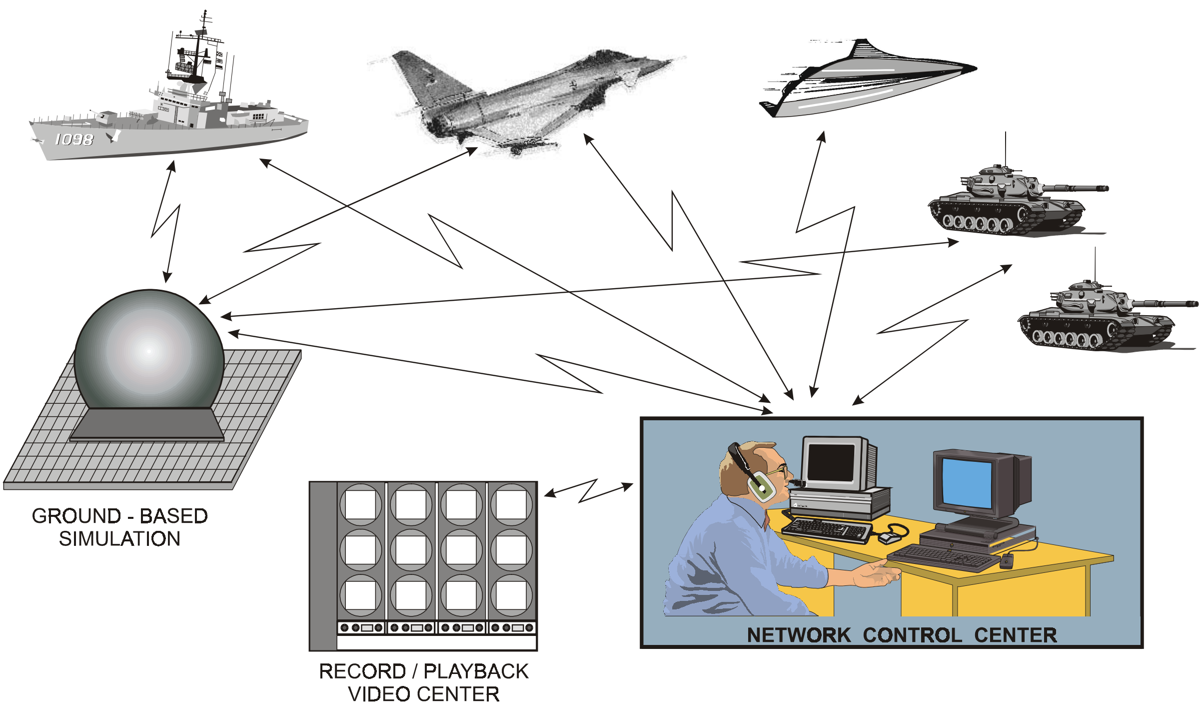

Figure 7: Embedded simulation for training and exercise

Of course, also ACMI type training is possible utilizing new range-independent air combat training and debriefing systems, such as described in [5].

After completion of training the behavior is assessed with respect to correctness (required behavior), robustness (behavior vis-à-vis changing environment) and adaptiveness. Based on this assessment, further iterations during the engineering steps might become necessary in order to make the satisfactorily behaving system evolve from them on a step by step basis.

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Requirements Capture and Analysis for a Decision-Aiding Application

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Summary: This paper is about human factors integration, and providing information displays to match the operators' requirements. It addresses Man-Machine Interfaces and visualisation techniques. It will describe a method of requirements capture that translated into highly acceptable and very effective information displays.

Background: The main background to this analysis methodology comes from two projects that have been conducted at DERA Malvern. Both projects were about developing a decision-support system. The task for which this system was required involved detecting threats, identifying their nature, tracking them and predicting their implications and the hazards they posed. The decision then concerned what resources to assign against the threat, and when. This required information about what resources were available and against what they might be allocated.

The Human Computer Interface (HCI) implementation for one system was strongly legacy-system based, with well-established functionality that simply had to be re-implemented with new technology, refining an existing task. The other, new application had a well defined purpose, but no functionality defined at the outset, and required development from nothing.

The decision-support requirement: Both of these projects were essentially about providing decision-support. For the newer Athena project this focused on the weapon allocator's rôle. The weapon allocator's task is to decide what response is required and to select the counter-weapons from those available. The decision-support system provides the overall tactical picture on a graphical map display, showing the options and intercept progress on an associated display. This provides the necessary information to select a weapon, displays the information reported back on engagement status, and enables subsequent shots to be scheduled and taken. The interface provides the facility for the allocator to transmit the weapon-firing request to the weapon controller.

The prototyping philosophy for this project, exploited a skeleton set of phases and modes of command and control against which to assess an offered solution for acceptability.

The legacy system: This was a capability maintenance project for equipment that required replacement — with the emphasis on exploiting commercially available technology. From a survey of what new technology could offer, coupled with a review of existing standards, a set of Guidelines was produced for implementing the replacement system, validated by prototype demonstrations and implementations for operational service.

Their aim was to aid the production of HCIs with effective handling and display of computer generated information. These included displays of graphical and tabular information, graded according to urgency,

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enhanced by symbology and colour, and supplemented by other media. The Guidelines also contain further information that impacts on HCI design, for example:

- operator rôle and target audience descriptions;
- impact beyond the work-station, *e.g.* the console design or control room layout;
- particular implementations identified as generic components, *e.g.* communications control panels; or
- particular implementations for specific operator rôles.

Two factors drove their further development. Whilst the existing Guidelines, for the most part, addressed a specific problem, it was fortunately one that comprehended whole control rooms. This meant they could be applied to other systems as a default solution with particular differences resolved by exception. There were several such applications for which the Guidelines were perceived to be relevant. To be able to mandate the Guidelines for future procurements, they would have to be interpreted for each new application. This in turn demanded a requirements capture and HCI assessment methodology to do this. The “greenfield site” Athena project provided the basis for the answer.

The Athena (greenfield) system: The Athena project began with no such functionality constraints. The objective was to build a Command and Control (C2) demonstrator for a decision-aiding system for anti-ballistic missile weapon allocation and control. The threat was well enough definable, but had not been translated into functional requirements: the tasks to support those functions were completely undefined. The Athena HCI Assessment Suite was evolved to provide the necessary requirements capture methodology for this project and to develop the highly useable, internationally demonstrated interfaces. Subsequently, the opportunity arose to develop this requirements-capture and HCI-assessment methodology and harness it to the Guidelines for how to use the technology derived from the legacy system project, in order to exploit the synergy and produce a generic HCI-analysis-and-design package.

The Guidelines comprise the following components:

1. Guidelines for the Guidelines (why and how they should be used);
2. generic core guidelines;
3. annexes and case studies;
4. assessment methodology.

It has been said that Command and Control is the glue that holds a system together — a system being defined as collection of separate components that are connected together. These cover aspects of the operator rôle (*e.g.* receiving briefing, detecting targets, prosecuting targets and reviewing task success) that are affected by the system context and, conversely, aspects of how the operator contributes to the specific functioning of the equipment through the generic tasks of direction, control, monitoring and appreciating the situation.

Figure 1 illustrates some of the component tasks required by such operator rôles. Here, performance information is derived from performing the task — from the attempts to perform the required functions. Not all performance information is relevant. The reporting criteria represent the questions while the reports represent the assessment results about interference with other ongoing plans. These intentions may be encapsulated in a user guide, which describe what the system is supposed to do.

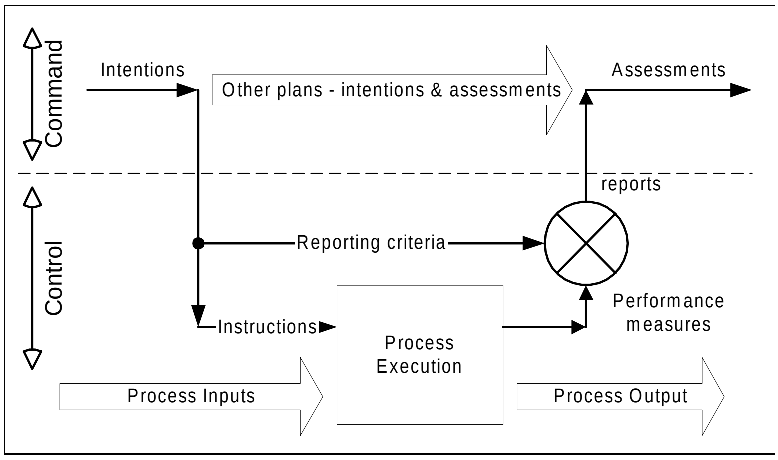

Figure 1. Elements of command and control

The point to develop here is that there are a number of generic human contributions to a command and control system by which the command node occupied by an operator rôle may be analysed. These generic command nodes or operator rôles are:

- command (and planning);
- communications (information exchange and status reporting);
- navigation and piloting;
- tactical situational awareness;
- system operation;
- system monitoring (alarms, alerts and warnings);
- operational co-ordination.

These operator rôles or command nodes then become the components that are held together by the command and control system. There is primary command requiring general situational awareness and planning of operations. There are communications with outside parties, both receiving information and transmitting. There are surveillance and watchkeeping tasks with tactical situational awareness. There is the notion of navigating, which may be position-plotting, course setting or directing the plan of execution. There is system or equipment operation. There is system monitoring with the associated alarms, warnings and alerts. There is the need to support internal co-ordination. All of these are aspects of the operator rôles that define the functional requirement for the work place and workstations. These must be designed to accommodate the potential operators who will perform their rôle or rôles there.

Principal system functions

The following are the principal system functions for applications with which a typical C2 system must integrate, both in terms of sources of command and items for control (see Steinhausen et al, 1978):

- command and communications, *e.g.* radio
- prime task integration, *e.g.* gun, missile launchers
- manoeuvring and transportation, *e.g.* tractors and trailers
- environmental defence, *e.g.* weather protection
- common support, *e.g.* power supply
- life support and habitability, *e.g.* clean air
- system monitoring, maintenance and repair, *e.g.* food, sleep

These are imbedding dimensions that are both mission and system related. This is because the system (and its operator interactions) must be justified by its mission purpose — there must be a reason for why it is there. Equally, by continuing to ask the question ‘How?’ — ‘rolling in’ — the answers, which define what the system must support, will fall naturally into these categories.

For instance, these principal system functions provide categories for analysing system failure effects and their impact. The design implications are then to determine what can be done to defend against such failures by preventive or corrective measures, and to assess the importance of doing so. Thus, these “system functions” provide a basis for analysing the “total system” requirements for operator interactions, both in terms of their environment and the systems they control. They can be analysed according to how the command and control system will orchestrate the concerted operation of what has to be done (jobs, tasks and functions) by their constituent components (people, missions and technology) in order to achieve the required purpose of the whole organisation.

The design process

The philosophy of the system evolution process must take into account two components: the abstract and the real system implementation. The design process for a workstation or console is naturally iterative between these two aspects, if only because at the outset the user does not know what is technically feasible, nor does the technologist know what the user might require if he knew what could be provided. As far as a system manufacturer is concerned, the human contribution to its operation is firmly in the abstract realm — just as much as, say, integrated-circuit design or software code is beyond the real world of those who use the equipment. However, from a total system perspective, there is some overlap between these two, where the human comes into contact with the equipment – the so-called “man/machine interface”. On one side of this contact area, the system must be integrated (the HCI); the human must adjust to the situation (the Human System Interface (HSI)) on the other. These different interests and their implications for integrating Human Factors into HCI design are described elsewhere (see Smalley (1997)).

At this point it will be helpful to distinguish between super-systems that contain everything that is subject to design, and sub-systems with respect to the HCI system design. The super-system is the context which drives the requirement (and is itself driven by its invariant hyper-system — the system in its most extended form, which provides the fixed context for the whole system implementation), whilst sub-systems contain the sets of co-ordinated elements for performing the tasks. This gives the following five-layered model:

1. hyper-system;
2. super-system;
3. system;
4. sub-system;
5. component elements.

The hyper system, super system and system levels relate to the abstracted environment; the system, sub-system and system elements relate to the real components.

In terms of implementation, this translates into three levels of interest, working outwards from the technology behind the hardware (levels 5, 4 and 3), to the operator at the console or workstation design (levels 4, 3 and 2) and then the operational context of the user, which is bounded by the control room (levles 3, 2 and 1). The prototyping process then allowed the system design to be drawn out, using a skeleton set of task phases and modes of command and control to draw out the required system operations and to assess the design concept for acceptability.

The Athena design evolution used an iterative process of designing a little and building a little, then running an operator-assessment trial to ensure that, with each step, the evolving design remained on course towards the end design. Thus each instance provided the stimulation to determine the way forward and take the system design from abstract concept to tangible execution.

Figure 2 depicts the iterative nature of the system design process for human interaction at any particular level of hyper-system and sub-system. Here, the console issues pivot between the hyper-system beyond the control room and the sub-systems of console components — between requirements set by the super-system and specification of sub-system components. This describes five major phases in this process: primary requirements capture (1-2), derivation of constraints and secondary requirements (2-3-4 and 8-4), feasibility checking (4-5), implications for host organisation (criteria of acceptability: 5-6-7) and design specification (7-8) leading to requirement definition for next level of detail.

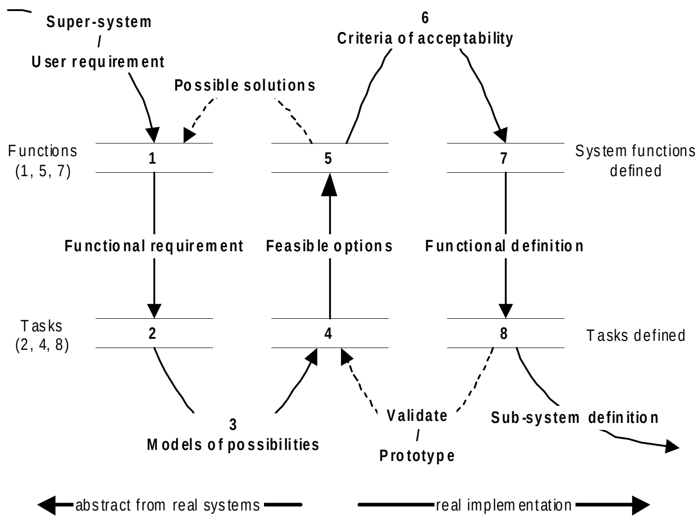

Figure 2. Analysis and design iteration

The draft system requirement and criteria are determined at (1). This is the requirement identified at the super-system level to fulfil the task, concentrating on the functional requirement.

The component functions (I/O signals) are drafted at (2). This translates the functional requirement into a functional specification at the component level.

Derivation of constraints and requirements: Model implications are derived at (3). This prototypes the subsystem by whatever models or simulations are appropriate for the purpose of representing it — in order to produce the information which will enable discrimination between alternative options for final implementation.

Feasibility checking: The feasibility that the system will work, as a function of its component behaviours, is assessed at (4). This concerns whether the components will live together compatibly. The check on system implications at (5) concerns whether the output of the subsystem is compatible with the requirement imposed by the super-system.

Implications for host organisation: It is necessary to agree or confirm the system interface at (6). Once satisfied that the super-system requirements can be met by the proposed system design, this is confirmed, so that the super-system can be reconfigured to receive the new system and its sub-systems.

Specify design: The system design stage entails refining the component options and specifying the system when down to one option at (7). If any options remain at (8), then iterate from (3) with model implications, determining feasibility, *etc*.

Command structures and decision nodes

Since the design process is in itself a decision process analogous to command and control, it should be possible to map across to a generic command and control structure.

There are two types of command and control: one has the command structure embedded in the system components, and is therefore real to the controlled system. For the other type, the command system is hosted by a separate entity (for example the people in an organisation) from the controlled system to which it is connected by formal, specifiable and configurable links or communication channels, and is therefore abstracted from the real system.

Figure 3 is an information flow diagram that illustrates some important aspects of the system of controlled functions that link the generic command nodes identified earlier. This shows the whole process running from primary situational awareness at the top left to internal system co-ordination at the bottom right.

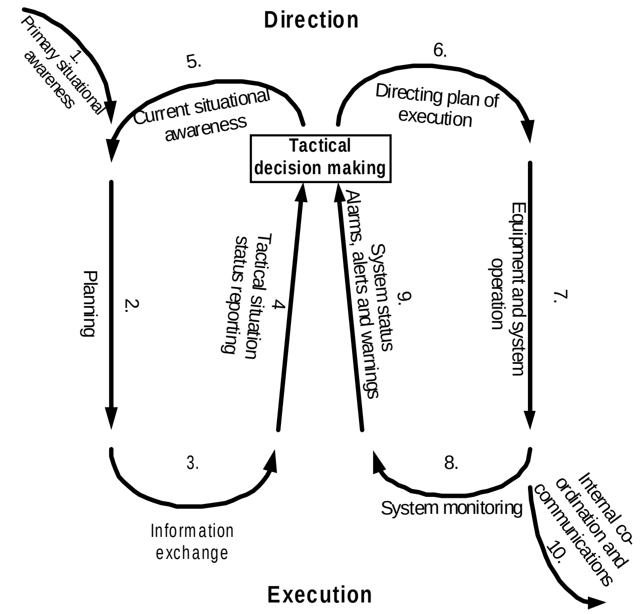

Figure 3. The C2 modes for tactical decision making

The left half of this diagram is concerned with the driving influences of the outside world. In the field, these are appreciated by commanders: they are analysed to generate the operational and functional requirement for the system. The right half is concerned with the system under control (whether for real or as a technical specification). The upper half is concerned with command and direction: the lower half is concerned with the execution and implementation of the system purpose. The flow lines in this diagram represent or provide for either of two processes:

1. the thinking processes or modes of using the information in a command and control system;
2. the sequence for analysing, designing and implementing a system.

These C2 modes (as opposed to the nodes described earlier) are as follows.

1. **Primary situational awareness** is concerned with answering **why** is this system here and doing what it is doing. It is concerned with collecting all the information that focuses on this answer.
2. **Planning** is concerned with taking in the current state of the mission field and determining what aims to drive for. This combines the why of primary situational awareness with the where of current situational awareness as the basis for deciding what the future targets should be and how to get there.
3. **Information exchange** is about **who** the other players are, what they might be doing and what their intentions might be.
4. **Status reporting** is about the end-point status of the mission field and players.

5. **Current situational awareness** is about maintaining awareness of the immediate state of the mission field — locating **where** specifically items are. This information merges with the primary situational awareness to drive the planning process (C2 mode 2) whose output may then drive the information exchange with other players and comes out with the status plotting and reporting of mode 4.
6. **Directing plan of execution** is concerned with **when** events are to happen, cued by the status of the mission field and conditioned by the state of the available technology.
7. **Equipment and system operation** is concerned with the hands-on operation in response to the directions from mode 6. This mode concerns the specific protocols, sequences of operation and the dynamics of control or perception required to control the equipment.
8. **System monitoring** concerns the process of maintaining general awareness of system performance and capability, of what reserves are left and of approaching decision points, danger areas *etc.* — in order to sustain the intended programme of action.
9. **Alarms, alerts and warnings** concern the feedback of system status information which might change the ongoing plan of execution.
10. **The internal co-ordination and communication** mode is about the internal comms system for liasing with other systems under control, for re-configuring the system, re-loading new software, stage changes, etc. This mode concerns the command of **how** the system is configured to achieve the desired results.

As the project progressed, and the HCI concepts evolved, it became possible to translate the skeleton command and control structure and decision-making requirements into the specific tasks, shaped by the particular implementations and applications. In other words, the analysis began with the generic man-centred task and then added the implications from the mission context and the technology available. This led to the specification of the system requirement. This also allowed variations in scenarios and the state of the operator to be taken into account.

The rating methodology

A progression of assessments was developed so that each provided relevant training or briefing for the higher-level assessments and requirements capture to follow. These comprise the Athena HCI Assessment Suite (see Smalley, 1998).

There are two sides to rating the HSI for decisions. These are the consequences in terms of the importance to the task. The other is in terms of the quality of the equipment interface provided to support the decision.

The Cooper-Harper rating method: At the heart of the assessment methodology is a modification of the well-established Cooper-Harper rating scale. This provides the thinking tool to take a particular task and assess the utility of the equipment offered to support that task. The ratings range on a ten point scale from something like fatal consequences to certain and effortless success.

The original Cooper Harper scale, was developed for aircraft handling assessment — it was developed by George E Cooper of the Ames Research Center, Moffett Field, California, and Robert P Harper Jr of Cornell Aeronautical Lab Buffalo, New York. Essentially, their rating method provides an algorithm for the operator to answer questions about the function under assessment until reaching a score, which is the assessment rating. The rating is obtained through three dichotomous decisions about the equipment under test for the task:

1. controllable/uncontrollable;
2. acceptable/unacceptable; and
3. satisfactory/unsatisfactory.

This is followed by a progressive refinement of the assessment. At no point is the required discrimination more complex than a good, bad or indifferent rating, and the resulting scores may be interpreted according to the table shown in **Figure 4**.

Score	Acceptability	Applicability
1-3	Satisfactory	Normal use
4-6	Unsatisfactory	Emergency use
7-9	Unacceptable	No operation
10	Fatal/uncontrollable	

Figure 4. Interpreting the Cooper-Harper scores

In summary, the C-H assessment technique provides a formal operability rating of the interface, in a way that is useful to the development of the interface and decision aiding equipment. This technique does not measure how well the operator can do, but produces a rating that can be translated into specific sentences about whether specific tasks can be routinely performed to specific degrees, i.e. it is a rating of the interface, using the operator as a measure.

These ratings were useful for two purposes: to check the completeness of the requirement capture, and to prioritise where development effort should be applied by producing a "maturity profile" to give an indication of how much further development effort might be required. This is important to indicate how far down the line an acceptable solution may lie.

Maturity of concept and design: We discovered that diverse ratings reflected unclear definitions of the task's purpose. Hence the tool could be used to focus attention on where clarification was needed from the expert users. Once the task was clearly defined (as a user guide for instance) a remarkable consistency of scoring was achieved. (See also Harris *et al*, 1998).

Analysing the rating: Whilst the C-H assessment gives a rating which relates directly to the importance of improving a function for operational purposes, it does not specify the nature of the improvement which might be needed. The important point here is that the C-H rating concept was extended to capture the reasons for the imperfection by asking for comments to defend the rating applied, locating where the specific difficulties occurred in the successive stages of making the decision — see **Figure 5**.

	Task	Psychophysical issue
1.	Monitor and detect	(signal detection)
2.	Identify and classify	(perception)
3.	Associate and correlate	(interpretation)
4.	Connection of meaning and decision taking	(execution)
5.	Response and action	(action)

Figure 5. Stages in making a decision

There is not time or space to pursue this in detail here. Suffice it to say that, for any decision-making function, the HCI could be rated for all its phases of operation for each of the different modes of command and control. Ratings and comments could then be merged and consolidated requirements could be obtained. This gave a clear indication of what needed to be done to move the design towards perfection — or at least a rating of 1-3.

Conclusion

In conclusion, the methodology that evolved has provided the basis for a generic C2 requirements capture and analysis tool, which has been refined and included for use with the HCI Guidelines developed at Malvern for future military airspace management systems.

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Panel Perspectives on Existing and Future System Concepts – Mission Management and Interoperability

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1 INTRODUCTION

The presentation is meant as an introduction to the Symposium Session on Interoperability in the context of Integrated Systems-of-Systems. It describes concepts, theories and paradigms which are discussed by the SCI Panel, or which are relevant for its future work. These perspectives touch two of the five Areas of Interest of the SCI Panel, which are described in Figure 1.

AREA OF INTEREST OF THE SCI PANEL:

"Integrated Mission Systems and their Operation"

Integrated Mission Systems

- Integrated Precision Strike Systems
- **Integrated Air Defence Systems**
- Peace Support Systems
- Integrated NATO Counter Proliferation Systems
- Integrated Special Operations Systems

Mission Management

- Situation Assessment
- Joint Mission Planning
- Command and Control
- Traffic Control

Figure 1

Integrated Mission Systems, which are the subject of this Symposium, are an example of Integrated Mission Systems. All RTO Panels are elements of a process in which concepts for improved military capabilities of NATO are generated, evaluated and finally realized. Figure 2 illustrates this process.

Paper presented at the RTO SCI Symposium on "System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces", held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

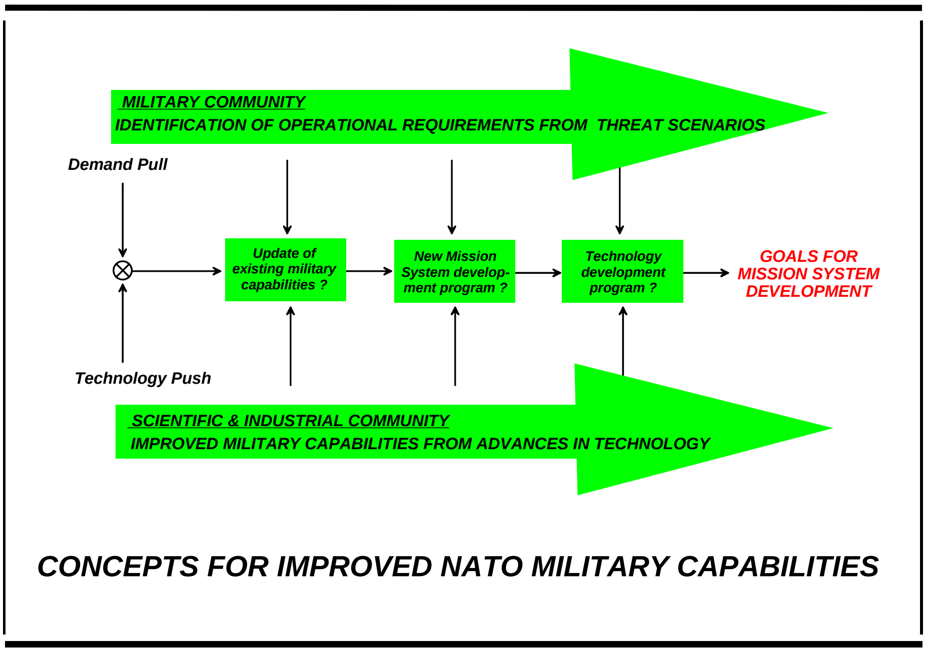


Figure 2

In this process, the Military Community normally identifies the operational requirements for new or improved weapon systems from emerging threat scenarios (demand pull). The Scientific and Industrial Community produces advances in technology, from which improved military capabilities can be derived (technology push). Interactions of both communities produce updates in existing military capabilities, new mission system development programs, or technology development programs. In the case of the SCI Panel, this takes the form of setting *goals* for Mission System development programs and for the corresponding technologies.

2 MISSION SYSTEMS AS MAN-MACHINE-SYSTEMS

The structure of Integrated Mission Systems is illustrated in Figure 3. This Figure is taken from the NATO/AGARD Aerospace 2020 Strudy (Vol 2) [1].

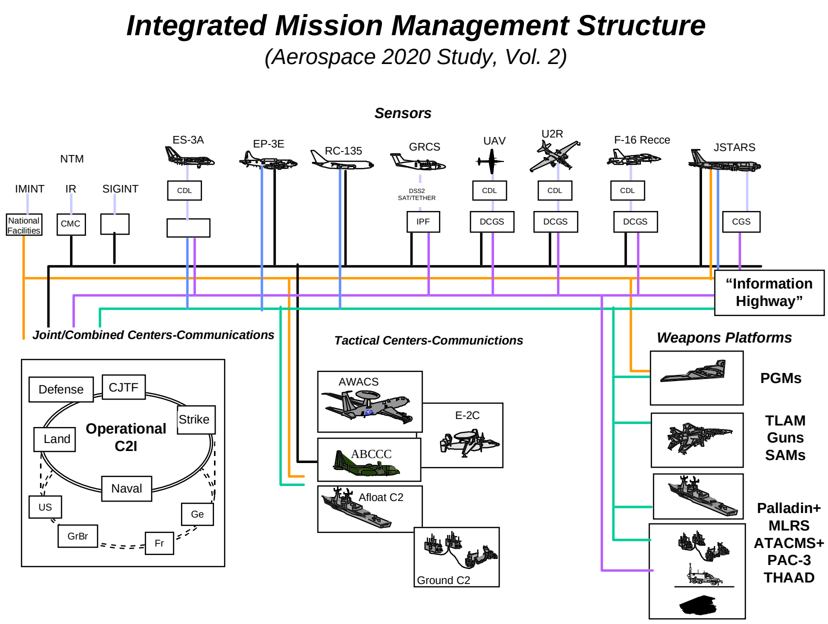


Figure 3

Sensor systems, Joint/Combined and Tactical Command&Control Centers, and Weapon Systems are tied together through powerful communication systems ("Information Highways"). This illustration shows the elements of an Integrated Mission System (*declarative system representation*), but hides the fact, that the system is operated and directed by Human Operators (commanders, operators, soldiers, etc.). In fact, Integrated Mission Systems are complex Man-Machine-Systems, and the understanding of their operations requires knowledge about such systems. Man-Machine-Systems are driven by *goals*. To illustrate this fact, we consider the Life Cycle of such a system, in Figure 4.

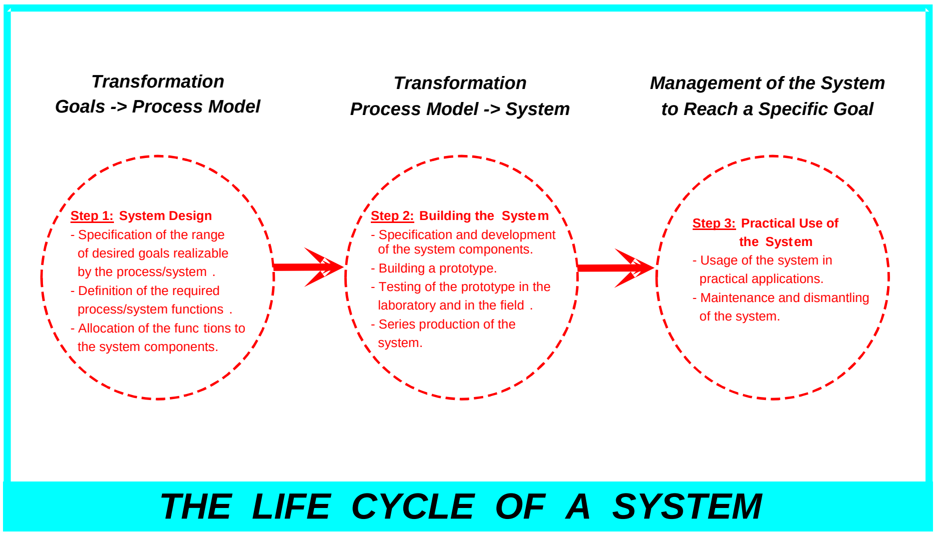


Figure 4

After the definition of *goals* for a Mission System development program (see Figure 2), these goals have to be transformed into a Process Model with the corresponding Functions and System Components (First step: System Design). In a subsequent second step, the system components are developed, a prototype is built, tested and possibly a series production is started (Building the system). In a third step the system is used to reach specific goals in practical applications. This is the phase of the Life Cycle where concepts of Mission Management and Operability have to be considered in more detail. The Figure 5 illustrates the Paradigm for Mission Management, and will lead us to the important aspects of automation.

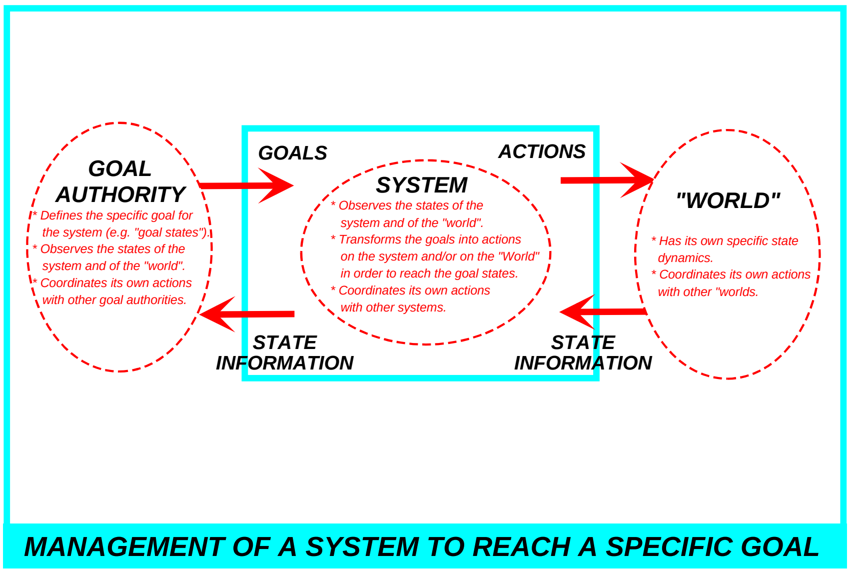


Figure 5

The Mission System is employed to reach a specific military goal. This goal is defined by the „Goal Authority“, which can be a Command&Control Center, or the Supreme Military Command, or a Political Authority. The system transforms the goal into the appropriate actions towards the “World”, which is the area where the goal shall be reached. The world can be a hostile area, or a crisis region, etc. Sensors will produce information about the state of this world and feed it back to the system, and also to the goal authority, where it can be compared with the desired state of the world so that subsequent steps can be defined. This process has the form of a network of control loops. We call it the *procedural representation* of the Mission System, because it explains how the system operates. In addition to the control loops, a coordination function is important to harmonize the control actions in the loops with other parts of the military system.

It has already been mentioned that Integrated Mission Systems are complex Man-Machine-Systems which are driven by human operators to reach specific goals. This leads us to the question how human operators do their job. Figure 6 shows the basic “Recognize-Act-Cycle” of human goal-oriented behavior. This is also called the “Observation-Orientation-Decision-Action (OODA)” Cycle.

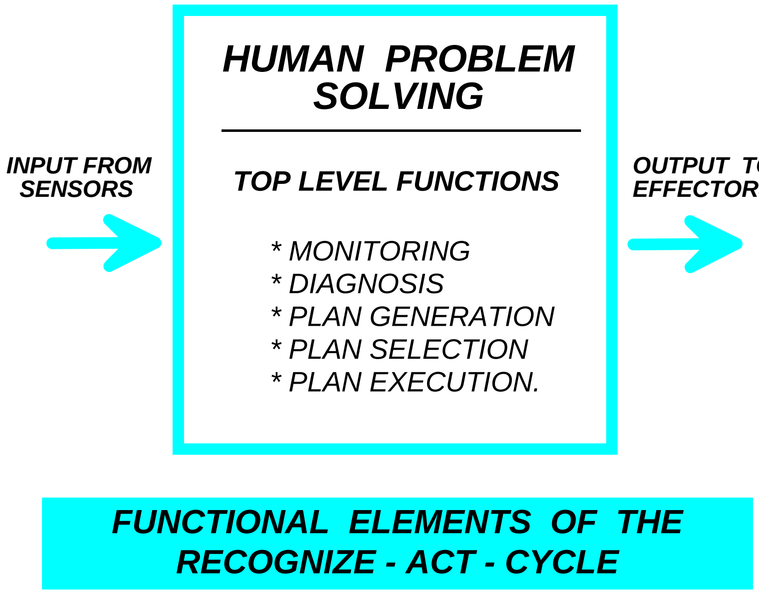
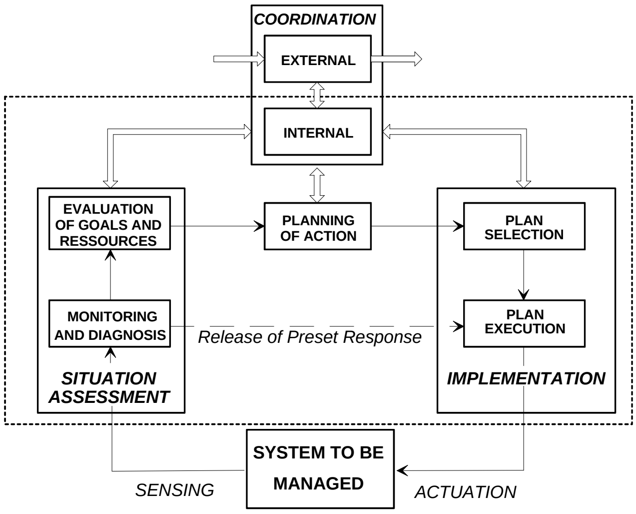


Figure 6

Human operators transform sensor inputs into effector outputs by performing a sequence of Mental Functions (Monitoring, Diagnosis, Plan Generation, Plan Selection and Plan Execution) in order to ovecome problems in reaching the desired goal.

3 MISSION MANAGEMENT AND INTEROPERATION

In Figure 5 we have discussed the Mission Management function, which is needed in order to reach the desired goal with the help of the system. The architecture of this Mission Management function - together with the elements of the Recognize-Act-Cycle in Figure 6 - have been studied in detail in Ref. [2]. This architecture is shown in Figure 7.

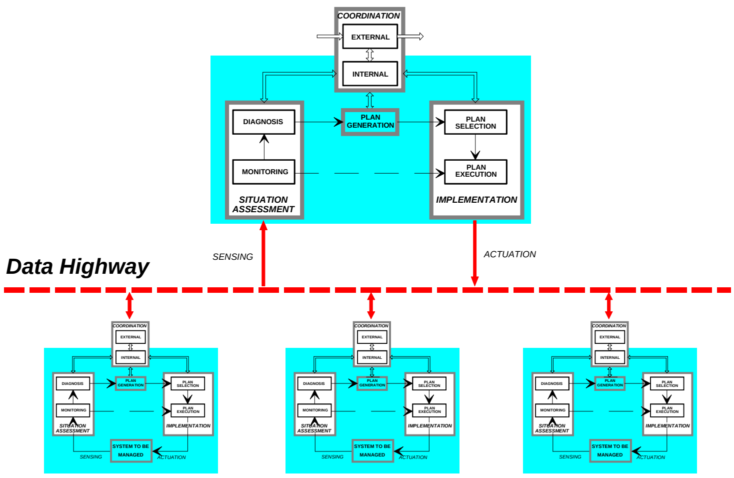


STRUCTURE OF MANAGEMENT FUNCTIONS

Figure 7

The block diagram describes the functional loop in Figure 5 with more details: An assessment of the present situation decides, whether a continuation of the Preset Response can take place, or if a new evaluation of the goals and of the available resources must be made. This evaluation generates possible plans for actions to change the situation in the desired direction, before a new plan can be selected to replace the preset response. This Mission Management function drives the system to the desired goal, independent of the fact if a human operator, or an automatic control system, or both carry out the described functions. A major goal of the automation of these functions in military mission management systems is the reduction of the Cycle Times (time constants) of the control loops involved. An other important functional element of this architecture of Mission Management is the Coordination Function. It controls the sequence of internal actions, and coordinates the actions of the loop with other (external) loops or systems. The lay-out of the coordination loop is the key to proper interoperation.

Integrated military mission systems (so-called Systems-of-Systems)- as considered in Figure 3 - contain a multitude of such elementary mission management loops in a well defined architecture. Figure 8 demonstrates, how such architectures can be constructed by proper coupling of elementary loops, using the coordination function.



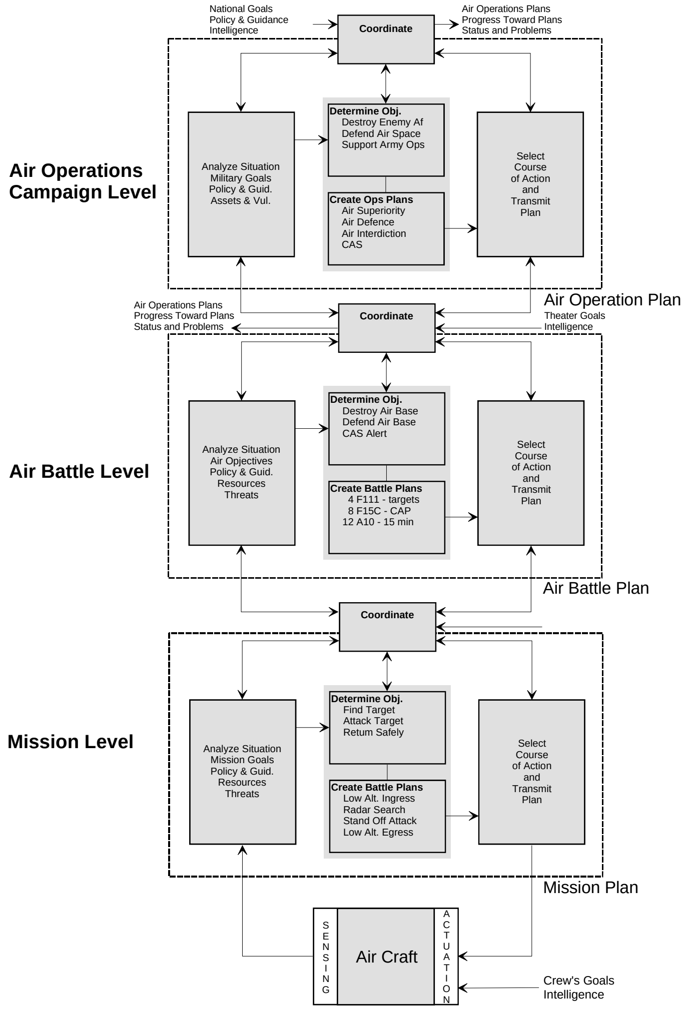
HIERARCHICAL COUPLING OF INTEGRATED MILITARY MISSION SYSTEMS

Figure 8

The example in this Figure shows a combination of a command mode (upper system) and a cooperative mode (lower three systems).

4 AIR DEFENCE OPERATIONS AND AUTOMATION

In Ref. [2] the ideas described in the previous chapter have been applied, to model Air Operations of the US Air Force as a multi-loop man-machine-system, presented in Figure 10.



EXAMPLE: PROCESS MODEL OF AIR OPERATIONS

See: AGARD-AR-325: *Knowledge-Based Guidance and Control Functions*. AGARD, January 1995.

Figure 10

The Figure shows only the control structure for one aircraft. In such multi-loop and multi-level systems-of-systems, cycle times (time constants of the involved control loops) typically range from one hour to two days (Figure 11), in present “manual” operations. It is expected that the introduction of automation can make these loops much faster.

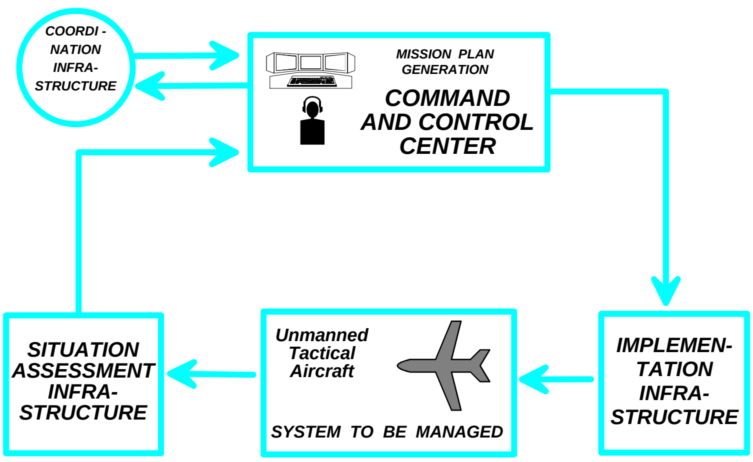
COMMAND & CONTROL LOOPS

Unit or Weapon System Level	*(< 1 h)*
Force Level	*(< 4 h)*
Component Level	*(< 24 h)*
Theater/Joint Force Level	*(< 48 h)*

TIME CONSTANTS OF THE COMMAND AND CONTROL LOOPS

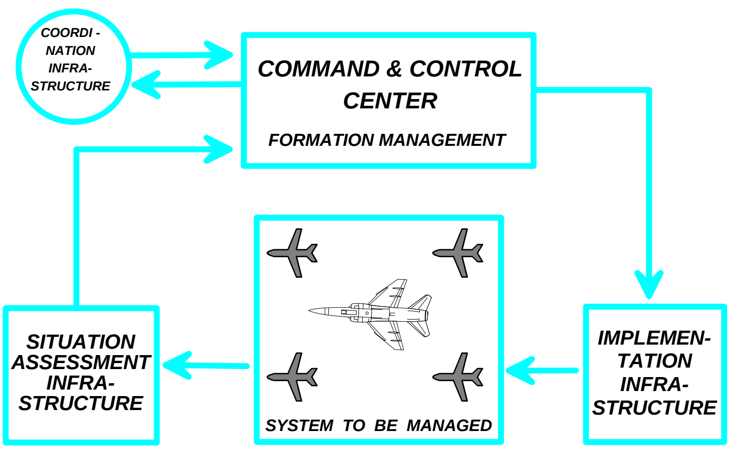
Figure 11

The following three Figures show examples for the integrated management of an Unmanned Tactical Aircraft mission, for the management of manned/unmanned flight operations, and for integrated management of the battlefield.



MISSION SYSTEM: ***UTA MISSION MANAGEMENT***

Figure 12



MANAGEMENT OF MIXED MANNED/UNMANNED MISSIONS

Figure 13

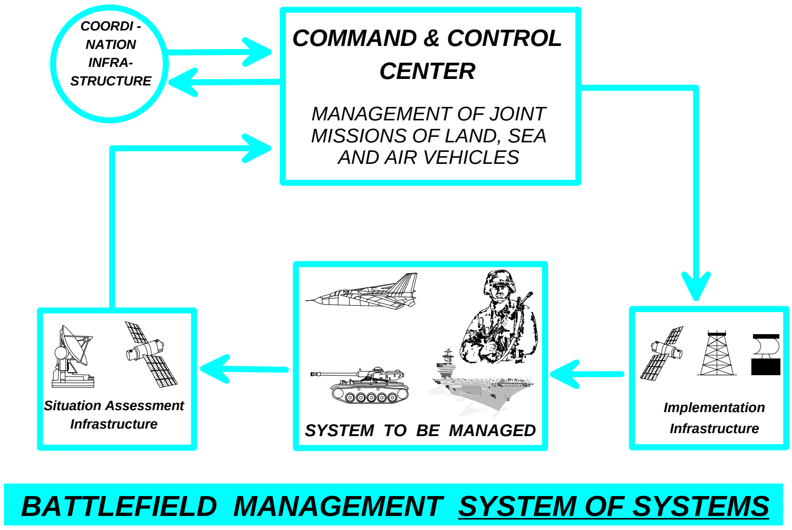


Figure 14

The important features of these loops are an integrated command&control function, integrated infrastructures for the implementation of the control operations, and for the situation assessment functions. The coordination of the actions of these management loops with other parts of the military system is performed through integrated coordination infrastructures.

5 PERSPECTIVES

It is expected that in the coming decades Total System Concepts similar to the one described in this presentation will be developed for Systems-of-Systems, like Integrated Air Defence Systems for multinational mobile crisis reaction forces, discussed in this Symposium. There are fundamentally two ways of introduction of such integrated architectures:

- To start with the realization of a Total System Concept from the beginning of the life cycle, and than to replace the existing systems by the new one.
- To transition stepwise from the presently existing multinational systems in a coordinated approach to the Total System Concept.

Experience shows that the second approach probably is the only way of introduction of the ideas of an integrated architecture for systems-of-systems. This will require agreement on the use of joint interfaces, architectures and the reduction of disparity of the equipment. Modularity of functions/subsystems and specialisation of the coalition partners on certain functions/elements would reduce the required effort for the transition to the integrated architecture.

The introduction of automation into this architecture is an important factor, in order to reduce the cycle times, and to realize more real-time flexibility in the command&control process.

The transition process should also be used to harmonize the infrastructures of the partners stepwise, in order to come to the required integrated infrastructures for control implementation, situation assessment and for the coordination function.

The stepwise transition to the integrated architecture is also a natural and flexible way of introduction of the technical basis for interoperability of the multinational forces.

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Tactical Data Links and Interoperability, The Glue between Systems

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ABSTRACT

In this time of open system architectures, systems of various makes and origin co-operate, pass, and share pieces of information. The pieces of information, thus exchanged, should trigger the same understanding by all users. Ambiguities in the translation, presentation, or interpretation of the data and information may be the cause of serious problems. This paper addresses some of the aspects of interoperability and describes ways of achieving, monitoring, and maintaining inter-operability in particular for tactical datalinks such as Link 11 and Link16. Emphasis is given to tactical data link interoperability with the NATO E-3A.

KEYWORDS

Interoperability, Tactical Data Links, NATO Standards Agreements, STANAGs.

1 INTRODUCTION

Military systems don't operate in isolation. There is a strong requirement, even a mandate, to be interoperable with other military systems or civil systems. Interoperability can be defined as the ability of systems to provide services to and accept services from other systems and to use the services so exchanged to enable them to operate effectively together [AAP-6].

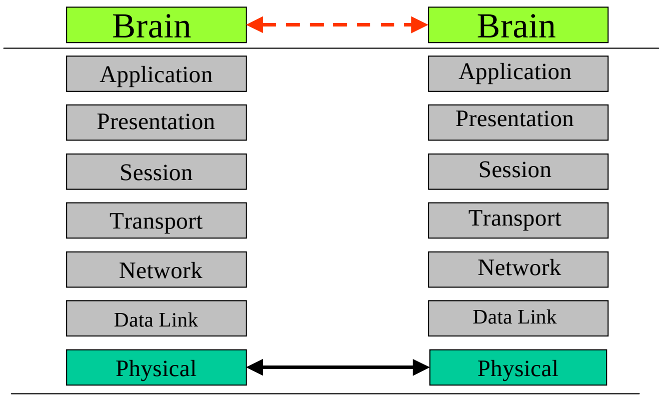
Interoperability is the glue that keeps operators, systems, units and forces and operations together. Interoperability does not depend on hardware, software and crew proficiency alone but must be supported by adequate operational procedures and training.

In this paper we describe various ways to describe interoperability and methods to achieve interoperability in the sense defined above. We will start in paragraph 2 of this paper with an extension of the well-known OSI (International Standards Organisation) 7-layers model. In paragraph 3, the formal agreements and procedures to achieve interoperability on tactical datalinks within NATO are addressed. In paragraph 4 we describe ways to achieve, monitor and maintain interoperability. In paragraph 5 the NATO Interoperability Environment Testing Infrastructure (NIETI) is described. In paragraph 6 we describe the plans for future work at NC3A and in 7 we focus on one particular aspect of these plans. Paragraph 8 addresses the management of tactical data links and finally the paper is summarised in paragraph 9.

2 EXTENSION OF THE OSI MODEL

We can describe interoperability in the terms of the OSI 7-layers, defining the layers that exchange data with one another.

Paper presented at the RTO SCI Symposium on "System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces", held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.



Extension of the OSI 7 Layers

Physical data exchange takes place at the lowest layer, via data-busses, telephone lines or radio links. The technical exchange, i.e. encryption, error correction etc. and the link management occur in the Data Link and Network layers. The procedural interoperability is performed in the four upper layers. The Transport layer performs the correct exchange of messages with functions such as receipt/compliance. The Session layer takes care of the proper sequencing of the message. The Presentation layer formats the messages. In the Application layer the messages or data are presented to the host and via the Man Machine Interface to the operator. The Brain-to-Brain layer, which represents operator interoperability, is essentially a layer above the Application layer and therefore beyond the OSI 7-layer model.

3 STANAGs, ADatPs AND PRACTICAL INTEROPERABILITY

Most of the lower level technical interoperability requirements for tactical datalinks are defined in Standard NATO Agreements, STANAGs. Mere STANAG compliance is often used as a definition for being interoperable. In practice however, STANAG compliance is just a necessary condition and STANAG compliance alone is not sufficient to guarantee inter-operability. The operational use of systems defined by STANAGS, is described by Allied Data Publications, so-called ADatP’s, defining the applicable operational procedures. In many cases, however, ADatP’s do not follow day to day military practice and lag behind in their description of the actual procedures used. The consequence is that many military systems, which are assumed to be interoperable by design, fail in practice in being fully interoperable amongst themselves or with other systems.

Military systems should also operate on a non-interference basis or be interoperable with civil systems, for example, JTIDS message exchange takes place in the radio-navigational frequency band and is only permitted on a non-interference basis. The JTIDS band will be used by a new GPS frequency and the European Community Project Galileo is also aiming at its share of this frequency band.

Within the NATO Consultation, Command & Control Agency (NC3A), the Air Command and Control Division (ACD) Surveillance Branch looks at the tactical datalinks such as Link16, IJMS and Link11 and the messages exchanged between the various Air Command & Control (C2) components in the NATO Nations.

This has been particularly interesting during the past years for the three new NATO nations, the Czech Republic, Hungary, and Poland. NC3A has played a key role in integrating their national Air C2 systems into the NATO Integrated Air Defense System (NATINADS). After the recent experience in Operation Allied Force, in which SHAPE and SACLANT rented the UK DERA TIM/MIDAS equipment to monitor tactical datalinks, it has become clear that such on-line monitoring of multi-tactical data links is an operational requirement.

4 ACHIEVING INTEROPERABILITY

Assume for the moment that we have systems, which are STANAG compliant, and where the ADatP's, to the best of our knowledge, describe actual operations adequately. Rather than focussing strictly on technical inter-operability, we also focus on the aim of the system. Do we achieve our military goals, or not? If we don't achieve the military goals, we may have an inter-operability problem. In this paragraph several ways to address potential or actual IO problems are reviewed.

4.1 Paper Analysis

The first step to achieve inter-operability is to perform detailed analysis on system implementation, behavior and performance. Analyze the proposed or actual implementation and compare it with the STANAGs, ADatPs and similar systems. Many potential interoperability problems can be caught early during the development phase of the system with this kind of analysis. This approach has been used in the UK and it enables the discovery of potential interoperability problems at an early stage.

4.2 Prototype Testing

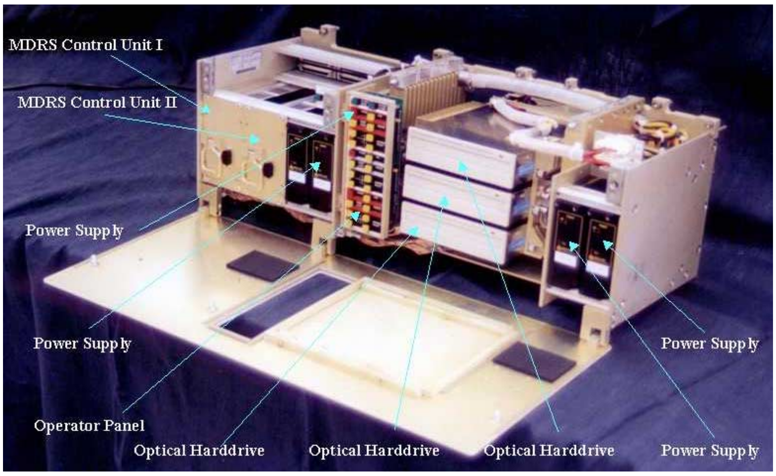
Testing a prototype of a system to verify its functioning against the various systems, with which the actual system might be required to operate, is the next step. Once it is thoroughly tested and verified, such a prototype could be used as a reference system for testing and validation purposes when the actual systems become operational. A problem is however the availability of operational systems against which a prototype can be tested. In many cases this requires specially scheduled flights. NATO has developed an approach to test the functional interoperability of systems via telephone lines using STANAG 5602, the Standard Interface for Multiple Platform Evaluation (SIMPLE). A first successful demonstration of this protocol took place in April 1999 and the next demonstration is planned in April 2000.

4.3 Live IO Problems

It is often necessary to analyze a live interoperability problem. In such a case, we have to trace the whole set of events leading to the problem through all systems involved. This may require data recording at all possible interfaces as well as availability of appropriate data reduction and analysis tools. This seems a sensible statement, but many military systems are not (yet) built in such a way that adequate data monitoring is possible. It adds to system complexity. Although it may be a requirement during development and testing of the system, it is often de-scoped for the final fielded equipment. Some examples of improved recording capabilities for the NATO E-3A are mentioned below.

4.3.1 AORTA Recording

During the recent years, the NATO E-3A community has formulated an urgent requirement for a replacement of the outdated, failure-prone and inefficient 800 BPI Magnetic Tape Transport (MTT)-based Mission Data Recording System (MDRS) in the NATO E-3A, which could not meet the new recording requirements (loss of up to 50% data recording). NAEW Force Command tasked NC3A to develop a replacement MDRS. The new NATO MDRS is a "plug & play" system with a virtually unlimited recording capacity due to the use of magneto-optical media and with a recording speed which is at least 5 times that of the old system. The integration of the NC3A developed MDRS does not entail any system baseline changes. The entire NE-3A fleet was retro-fitted with the new MDRS in fall '99.



AORTA Recording Equipment

4.3.2 Voice Recording

A 10 channel voice-recording and replay prototype was also developed on behalf of NAEW Force Command. This system used the latest technology (MPEG-2, layer 3 perceptive noise shaping techniques) and was successfully demonstrated with a live mission recording.

4.3.3 ESM Data Recording

Special ESM recording equipment, developed by NC3A, was successfully demonstrated in January 2000.

4.3.4 Online Reduction

As a future requirement we see a need for on-line reduction and analysis of all data recorded. Analysis of flight data is currently performed off-line, after the flight and on request. Release of the classified data can take time as well.

4.4 Inter-System Performance Monitoring

The other problem is that online monitoring and reduction of inter-system performance is difficult. It requires special equipment, skills and manpower and is costly. Nevertheless, it is often cost-effective when compared to the risks and investment in an operation or exercise.

Apart from providing military systems with an adequate recording capability, one should have the possibility to simulate system behavior in a controlled environment. This requires a substantial validation of the simulation system to be sure that actual operations are mimicked adequately (here the presence of the validated prototype equipment becomes very useful). Experience to date with the new NATO nations showed that it was necessary to test the data links using prototype systems at NC3A. For instance, the ASTERIX protocol is highly complex and implementations by different systems, in this case EUROCONTROL and the Air Sovereignty Operations Center (ASOC) system were not consistent at the Presentation layer.

At NC3A, a number of testbeds already provide a monitoring and a simulation capability for the integration of the new NATO nations air defense assets into NATINADS. Other equipment, such as the Deployable ERCS Prototype Terminal (DEPT), is easily transportable and is used to support real operations. It could be used to provide the monitoring and analysis support for interoperability assessment as well.

Monitoring interoperability requires adequate recording, reduction and analysis capabilities. For mission critical systems, such as tactical datalinks, the presence of online monitoring facilities is almost a must, certainly in the early phases of their operational usage. Experience between the US and the UK as well as NATO experience with Link16 showed that the presence of a monitoring and analysis capability, which spotted problems, was able to provide adequate solutions or work-arounds in many cases in near real time. The monitoring capability may also be used as a hot stand-by or perhaps even as an initial deployable asset.

The ability to investigate and solve interoperability problems in near real-time and extract data from recorded tactical datalinks was demonstrated when NC3A tested the UK DERA TIM/MIDAS equipment [ACE99] on behalf of the SHAPE Bi-SC Datalink Management and Interoperability Cell (DLMIC) for the first days of exercise Central Enterprise ‘98 at Wilhelmshaven (GE) and when SHAPE rented this equipment to monitor Operation Allied Force from Lecce (It).

Specific systems and tools to perform on-line data analysis in support of interoperability assessment are available from various vendors for different applications. Apart from the TIM/MIDAS equipment, referred to above, other systems are in use and will be evaluated in the near future. A concept of operation for monitoring Link16 operations was recently developed and it is expected that this concept of operation for a Deployable Operational Multi-Link Integration Network Management and Interoperability Evaluation System (DOMINIES) will be endorsed within a short time.

4.5 Training

Complex systems like tactical data links do require adequate training. Too often, the operational community considers the tactical data link terminal as a mere radio and does not put sufficient effort in the proper training and exercising of the tactical data link operators. Inexperience and lack of training are two important causes of interoperability problems.

4.6 Impact Assessment

Once an IO problem is discovered, the operational community has to make an assessment of its impact. This assessment will be the prime driver for prioritizing the solution of the problems or the finding of appropriate work-around. Knowledge of existing IO problems, their impact and possible work-arounds helps to improve interoperability.

5 THE NIETI PROJECT

NATO is investigating approaches to develop a NATO Policy for C3 interoperability. This NATO Policy for C3 interoperability will be executed by means of the NATO IO Management Plan (NIMP) [Vogt99] and a Rolling Inter-operability Plan (RIP). The product will be the NATO Common Inter-operability Standards (NCIS) to be used in the NATO C3 Common Operating Environment (NC3COE). The actual development and testing is planned to be performed by the NATO Interoperability Environment Testing Infrastructure (NIETI) and this body should assume responsibility for NATO-wide C3 interoperability testing using national and NATO organic systems. The NIETI Project Team is investigating the feasibility of this concept and it will report in February 2000. NIETI could perform many of the higher level interoperability test activities. It would provide a focal point for any questions and problems on high-level interoperability. The NIETI could also maintain a NATO-wide database of known IO problems. Many interoperability problems occurring in day to day practice are not easily tested and systems thus require continuous monitoring.

NIETI will rely on national and NATO organic systems. Many of the NATO organic systems exist already, either as prototype or in final form at NC3A, The Hague, and could be used for interoperability testing. A specific example is the Enlargement Air C2 & Surveillance Testbed (EAST) used for RAP and C2 system interoperability testing.

6 FUTURE WORK AND THE WAY AHEAD

The ACD-Surveillance Branch at NC3A performs prototyping and testing of RAP & C2 systems. Many of these systems intercommunicate by means of tactical data links such as Link1, Link11, Link 11B and Link16. The ACD Surveillance laboratory contains many of the C2 systems used within the new nations and acts as a natural focal point for the high-level interoperability testing of tactical datalinks. This requires appropriate terminal equipment, a representative host system and crypto equipment to operate with external systems and testing agencies.

In addition, the Surveillance Branch employs the Deployable ERCS Prototype Terminal (DEPT) a truck-mounted shelter, equipped with a JTIDS Class 1 terminal and a means to process, record and pass the received air-picture to remote users. The DEPT is currently used to support exercises by providing the E-3A derived recognised air-picture (RAP) to ground sites not equipped with JTIDS and it acts as a positional reference for out of area operations of the NATO E-3A.

This DEPT could be the nucleus for a future deployable NATO tactical data link monitoring and test system. To perform this task, it should be equipped with a bilingual Class 2 or a MIDS terminal, with Link 11 equipment and with a STANAG 5602 (SIMPLE) compliant interface. It should contain a host system and MMI able to provide the necessary messages and interaction to stimulate and monitor the datalinks under operation or test. It would be a prototype for the DOMINIES system, which would provide on-line JTIDS net management and monitoring for the resolution of interoperability problems which cannot be foreseen in laboratory testing. The upgraded DEPT would be the operational counterpart to the high-level inter-operability testing performed in laboratories at agencies like NC3A and national facilities. In particular the assessment of the higher layers of interoperability testing, i.e. the human- machine -interface (HMI). The unambiguous interpretation of data link messages at the so-called brain-to-brain level could be tested with such a deployable system in an operational multi-tactical data link environment.

NATO will be operating in a multi-link environment, which will pose special interoperability problems. “Racing” conditions can disrupt the integrity of information in systems employing multiple datalinks, i.e. the same information is received in different formats, at different times and perhaps slightly modified over different data-links. How will it be processed? Who has reporting responsibility? What source should be selected? How do we merge these data? These are just a few of the questions that will require solution.

7 USE OF THE UPGRADED DEPT

The new NATO nations have a requirement to receive the E-3A air picture. Various methods to implement this requirement exist and vary from Receive Only Link11 (ROLE) to a full Link16 implementation. The DEPT would be used to initially demonstrate the capabilities of such implementations. It would also provide adequate means to test and debug an implementation because airborne assets able to provide a NAEW picture are expensive will not be available on a day to day basis as required for testing or implementation. The DEPT will also provide an efficient means to test ACCS sites during the acceptance phase. These sites are in general not within line of sight from one another and therefore have to rely on airborne assets, like the NATO E-3A, to provide Link16 data during their implementation and acceptance testing. Equipment such as the DEPT upgrade will be used to provide the required test inputs to test the ACCS systems. Moreover, due to the on-line analysis and replay capabilities embedded in the DEPT, test results can be made available almost immediately instead of having to wait days or weeks before recordings are reduced and released for comparison. The DEPT is available 24 hours a day and analysis data can be produced almost immediately, correction of interoperability problems of a technical or procedural nature, can be undertaken without undue delay. The schedule risk in implementing tactical datalinks for the Mid-Term upgrade of the NATO E-3A, ACCS or the new NATO nations will be decreased substantially.

The DEPT in operation

8 MANAGING INTEROPERABILITY

The management of interoperability requires preparation well before the operation/exercise and a monitoring and management capability during the operation or exercise.

Preparation depends on specific interoperability requirements and should be performed as much as possible hand in hand with the preparation of the Air Tasking Order (ATO). It could mean that frequency selection and co-ordination has to be performed as in the case of Link11 or that a JTIDS network has to be designed to cater for the individual cross-tell requirements of the participating units. In the case of a JTIDS net consideration has to be given to national frequency constraints, which are imposed on the use of the JTIDS frequencies by various nations.

Live operations require a monitoring and management capability. This monitoring and managing capability can be performed in the current airborne platforms or in ground-based platforms. In the case of problems and their subsequent analysis, a fast reduction of the data-recording is a must. We foresee that online data-reduction and tactical data ink monitoring and management equipment will be part of the next generation of assets.

9 SUMMARY

In this short paper we provided an overview of the methods to achieve and maintain interoperability. We described the paper analysis, which will solve many problems right from the beginning and the follow-on activities such as the development of prototype systems, the use of prototype systems during system implementation and acceptance and the need to manage and monitor interoperability. We provided reference to NATO and NC3A activities in this field.

In this paper, we have shown that interoperability at all levels, including the brain-to-brain level, must be examined and monitored to achieve complete inter-system interoperability. Finally we want to emphasise the fact that interoperability provides the glue between systems.

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Interoperability Modeling of the C4ISR Systems
La modélisation de l'interopérabilité des systèmes de commandement

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Abstract

Nowadays, as soon as a crisis or a small conflict is emerging throughout the world, coalitions of « responsible » nations are formed in order to solve it. The expected finality is to aim for an increased efficiency by coordinating their military means and technical systems. In merging these systems, we have to cope with a major problem, which is to make heterogeneous systems cooperate. This heterogeneity, inherent to national design and applications concepts, generates big deficiencies at the interoperability level. Since the solution of making gangways is not easily and reasonably generalized, the right thing to do is to provide all systems (entering in a coalition) with **interoperability mechanisms.** In this paper, we propose a formal approach which is relying on three main concepts : openness structure of a federation of systems, interoperability space with the definition of an interoperability matrix, intercooperability domain in which we are able to define parameters that allow us to assess interoperability

Résumé

Les nations sont de plus en plus souvent conduites aujourd'hui à former des coalitions, dès que se profilent de par le monde, soit des crises soit des conflits mineurs. Ceci, aux fins d'être plus efficace par la coordination de leurs moyens militaires respectifs et la réunion de leurs systèmes techniques afférents : réseaux, systèmes de commandement. La réunion de ces derniers, dès que l'on cherche à les faire coopérer, pose un difficile problème consécutif à leur hétérogénéité. La solution des passerelles n'est qu'une solution d'attente ne pouvant être raisonnablement généralisée ; aussi, convient-il, de doter ces systèmes de mécanismes d'interopérabilité. Dans cet article on propose une démarche formelle s'appuyant sur trois concepts principaux : structure d'ouverture pour une fédération de systèmes, espace d'interopérabilité et matrice d'interopérabilité, domaine d'intercoopérabilité.

Keywords : interoperability, cooperative systems, distributed systems, knowledge shareability.
***Mots-clés** : interopérabilité, systèmes coopératifs, systèmes distribués, connaissance partageable*

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1 Introduction and motivation

We often observe that more and more nations are often involved in international coalitions to face either crises or emerging minor conflicts. These coalitions are formed for the purpose of increasing efficiency, by the coordinated action of military means and the gathering of their relating technical systems : networks, C4IRS. Their merging generates situations that are at times technically new and complex. The major problem we have to cope with is to make the systems cooperate. In the cooperation's view, most of the time, they are **heterogeneous**; as a result, they present big deficiencies at the interoperability level. One could object that it is always possible, to solve this question by making gangways. In that case, one should be aware of what represents a temporary solution, and what is more, this solution cannot be easily and reasonably in a general use. What seems reasonable is to provide all systems of the coalition with **interoperability mechanisms** in order to obtain (inter)cooperation. We use the term **(inter)cooperate** intentionally to highlight the new

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needs differing completely from the simple exchange messages, as they can arise from the following statements :

- To exchange knowledge, whose the validity depends on time,
- To exchange know-how in operating processes and methods application.
- To contribute to elaborating tasks belonging to dynamic processes.
- To share, in timely and appropriate conditions, useful knowledge for the evolution and the action of other systems of the cooperation.

1.1 Cooperative framework of a coalition

A coalition is put in place to face an unusual situation relative to a crisis or upcoming conflict.

- A coalition aims at a goal in order to make the situation evolve in a way favorable to the partnership's interests.
- Systems put in the coalition are engaged to (inter)cooperate for executing a common mission, which has been established under particular conditions, with temporal constraints. Each system leads adequate actions as required by the mission.

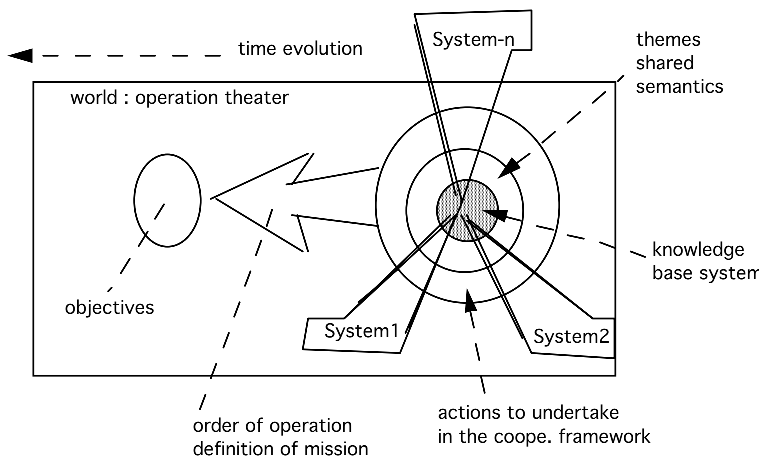


Fig. 1 Coalition framework

1.2 Cooperative system in a coalition

We will call **(inter)cooperative** system, a particular system that owns all criteria defining it as a system, and in addition has certain abilities when it is placed in a coalition framework :

Openness ability :
Quality of a system, previously connected with others, to share a common understanding with them, relative to some themes of a coalition, for instance : ground evacuation, medical assistance. As it will be shown later on, the openness of a system appears to be a subset of the structure openness of the coalition.

Interoperabllity ability :
Capability of a system to (inter)operate with (interoperable) actions, relevant to the cooperation, more precisely orders and missions fixed within the coalition. Characteristics may be attached to it : possibilistic measure, interoperable competence, matrix of interoperability.

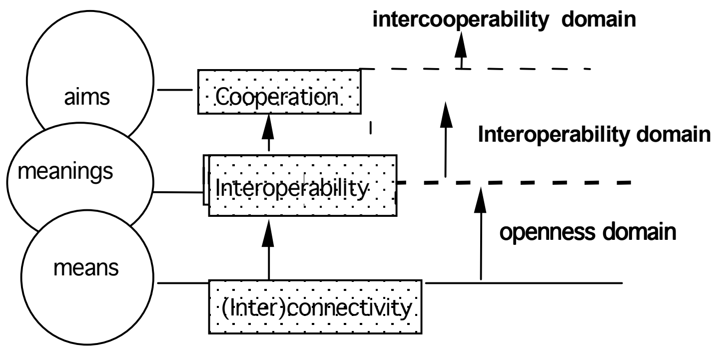
Intercooperability ability :
We will consider that a system is intercooperable when, it is able to share its knowledge but also know-how with its neighboring systems, in an optimal way, according to the comprehension it can get of the evolving situation.

Ability to conduct actions :
One admits that a system owns all the competence to do the required job in the coalition, and consequently, it can completely interoperate and furthermore intercooperate on all actions assigned to it. Of course this ability can fail if the conditions of temporal intervals are not strictly enforced; an action is only valid in a precise temporal interval.

In this paper, we will consider that C4IRS systems are belonging to the category of (inter)cooperative systems.

1.3 Formal approach basis

In our view, interoperability must be only considered as a **prerequisite of intercooperation**. In that scope, we will establish a clear distinction as in [Bares-1996], between three different domains that must be taken into account in such an approach. All systems that are put in relationship in the coalition must have certain criteria and characteristics which are defined in these domains. What's more, they are relevant of techniques and ways of modeling which are very different.



Let us describe briefly what we put in each of these three domains.

(Inter)connectivity:
This concerns essentially all necessary means to allow systems to communicate with each other, through a liaison and its relevant software mechanism. We will consider interconnectivity in our approach as a prerequisite of interoperability.

Interoperability *:*
If we consider now that C4IRS systems must exchange more than simple messages, i.e., knowledge, we must go beyond interconnectivity framework, because the exchange of knowledge supposes that we have symbolic representations to carry this knowledge. Moreover, C3I systems in the future will be called upon, to bring each other a mutual assistance (a requisite in the NATO definition of C3IS) in their cooperative action to reach a common objective (called intercooperation later on). In such a perspective, C4IRS systems must be in position to have a mutual comprehension of what they are doing, of what processes they are running, and so on. At that point, we have to determine modalities that can obtain ''intelligence'' and how to interpret it, in the exchange mechanisms.

To sum up, we can characterize the interoperability domain by the following points :

- A C4IRS becomes interoperable when it can organize itself and enriches its exchanges within an **openness structure** characterizing the coalition.
- The precedent point represents a necessary but not sufficient condition in an interoperable exchange; in addition, we need to have a common vision of the universe in which systems are going to cooperate with others.
- To take into account semantics in the mechanism of exchange.

Intercooperability :
This represents the final objective to reach, through the definition of a world, in which all (cooperative) systems are able to share all elements constituting their common activity in the coalition, but also, to take systematically advantage of everything that is appealing to intelligent behavior.

2 Openness concept for a cooperative system

We feel the need to go beyond the simple concern about interconnectivity (and the simple fact of exchanging data and messages) in order to start to tackle the question of semantics, which will begin more required in interoperability. We must be able to have a basic understanding of what is taken into account in the exchange mechanism. The role of what is called in this paragraph **openness domain**, is to specify, beyond interconnectivity, ways and limits of opening which are necessary to have a basic interoperability.

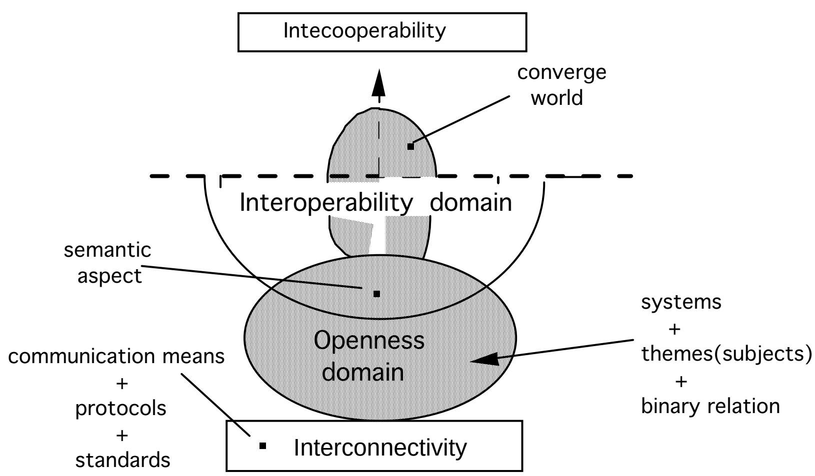


Fig. 3 Openness domain place in interoperability

We should first mention what systems and themes[1] are about to be concerned by missions relevant to the coalition/cooperation.

- *System in the coalition* : a system i will be designated by : $\mathbf{S}^{\mathbf{i}}$ where $i \in [1, n]$, n = number of systems placed in the coalition. They are supposed to be able to share a minimum common knowledge and to have common comprehension of fundamental orders.
- Notion of theme : a theme of the coalition is a set of knowledge required for it and describing a speciality, a feature, an ability. **A theme** t will be designated by $\mathbf{T}_t$ with $t \in [1, q]$ (q is the number of themes of the coalition). $\mathbf{T}_t$ encompasses a variable number of elementary actions (depending on the mission). An action **j** will be designated by $\mathbf{A}_{\mathbf{j}}$. These themes can be stated by syntactic formulas obeying the syntactic rules of a formal language.

[1] Here a theme must be considered like a set of (interoperable) actions.

2.1 Context of openness

We introduce now the concept of **openness context** to emphasize the semantic point that will be attached to themes and systems operating in the cooperation. We will formally define a context of openness by a triplet :

(S, T, R),

where : S :: $\{S^i\}_{i = 1,2,..,n}$ the set of the (inter)cooperative systems,
T :: $\{T_t\}_{t = 1,2,..,q}$ the set of the themes specified in the coalition,
R is a binary relation : $R \subset S \times T$.

The context may be given a priori when the coalition, put in place, is defining the mission of every system. It can be also defined a posteriori when the coalition is running and evolving.

Let us consider the following example : a US system S^1, a French system S^2, a German system S^3, which are supposed to interoperate within the framework of civil rescue in the Balkans. These 3 systems are competent on the 3 following themes : T_1 ground evacuation operations, T_2 airborne transportation, T_3 logistical medical aid; this supposes they are able to (inter)operate on different actions relevant to the themes and secondly to exchange knowledge required to achieve their respective missions.
Let us suppose we have all following couples :

$R(S^1, T_1),.., R(S^1, T_3), R(S^2, T_1),.., R(S^2, T_3), R(S^3, T_1),.., R(S^3, T_3) \subset S \times T$, that means :
the relation R on $\{S^1, S^2, S^3\} \times \{T_1, T_2, T_3\}$ is **total**

This openness context is summarized by the table :

Relation R	T1	T2	T3
S1	*	*	*
S2	*	*	*
S3	*	*	*

Tab. 1 Openness context example

Considering strictly the semantic point of view, systems are totally open to the themes involved in this coalition. This example describes a situation which is ideal and will rarely take place in reality. From a strict point of view, S^1, S^2, S^3 , must be considered as **totally open** on themes required in the coalition. Consequently, we get a unique totally open couple:

$(\{S^1, S^2, S^3\} \times \{T_1, T_2, T_3\})$

2.2 Notion of interoperable group (IG)

The table 1 describes an ideal case, because all systems of the set S are related to all themes of the set T.
Condition of openness :

$\exists$ i, t | $S^i \in S$ and $T_t \in T$,
we have :
$(S^i, T_t) \subset R$.

Let :

$S :: \{S^i\}_{i = 1,2,..,n}$,
$T :: \{T_t\}_{t = 1,2,..,q}$,
$R \subset S \times T$
$S \in P(S)$
$T \in P(T)$

We define an (totally) interoperable group as :

IG :: < #-interoperable-group(< s >ρ< t >) >

ρ means that R is a total relation on s x t, in other words, there exists only one dependency between the subset s and the subset t.

2.3 Openness structure of the coalition

We are presently formalizing the openness structure of a coalition C, through its dependant IG. For that purpose, let us consider this openness context of C:

	T_1	T_2	T_3	T_4	T_5	T_6
S^1	*	*			*	*
S^2		*	*	*	*	
S^3	*		*		*	

Tab. 2 Openness structure of the cooperation C

We will notice that this openness structure of C, is composed of 8 subsets. We obtain one after the other :

IG-1 ($\{S^1, S^2, S^3\}$ ρ $\{T_5\}$),
IG-2 ($\{S^1, S^2\}$ ρ $\{T_2, T_5\}$) ,
IG-3 ($\{S^1, S^3\}$ ρ $\{T_1, T_5\}$) ,
IG-4 ($\{S^2, S^3\}$ ρ $\{T_3, T_5\}$) ,
IG-5 ($\{S^1\}$ ρ $\{T_1, T_2, T_5, T_6\}$) ,
IG-6 ($\{S^2\}$ ρ $\{T_2, T_3, T_4, T_5\}$) ,
IG- 7 ($\{S^3\}$ ρ $\{T_1, T_3, T_5\}$) ,
IG-8 ($\{\emptyset\}$ ρ $\{T_1, T_2, T_3, T_4, T_5, T_6\}$).

Let us construct now the diagram with the different IG we previously determined.

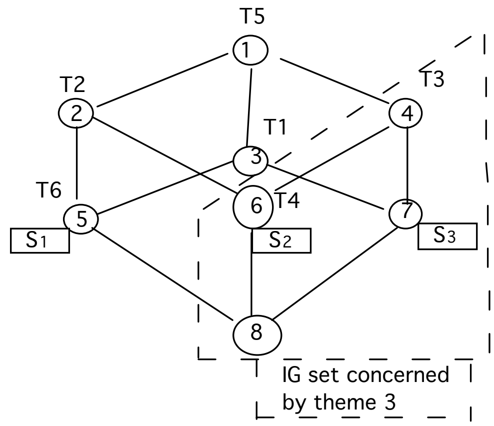


Fig. 4 Open structure formalization (OSC)

Fig. 4, which formalizes the openness structure of the cooperation C, presents a great deal of interest. From this diagram, we can interpret easily the openness structure when considering the following points :

- Every IG indexed by a number inherits all themes linked up to it in the diagram.
- Every node number is constituted of all the systems which are linked down to it.

3 Interoperability space

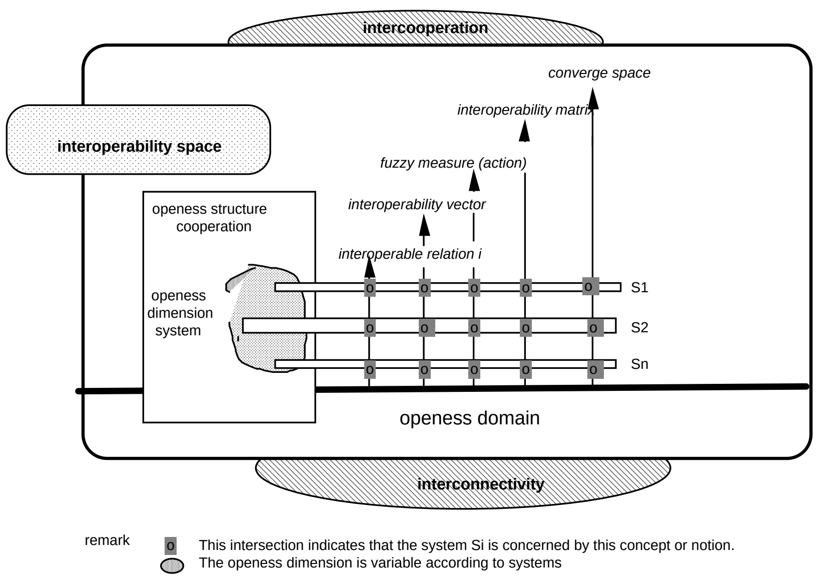


Fig. 5 Interoperability space

We will consider that an action is not interoperable in itself, but only with system(s) that are able to handle it. For that reason, we will always designate an interoperable action by a couple :

$$(S^k, A_j) \text{ where } S^k \in \{S^1, S^2, \ldots, S^n\}$$

Remark : This couple : (S^i , A_j) must encompass time variable (reification), because systems, and more actions, are likely to modify in run time. We will consider that its validity will depend on a temporal window or « window opportunity », which will be denoted as follows :

$$(S^i, A_j, \theta_M),$$

the system i acts (or (inter)operates) on the action j, in the temporal interval θ, assigned to the mission M.

The time parameters will be fixed by those who are in charge of the coalition.

3.1 Fuzzy Measure of an interoperable action

A fuzzy measure refers to a means of expressing uncertainty when, not disposing of complete information, it is impossible to use probability. We are going to determine numerical coefficients, or **certainty degrees**, to indicate how it is **necessary** that such a system can interoperate on (or with) such an action beforehand declared as **possible**. In doing the (reasonable) hypothesis that a system only executes one interoperable action at a time, we can for instance, form a **universe W** from the following singletons :

$$W = \{(S^i, A_1), (S^i, A_2), (S^p, A_3), ...,(S^q, A_n)...\}, \text{ with : } d\,(S^i, A_n) \;:: \text{degree of possibility}$$

$$d\,(S^i, A_n) \in [0, 1], \text{ this value assesses the possibility which } S^i \text{ executes the action } A_n.$$

A fuzzy measure is completely defined as soon as a coefficient of possibility has been attached to every subset of a **universal set U**. If the cardinal number is n, to be rigorous, we must state 2^n coefficients, in order to specify the measure of possibility. Here, we will proceed more simply in observing that each subset of U may be regarded as an union of singletons it encompasses. So, the determination of the possibilistic measure can be done from only n elements. So, to define an interoperable action we here introduced :

(a) A **feasibility** measure comparable to a possibility,

(b) A **imperativity** comparable to a necessity which will be dual of (a),

(c) A **credibility** measure to assess trust put by systems in the fulfillment of an action by anyone of them.

(a), (b), will be defined thanks to distributions of possibility. Therefore we will represent an interoperable measure in a “fuzzy cube”.

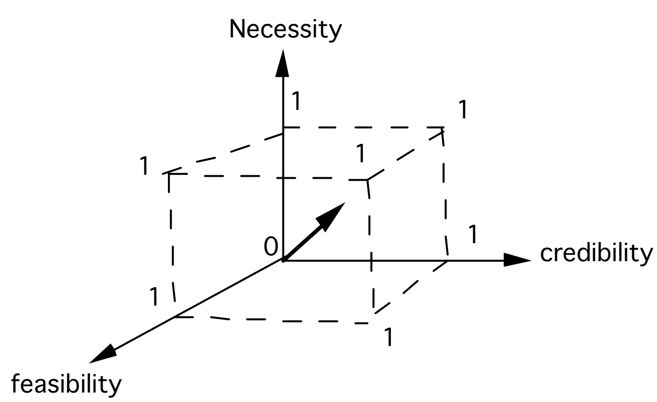


Fig. 6 Fuzzy representation of an interoperable action

3.2 Interoperable competence relation

Presently we define a **relation** $\Re$, in a propositional calculus view, the arity of which is 3, and by which any system gauges its aptitude to operate an action of the coalition. This relation must be applied by every system to every action of the cooperation. It will be denoted as follows :

$\Re$ :: «is able to (inter)operate» , we form the proposition : $\Re(S^i, \{A_j\}, \theta_M)$,

$\forall$ i $\in$ [1, n], (n : number of systems)

$\forall$ j $\in$ [1, p], (p : number of actions)

Remark :

S^i considers that it is competent to interoperate on $\{A_j\}$,

all Aj can be described with words of a formal language

Each system is bound to determine a first condition, **necessary** but not **sufficient** of its interoperability. According to its own knowledge and truths about its neighboring world, a system is able to say if such an action is normally interoperable. In fact, the relation $\Re$ which allows to define an **effective interoperability** : a system S^i gauges its competence to operate on any action, in window time θ attached to the mission framework M, under normal and usual conditions.

As $\Re(S^i, A_j, \theta_M)$ is considered like a proposition,

so we can assign a truth value to it :

if Value(Val) [$\Re(S^i, A_j, \theta_M)$] :: True (T/1)

that means :

S^i can interoperate on A_j, in time window θ, fixed by

mission M. $\forall$ i $\in$ [1, n], $\forall$ j $\in$ [1, p]

Val [$\Re(S^i, A_j, \theta_M)$] :: False (F/0)

$\Rightarrow$ **interoperable incapacity** of S^i on Aj.

Remark : In practice, those who responsible for S^i are entitled to apply this relation, and thus, to decide about the interoperable (in)capacity of their interoperability .

3.3 Matrix of interoperability

For a given system S^i, If we successively apply the relation $\Re$ to couples (S^i, A_j), j varying from 1 to p, we obtain for example:

Val [$\Re$ (S^i, A_1)] :: T

Val [$\Re$ (S^i, A_3)] ::: F

....

Val [$\Re$ (S^i, A_p)] :: T

Tab. 3 Application of the relation of interoperability

We bring together these elements in order to get a binary vector. There are as many vectors as systems in the coalition.

Let a component of vector $V(S^i)_j$ (row j), if we have :

val [V (S^i) $]_j$ :: F
$\Rightarrow$ $\neg\exists\Re$ $(S^i$, Aj) for openness structure of the coalition, and therefore, S^i has no semantics to evaluate,
[V (Si)]j is not supposed to exist.

From the binary vector, or from the world resulting of the interpretation $\Re$, it becomes possible to affect fuzzy measures to each vector's components whenever the value is not false. These fuzzy vectors will be established in the following conditions :

We take:
either couples of the world $\Re$, such as : ((V $(S^i)_{j = 1,2,..p}$) :: 1,
or vector's elements V (S^i), such as : [[V $(S^i)_{j = 1,2,..,p}$]] ($\Re$) :: 1

We assign a fuzzy measure to them, respectively corresponding to 3 dimensions, as described in 3-1:

Φ $(S^i$, Aj) $\rightarrow$ measure of feasibility,
N $(S^i$, Aj) $\rightarrow$ measure of necessity,
λ $(S^i$, Aj) $\rightarrow$ measure of credibility.
. $i \in [1, n]$, $j \in [1, p]$

Every system is able to establish its own interoperability vectors.

whenever for $j \in [1, p]$, val V $(S^i)_j$ = T $\rightarrow$ semantics evaluation to do.

This evaluation of the semantics has been made necessary because : either unpredictable facts arrived in the own system's world or an unexpected mission could have modified the world of S^i; which means that Aj has no longer the same meaning for the system S^i and possibly also for the coalition. In gathering all vectors of interoperability $V(S^i)$, we get this way, what call an **interoperability matrix**.

$[I (S^i)_{i = 1,2,..,n}] = [V(S^1) V(S^2) ......V(S^n)]$

This matrix represents only an apparent interoperability. It can be used in different ways :

- to indicate what is theoretically the most interoperable system, relatively to a determined action,
- to give most the adequate system to operate under special conditions : a mission which imposes a temporal constraint to operate an action. We will construct three kinds of interoperability matrices.

a) Matrix of feasible interoperability

This matrix gives a dimension of feasibility of the interoperability of the federation $\{S^i\}$ will be denoted by :

$$[I\text{-}\Phi (S^i)_{i = 1,2,\ldots,n}]$$

b) Matrix of imperative interoperability

The matrix of necessary interoperability is also constructed with fuzzy vectors of necessity as described above. It presents a great interest in informing us about necessary conditions which are imposed to some systems in their way of interoperating. This matrix will be denoted by :

$$[\text{ I-N } (S^i)_{i = 1,2,3}]$$

Example with 3 systems and 4 actions :

$$\left[I - N(S^i)_{i=1,2,3}\right] = \begin{bmatrix} 0.8 & 0.8 & 0.0 \\ 0.0 & 0.6 & 0.8 \\ 0.8 & 0.0 & 0.6 \\ 0.8 & 0.6 & 0.8 \end{bmatrix}$$

Tab. 4 Matrix of imperative interoperability

We observe that in the previous matrix, system 1 must have the strongest interoperability in spite of its component $V(S^i)_{2,1} = 0$, which can incidentally indicate an interdiction to interoperate on action A_2.

c) Matrix of credible interoperability

This matrix gives us a visibility on systems which are about in the best position to interoperate successfully. It will be denoted by :

$$[\text{ I-}\lambda\text{ } (S^i)_{i = 1,2,..,n}]$$

Example with 3 systems and 4 actions :

$$\left[I - \lambda(S^i)_{i=1,2,3}\right] = \begin{bmatrix} 0.3 & 0.0 & 0.3 \\ 0.0 & 0.0 & 0.3 \\ 0.8 & 0.3 & 0.3 \\ 0.3 & 0.6 & 0.3 \end{bmatrix}$$

Tab. 5 Matrix of credible interoperability

We observe that in this example, system 2 presents small degrees of credibility; this means that all systems consider that it is likely to be the least successful in the cooperation.

4 Cooperability domain

In this paragraph, we will try to go beyond the system's interpretation regarding actions and to see how any systems can interpret the other systems' ability for interoperating on actions. What one can summarize simplistically :

(1) interoperability (S^i) $\rightarrow$ system S^i interprets [S^i (interoperability) / {action(s)}], $\forall$ i $\in$ [1, n]
(2) intercooperability (S^i) $\rightarrow$ systems {S^k} interprets [(S^i) interoperability /{action(s)}], $\forall$ i, k $\in$ [1, n]

We can still illustrate (1) and (2) in an explicit manner :

(1) for the domain of interoperability :

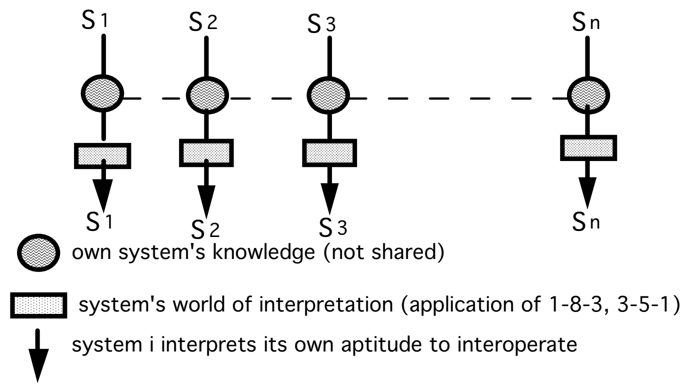


Fig. 7 Interpretation in the interoperability domain

(2) for the domain of intercooperability :

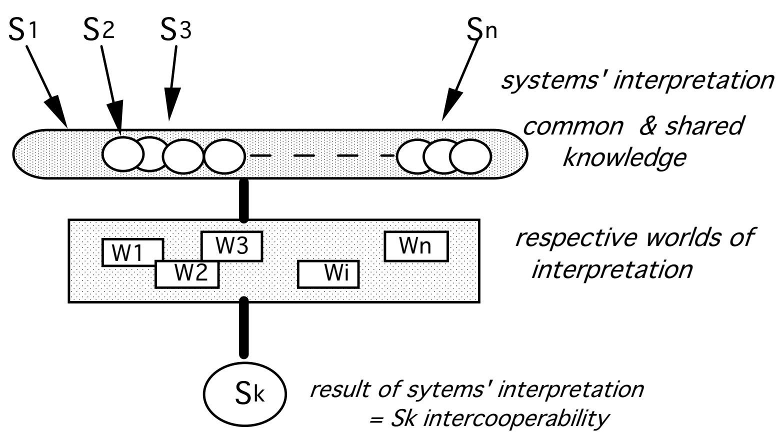


Fig. 8 Interpretation in the intercooperable domain

4.1 Intercooperability competence relation

So, what is going to get more important for systems in intercooperation it is the necessity to satisfy a permanent need of **mutual understanding**. In a practical way, that means they must :

- either share the same meaning relatively to the different objects they have to handle in their common universe’s actions,
- or to take necessary steps to make **semantics** converge.

When defining the relation of the interoperability competence in 3.2, we have considered that systems, obviously placed in a symbolic context are able to interpret their own ability to interoperate on actions as requested by the coalition. In this paragraph we are now envisaging to go beyond, by seeking to extend the system’s interpretation ability in defining a **relation of intercooperability competence**.

We will consider that a system S^i has a competence in intercooperability when, it will be able to "judge" the ability of adjoining (cooperative) systems to interoperate on a set of actions $\{A_j\}$, in a time window θ, fixed by a mission M. This competence will be designated by the following quadruplet :

S^i / S^k , { A_j }, θ_M (the symbol / indicates the way of interpretation) $\forall$i , k $\in$[1,n], j $\in$ [1, p]

We will define a relation of intercooperable competence in the same way we do for the interoperability competence, this one will be designated by $\Re'$, in the following conditions :

$\Re'$ :: « is able to (inter)cooperate »
$\Re'$ :: « interpret the other systems' aptitude to interoperate on $\{A_j\}$ », we form the predicate relation :
$\Re'$ [$S^i / (S^k, \{A_j\}, \theta_M)$] $\forall$ i, k $\in$[1, n], $\forall$ j $\in$[1, p].

This means that : S^i judges that (confidence in the success of) S^k is able to interoperate on {Aj} in the time-window θ_M (this evaluation is made with a fuzzy measure of credibility).

In a predicate calculus view, the relation $\Re'$ defined in these conditions, is equivalent to a **propositional function**:

S^i, S^k, A_j, representing the variable, θ_M may be considered here as a constant [2]. So, for a given S^i, we can evaluate the truth value of the predicate :
S^k is interoperable on each A $_{j=1,2,..,p}$

(1) if *Val* [$\Re'$[$S^i / (S^k, \{A_j\}\theta_M)$] :: True,
that means : S^i interprets that S^k is able to interoperate on the actions $\{Aj\}_{j=1,...,p}$,

(2) if *Val* [$\Re'$[$S^i / (S^k, \{A_j\})$] :: False,
S^i considers that S^k is unable to interoperate on{Aj}j =1,...,p,

Nota bene : θ_M has been considered as a constant in (1) and (2), for previously mentioned reasons.

4.2 Vector of intercooperability

As we do in 3-3 (for the vector of interoperability), for a given system S^i , we are going to apply the relation $\Re'$ successively to tuples :

$$S^k / (S^i, A_j, \theta_M)\ j = 1,...,p.$$

As we continue to consider θ_M a constant in the predicate relation, from now we will simply consider the triplet :

$S^k / (S^i, A_j)$ j = 1,...,p
on which we can apply the predicate calculus rules. For instance, we shall obtain :

$$\text{Val } [\Re' (S^i / (S^k, A_j)_{j=1}] :: 1$$
$$\text{Val } [\Re' (S^i / (S^k, A_j)_{j=2}] :: 0$$
$$\ldots\ldots\ldots\ldots$$
$$\text{Val } [\Re' (S^i / (S^k, A_j)_{j=p}] :: 1$$

Tab. 6 Definition of an intercooperability vector

[2] We make the hypothesis that the time-window's limits are well defined in the cooperation. This hypothesis cannot be maintained if we are not sure of this fact.

Let us keep in mind that the letter p corresponds to the maximal number of actions in the coalition. In bringing together these elements we obtain a binary vector, called the **vector of intercooperability**, will be designated by :

$$V\,(S^i\,/\,(S^k,\,A_j))_{j\,=\,1,..,p;}\;\;k \in [\,1,\,n\,].$$

4.3 Matrix of intercooperability

In gathering the vectors of intercooperability, we will get what we are now calling an **intercooperabilility matrix**. Although the interoperability matrix is unique, it is necessary to establish two categories of matrices in the domain of intercooperability.

1) The first category, called intercooperability-system, is going to indicate how the set of systems interpret their respective interoperability .
2) The second one, called intercooperability-action, is regarding actions, i.e. a matrix to comprehend the interoperability of the cooperation from its actions.

4-3-1 Matrix of intercooperability-systems

Now the question is to comprehend how the federation of systems, interprets the ability of interoperating one of them. Let us keep in mind that all systems are more or less interoperable according to the other systems' judgment. The intercooperability matrix of a system S^i will be denoted : **[C(S^i)]** and presents a great interest. In fact, we can make special computations about rows and columns of [**C(S^i**)]. Therefore, we obtain some interesting elements to characterize what we are going to call **intercooperable capacity** of the cooperation, i.e. the visibility about the more or less easiness of system's interoperation.

Properties of a column

Let [C(S^k)] be the matrix of intercooperability-system of the system S^k, and consider the mth column of this matrix. If we sum up all components of the **vector column m** of the matrix [C(Sk)], we are going to get a certain scalar, designated by : $\alpha_c\left(S^k\right)$.

$$\alpha_c\left(S^k\right) = \sum_{j=1}^{p}\left[C(S^k)\right]_{j,m}$$

4.3.2 Matrix of intercooperability-action

We now define an other kind of matrix which is going to allow us to have a visibility of the intercooperability of all systems of the coalition. This special matrix is going to indicate what are the systems which are in the best conditions to interoperate on actions. These matrices will be called **matrix of intercooperability-action** for that reason**.** Let us go back to the matrices of intecooperability-system; if we take the jth row in each of the previous matrices, we are forming a new matrix that reports about the systems' intercooperability capacity relatively to the action A_j. This matrix will be designated by [C(Aj)].

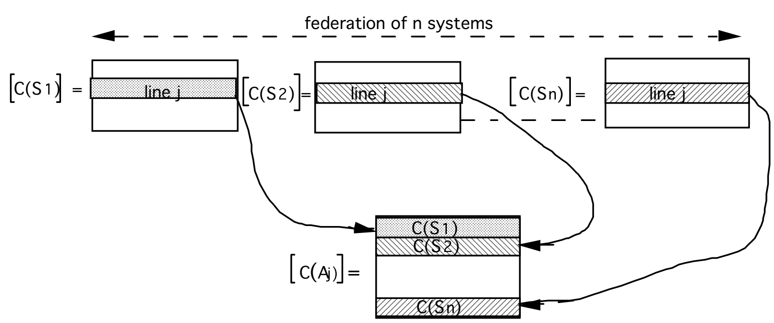


Fig. 9 Matrix of intercooperability-action

The matrix of intercooperability-action presents interesting features :

- its shape is square,
- it allows to understand what are the systems of the federation which are in the best position to interoperate on such an action A_j,
- it gives an idea about the lesser or greater systems' easiness to interoperate on particular actions,
- its columns and rows have interesting characteristics.

If we compute the p matrices corresponding to all actions of the coalition, we have a good visibility of the intercooperability in the coalition framework. That means we are able to say :

- what are the actions which are difficult to carry out,
- what are the ones which are likely either to get the coalition into trouble or to force the cooperation to face difficult issues.

5 Conclusion

In this paper, we have introduced notions of openness context and interoperable group. We have afterwards demonstrated that it was possible to formalize the structure openness of a federation of systems (representing the coalition). Then we have defined a notion of an interoperable action to which we have attached fuzzy measures **: feasibility, imperativity, credibility (**determined through distribution of possibility). By introducing a relation of **interoperability competence**, we have shown that it was possible to construct a vector of **effective interoperability**, resulting of the system's interpretation of the facts in its own logic world. In this way, we got a quantitative evaluation of interoperability pertaining to a system of the coalition. These vectors of interoperability define a **matrix of interoperability** which gives a right visibility about the global interoperability pertaining to the set of all systems of the coalition. We afterwards went beyond this ability of a system to interpret its own ability of interoperating and to see how it could interpret the other systems' ability for interoperating on actions. For that purpose, we have introduced a relation of intercooperability competence, defined in a predicate calculus field, which may be regarded as an extension of the relation of interoperability: this relation enlarges our comprehension field about the interoperability of the others. We establish two kinds of matrices; the first one regarding the systems' interoperability, the other one concerning the actions. These matrices present interesting properties, which have allowed us to establish a whole family of parameters, and doubtless represent a first significant step in our way of seeing the interoperability issue.

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Mobile and Netted Air Defence Systems

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Summary: This paper describes a sensor- and weapon independent co-ordination and communication concept for use in coming generations of mobile SHORAD and medium range air defence systems. Actually, the proposed concept will handle most known weapon systems. The presented system generates and maintains a ratified total air picture from available track information, whether from system specific radar sensors or from system external sensors via data links. Airspace Control Means, and their effect on Threat Evaluation and Weapon Allocation operations, are totally integrated in the system, allowing full and safe use of friendly aircraft during air defence operations. Powerful training- and simulation software allow fully synchronised system training sessions from classroom equipment or from any operator position in the system.

System Architecture: Most air defence systems comprise sensor(s) and weapon co-ordinated by a C2 element via some form of inter-communication medium. Communication with other air defence assets (lateral) and higher command usually happens via dedicated point-point data links, using formats and protocols defined in National, NATO, or US standards.

The air defence system concept described in this paper mainly utilise international communication standards (ISO) and Wide Area Network (WAN) connectivity, which reduces system vulnerability towards errors and single point failures.

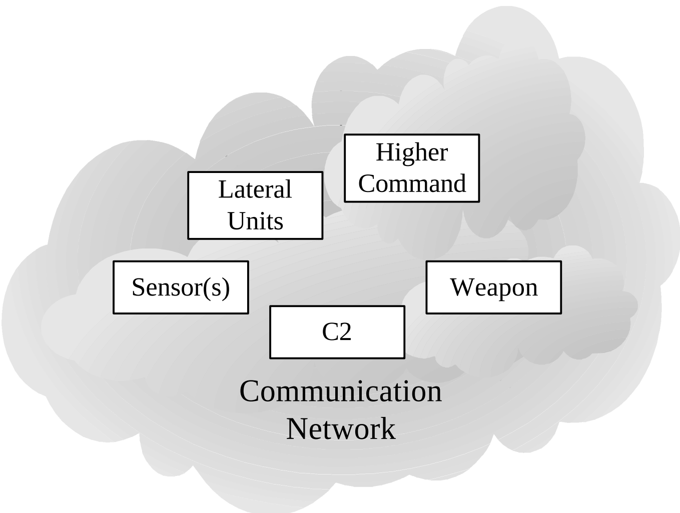

Fig. 1 Air Defence System

Traditionally, an air defence unit comprises sensor, weapon and C2 interconnected by cables, functioning as a stand-alone weapon units. If any part of such a unit becomes unserviceable or damaged, the whole weapon

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unit is out of operation. It is possible to interconnect several such stand-alone weapon units to introduce redundancy, but this introduces additional mandatory requirements:

- air picture synchronisation (fusion)
- real-time communication
- secure communication
- co-ordination of firing between systems
- synchronised training and simulation

The concept proposed in this paper overcome the mentioned obstacles and provides inherent element redundancy. The concept is based on solid experience from air defence system implementations in Denmark and elsewhere.

Concept: The proposed concept deals with 5 main design requirements:

- communication
- common air picture
- sensor co-ordination
- weapon co-ordination, control and maintenance
- training and simulation

Communication

The most essential part of the proposed system is communication. In order to stay mobile, the communication system must support wire-less operation and provide as much bandwidth as possible. During crisis or war the wire-less environment is noisy and most likely contaminated by intentional jamming. This mandates some essential requirements to the chosen communication system:

- error correction
- frequency agility
- line-of sight
- directional antennas

It is our experience that an area system based on mobile communication nodes using frequency agile radios, with forward error correction, is a good choice. Nodes should be equipped with directional antennas and should support down-the-hill connections to a number of system elements by cable or by radio. The nodes must be interconnected in a meshed network, covering the entire area of interest.

Communication stacks should include TCP/IP protocols and standards well known from the Internet. A lot of standard software is available covering every aspect of network communication and system management.

Common air picture

Every sensor in the system, whether active or passive, should be connected to a node in the communication network. The sensors must be equipped with sufficient processing capabilities to maintain 2 track tables, a local table and a copy of the track table in the network.

For each processing cycle, individual sensors compare their local track tables with the network table and decide, from a quality comparison, whether any of the local tracks are missing, or have a higher quality figure, than in the network table. If yes, then each sensor will broadcast such tracks. This ensures the air picture in the network is fused, current and of the highest quality possible, while still conserving bandwidth.

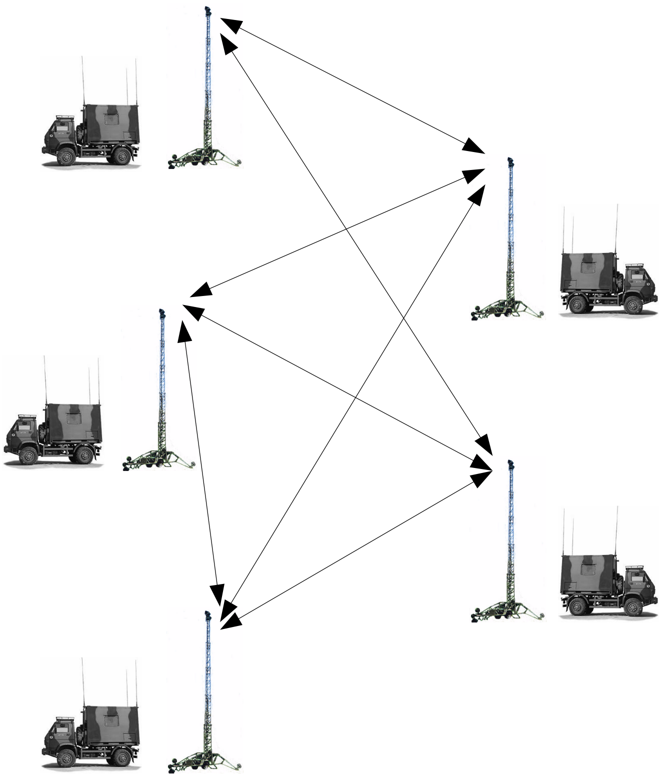

Fig. 2 Meshed communication network example

The quality figure is naturally an essential parameter and should comprise all available track information in as near real-time as possible.

Tracks in the common air picture should be identified, if at all possible. Most active sensors are equipped with IFF equipment, and can contribute to the identification process. This is normally not sufficient to give sure identification of a track, as IFF equipment can fail, remain switched off or be loaded with the wrong identification codes. Additional identification is required, and can be provided, by the co-ordination elements in the system, from available Airspace Control Means (ACM).

A common identified air picture is a requirement in any air defence system, but it needs sensor co-ordination and subscribers before it's potential can be exploited.

Co-ordination

It is desirable to keep the number of personnel in a given operation to a minimum. It is therefore obvious to control participating sensors remotely and leave the sensors unmanned. A number of sensor control facilities could be placed anywhere, hooking up to the network via one of the access nodes in the system. One control element would suffice, but for redundancy- and continuity reason at least two such elements would be required per system.

Operators in the Co-ordination element would maintain the ratified air picture and operate the sensors according to daily orders, e.g. frequency selections, IFF codes, antenna rotation speeds, blinking, identification, etc.

A netted and ratified air picture is now established, ready for use by subscribers within communication coverage of an access node. In an air defence system subscribers would typically be air defence co-ordination and control facilities and associated weapons.

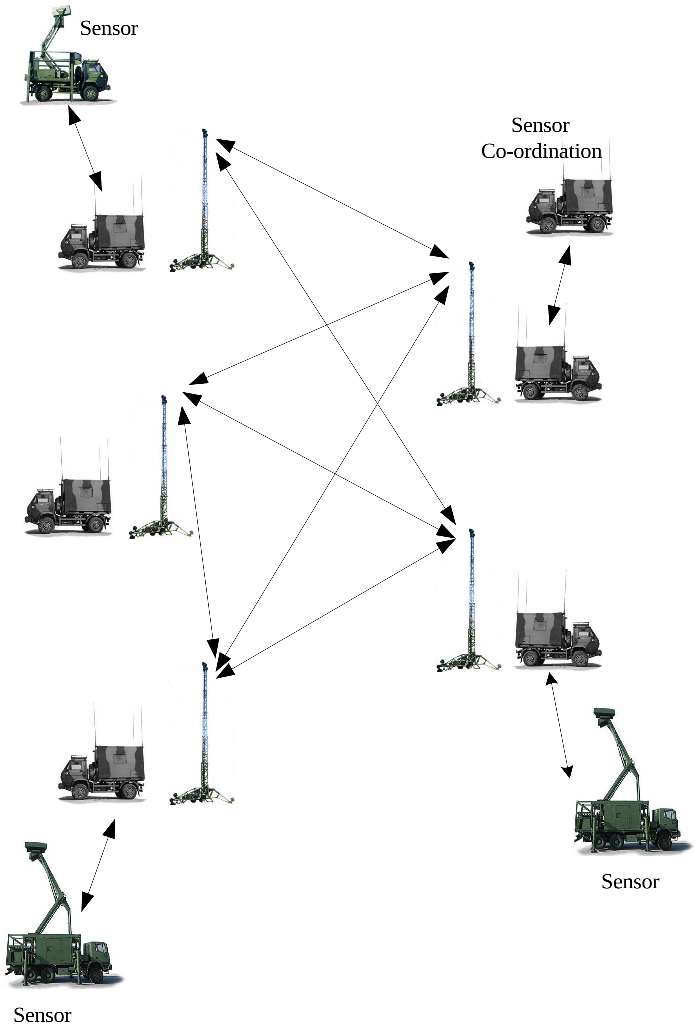

Fig. 3 Network with sensors and co-ordination

Weapon co-ordination, control and maintenance
Much in the same way as with the sensors in the system, it is possible to remotely control and co-ordinate a large number of air defence weapons from a central co-ordination and control element.

The air defence weapon in question will interface to a communication access node, anywhere in the system, and report its position and address to the central co-ordination and control element. If several weapons access the same node, some type of radio sub-net is established using TDMA- or wireless Ethernet protocols, compatible with the number of weapons in the sub-net and with the required reaction time. One example could be a cluster of V-SHORAD weapons, within radio coverage of a given access node, using VHF radios for communication.

Another example could be medium range SAM, e.g. HAWK, with it's own dedicated fire control element, interfacing to the nearest access node by radio or fibre-optic cable. A typical HAWK set-up would comprise 3 launcher, each with 3 HAWK missiles, and 1 illuminator radar, interfacing to the fire control element by fibre-optic cable

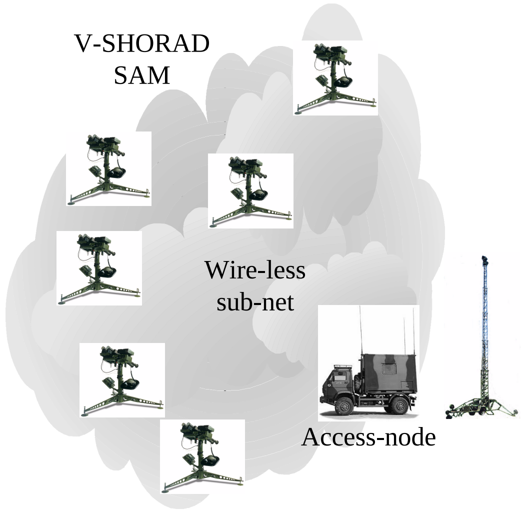

Fig. 4 V-SHORAD wireless sub-net

Figure 5 below shows a typical set up at an access node with Enhanced HAWK as the main air defence weapon and V-SHORAD for close-in air defence. Fibre-optic cable is preferred over VHF radio communication as the access medium mainly for bandwidth and security reasons. The fire control element with the Enhanced HAWK weapon should be designed to operate equally well as a dedicated fire control element with weapons attached or as a main fire direction element for the entire air defence system. Just one main fire direction element could co-ordinate firing within the total air defence system, using Threat Evaluation and Weapon Allocation algorithms tailored to accommodate the range of weapons employed in the system. Suitable TEWA algorithms, for this type of air defence system, are found elsewhere in these proceedings.

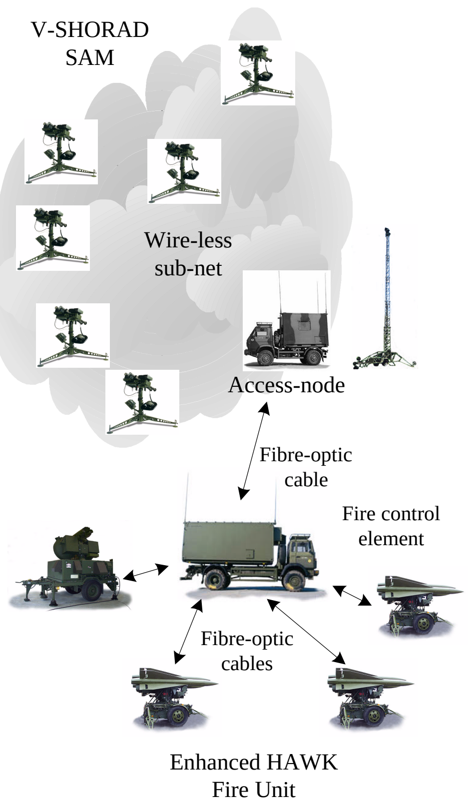

Fig. 5 V-SHORAD and HAWK access

Using identical fire direction and fire control elements in the system, ensures a high degree of redundancy during operation, i.e. any fire control element could assume the role as central fire direction element if damage has occurred or during movements.

A very essential part of weapon co-ordination and control is distribution of common Airspace Control Means (ACM) throughout the system. ACMs define all aspects of airspace control in the total area of interest. ACMs are used by the central fire direction element to allow safe transition of friendly aircraft in the area while at the same time being able to utilise associated weapons to their maximum potential. ACMs also serve with additional information in the air picture identification process, by allowing procedural identification of own aircraft in the area.

During operation all actions, and the result of these actions, may be recorded for post operation analysis, or for use in training scenarios.

A mobile air defence system has now been defined, establishing and maintaining a ratified total air picture for use by a variation of air defence weapons. Fire direction and co-ordination elements have been introduced, able to address the weapon in the system which is best placed to deal with a given threat. The use of common ACMs throughout the system ensures maximum protection of own aircraft from own fire while at the same time utilising associated weapon to their maximum potential.

Two final and important aspects of co-ordinated air defence is the ability to communicate with air defence assets of neighbouring forces (lateral communication) and to receive orders and transmit status to higher command. This is traditionally done via dedicated gateways, and, dependent upon the standard used for communication, the flow of information can be one-way, two-way, tactical information only or everything of interest. Much used standards are Link-11B and ATDL-1 for point-to-point tactical communication, LLAPI for point-to-point exchange of both tactical and strategic information and Link-11 or Link-16 for tri-service network operations. In addition to these standards, which only deal with the exchange of data communication, other standards define gateways for the exchange of voice.

Gateways are usually located within access nodes of the system, and may be addressed and used by all elements of the system. Only one gateway per system is used at a time to another system, meaning that only one access node will be active as gateway. Which one, does system management at all times define.

It is now possible to show an entire mobile and netted air defence system with all it’s interfaces:

Maintenance
It is quite normal to allocate a mobile maintenance facility to a mobile air defence system. The maintenance facility will typically store spare parts to intermediate level and be able to repair sub-assemblies to printed circuit card level (exchange of printed circuit cards).

In a netted system as discussed here provides some interesting possibilities for on-line and remote maintenance. The maintenance facility can connect to an access node, and via the network access all elements of the system. If all elements are foreseen with diagnostic tools, and the software to invoke these tools, e.g. SNMP (Small Network Management Protocol), it will be possible to monitor, on-line, the inside of all computers, routers and switches in the network from the remote maintenance facility. It is therefore possible to receive immediate warning if a problem is developing, and to pinpoint the location and nature of the problem. This will improve the faultfinding process and greatly reduce the time to repair. It is even possible to remotely re-route connections in a router, if congestion occurs or if a port on the router is damaged.

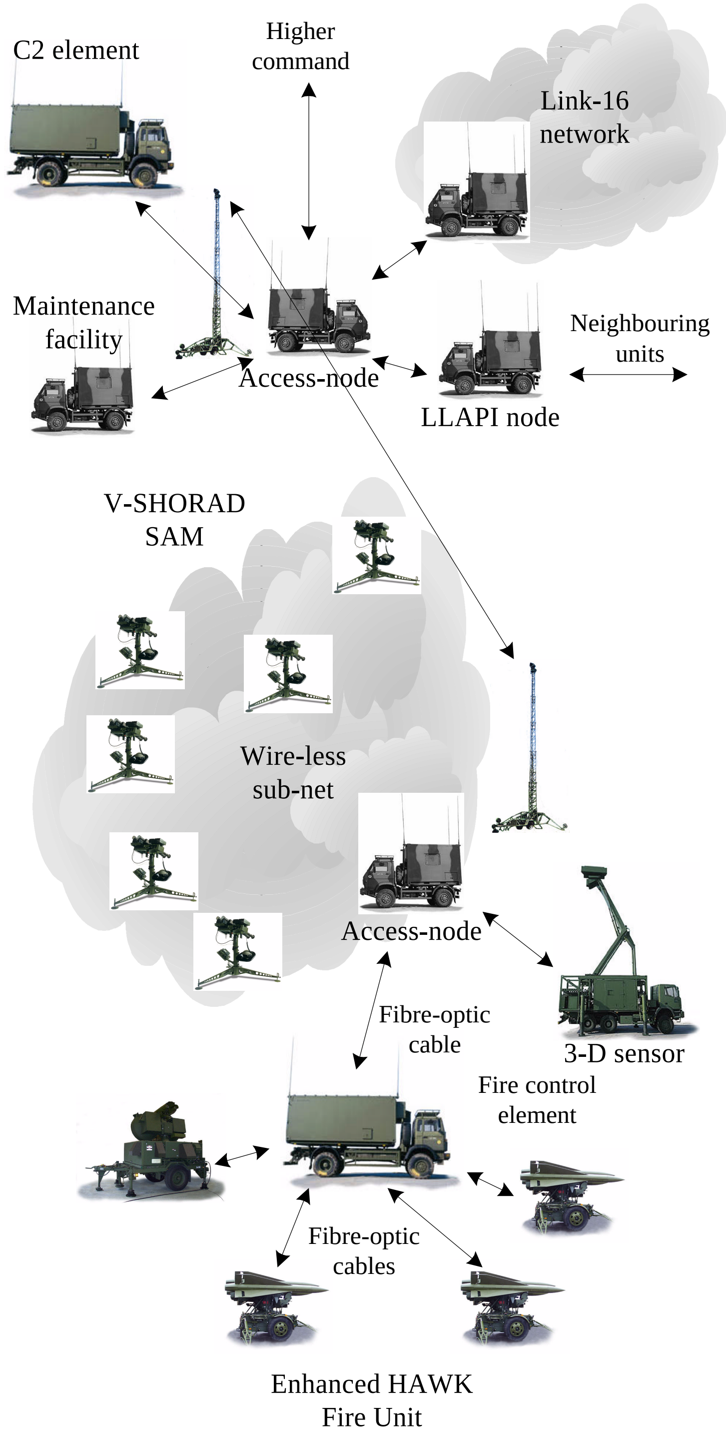

Fig. 6 Total air defence system

Training and simulation

In a netted system as suggested above, training of operators can take place anywhere in the system. A common training scenario will run on one of the workstations in the system, ensuring a completely synchronised execution throughout the system. It is also possible to train operators at positions in parts of the system by simulating the parts not participating. It is even possible to train operators in a classroom set-up, simulation elements of the entire system including external data links.

A given training scenario may be constructed at an operator position in the system, or at a classroom workstation. It is possible to use recorded live scenarios and edit these for use as a common training scenario. This ensures known and realistic scenarios, which may be used for elementary, as well as advanced, training of any type of operator in the system.

Actual implementations: A mobile and netted air defence system, like the one described in this paper was designed by TERMA Elektronik AS. The system is now being delivered to the Danish Airforce under the acronym Danish Enhanced HAWK (DEHAWK). The system under delivery comprises 3-D radar sensors, STINGER missiles on lightweight tripods and enhanced HAWK missile sub-systems.

Great emphasis was put into the design of a sensor and weapon independent system, supporting virtually any type of radar sensor and virtually any type of air defence weapon. TERMA developed the Operation Centre (OC) which may serve as central fire direction element, without weapon, and/or as fire control element with a flexible weapon interface capability. When the HAWK missile is phased out, a new missile is quite easily interfaced. A powerful Weapon Engagement Controller (WEC) was also developed to serve as fire control element for manpad missiles or AAA guns in wireless sub-networks.

The area communication system, including access nodes and communication equipment, was delivered by the Danish Airforce as government furnished equipment (GFE).

Some DEHAWK key figures:
Area communication system: 2 Mb trunks, C-band.
Radar sensors: 3-D, C-band, 100 Km range.
M-SAM: Enhanced HAWK with fibre-optic cable interfaces to the OC. Cable lengths: up to 1 km.
V-SHORAD: STINGER with Weapon Engagement Controller. Up to 12 Fire Units per sub-net.

Vulnerability Assessment of Surface-to-Air Missile Systems

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ABSTRACT.

The susceptibility of a surface-to-air missile system to surveillance and target acquisition sensors operating in the infrared wavebands of 3-5 and 8-12 µm has been analyzed by testing. The trials were carried out accordingly STANAG 4418 and AVTP Trial series 05, with and without camouflage systems installed. It is described the planning and execution of the tests, the equipment employed and the data analysis procedure. The effectiveness of the camouflage systems to reduce the thermal signature, has been assessed using the acceptance criteria established on STANAG 4418. Some examples are discussed.

1. INTRODUCTION.

The measurement of overall thermal radiation determines the energy level projected to a sensor for a given target position. This radiation makes it possible to detect and recognize vehicles at great distances, using IR sensors, like the ones used in thermal cameras, surveillance systems and missile heat seekers.

Infrared radiation is absorbed and scattered by the atmosphere. For that reason detection at tactically relevant ranges is possible only in the so-called "atmospheric windows". Two of the most typical are the wavebands of 3-5 (short band) and 8-12 µm (long band), or sub-bands within the above ones. In these regions of the spectrum, the radiation reaching the sensor is due mainly to self-emission from the vehicle hot parts (except for a component of solar reflection in the short band). This allows that thermal imagers could work at day and night, and detection results from either a positive thermal contrast when the object emission is higher than its surroundings, or from a negative thermal contrast when the background emission is higher.

2. TARGET ACQUISITION.

The ability to detect, recognize or identify a vehicle by means of thermal imagers depends on a series of factors, among others:

- nature, size and activity of the vehicle,
- environment and background,
- performance of the imager.

The nature of the vehicle plays an important role in the recognition and identification tasks. Usually they are carried out looking for some characteristic feature of such vehicle (e. g. wheels in a truck, barrel in a cannon, tracks in a tank).

For a given imager and environmental conditions, the size of the vehicle determines the maximum range at which it can be detected, because is necessary to have at least two pixels for a 50% probability of detection (Johnson's criteria). The activity of the vehicle has a strong impact on its thermal signature, increasing the thermal contrast of certain parts. For example, a truck with the engine running presents a higher contrast in the exhaust system and in the surfaces covering the engine, if the vehicle has recently moved the tires threads are hotter, if a cannon has been shooting, its barrel is hotter too. In these cases detection or recognition of the target is easier.

Environment and background have great importance for target acquisition tasks. During daytime hours solar heating can significantly increase the thermal signature. However, solar heating also increases the background thermal clutter; so, vehicle targets are often easier to detect during night time even though their thermal signature is lower in this condition.

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Given a particular set of target, environment and background, the performances of the thermal imager determine if any of the acquisition tasks are possible. The system should have a thermal sensitivity enough to detect temperature differences between target and background as low as possible, and provide the spatial resolution required for the specific task. Thermal sensitivity will limit detection range, while spatial resolution will limit recognition range. Spatial resolution must be higher for recognition than for detection, and for identification than for recognition. Surveillance systems usually have optics with two or three different focal lengths; so, they can perform detection tasks covering a wide area (field of view), and recognition or identification in narrower areas.

All of the above means that when planning a trial to characterize the susceptibility of a system, to surveillance and target acquisition sensors working in the infrared, it will be necessary to take into account the factors before mentioned.

3. TRIALS PLANNING.

The aim of this kind of trials is to collect a set of infrared images of the targets under study; so, after an appropriate analysis, the infrared signature of them could be characterized.

Because the shape of the targets is different for different positions relative to the imager, it is necessary to acquire images from several points of view around the target (minimum eight). This should be made installing the sensors in a fixed location, and moving the target as required. The elevation angle is also important, because surveillance systems are usually installed on board air platforms. To acquire top views of the target is not easy, specially for the larger ones; normally it is necessary to use wide field of view optics, and that means low spatial resolution. So, a reasonable solution is to put the imagers at a fixed elevation angle, representative of common surveillance systems.

If the target to be tested has some kind of camouflage system available, the trials should be carried out with and without the camouflage system installed, in order to assess its effectiveness.

The targets should be tested in a thermal state representative of operational conditions. For a vehicle this is done following a warming-up procedure (e. g. driving on a hard surface for 30 minutes clockwise and 30 minutes anti-clockwise). During daylight time the vehicle must be kept in the shade for at least 6 hours before warming-up, in order to avoid an inappropriately hot signature. If testing a power generator it must be running at an operational rate.

The trials should be repeated for different environments. Typical conditions are: clear summer’s day, overcast day, clear night and overcast night. Measurements should not be made during rainfall or high wind speed. As it has been said before, the background also has a strong influence in target acquisition tasks. Because backgrounds are very different for each operational scenario, and experience seasonal changes, it is very difficult to carry out tests that cover all the possibilities. An alternate solution is to use a uniform background at a known temperature. In this way, it is possible to make comparisons between infrared signatures, associated to different vehicles and environments.

To acquire infrared images of the targets under analysis, the appropriate thermal imagers must be chosen. Ideally, they should be the same used in real threats. Because, normally, this is not possible, the following should be taken into account:

- the sensors must work in wavebands typical for thermal infrared (3-5 and 8-12 µm),
- sensitivity and spatial resolution must be representative of current threats.

The resolution over the target depends too, on the range at which the sensors are set up. It should be such that the target, in its largest dimension, fills the field of view. At least, the target must cover two times the Instantaneous Field of View.

It is convenient to use calibrated thermal imagers, in order to obtain temperature maps of the target surface. Although surveillance and target acquisition systems do not have that capability, is interesting to identify quantitatively the hot spots on the target; so, adequate methods for temperature reduction could be applied.

4. TRIALS EXECUTION.

The methodology explained above has been used to assess the vulnerability, in the thermal infrared, of a Spanish Army surface-to-air missile system.

The system consists of nine different targets, namely:

- Fire control unit.
- Missile launcher.
- Cannon.
- Launcher’s power generator.
- Cannon’s power generator.
- Truck 10 Tons.
- Truck 8 Tons.
- Truck 5 Tons.
- Light vehicle 1 Ton.

Camouflage nets for all the targets were available, and they were used in the tests. Measurements with the nets installed were made, for each target, immediately after the measurements without net; so, the thermal state of the vehicle was the same in both cases.

Before entering the measurement area, the vehicles followed a warming-up procedure as described in section three. The power generators were running at their operational rate.

The measurement area was a concrete surface with marks for the eight horizontal aspects, in which the vehicle was going to be tested (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). Orientation was defined such that 0° is the left side of the vehicle, and aspect angle increases as the vehicle is rotated anti-clockwise, as viewed from the top.

The targets were placed under a sun shield to avoid direct sunlight during the measurements. A hessian screen, shielded from direct solar radiation was used as background, and its temperature was monitored during all the test.

Environmental conditions were clear summer’s day, and clear night.

The thermal sensors were installed at a range of 60 meters, on a slightly elevated place.

Surface temperatures in ten selected points of the targets were measured by means of calibrated thermocouples. These data were used as a reference, for temperature maps recorded with the thermal imagers.

The equipment used was the following:

- Two calibrated thermal imagers Agema SWB (3-5 µm) and Agema LWB (8-12 µm).
- Digital recording unit.
- TV camera and video recorder.
- Laser rangefinder.

- Weather station (with sensors for pressure, ambient temperature, humidity, solar irradiance, wind speed and direction).
- Datalogger and thermocouples K.
- Monitors.

5. DATA ANALYSIS.

Target acquisition in the thermal infrared can be made when one of the following conditions is met:

- Thermal contrast between target and background is higher than a given threshold.
- The target exhibits a textured appearance, with areas of constant temperature bigger than a specified size.

The first condition is important for detection tasks, because thermal imagers are able to sense small temperature differences from long ranges. The second one is specially meaningful for recognition, because man made objects usually have regular patterns that are difficult to find in natural backgrounds.

Processing of the thermal images for each target and condition, is necessary to obtain thermal contrast and textures. The procedure applied has been the following:

- For each pixel of the image the temperature difference with respect to average background is calculated.
- All the pixels on the target having temperature differences higher than a threshold are marked out, and the corresponding area calculated.
- Starting from the lowest temperature in the thermal image, a search for constant temperature areas is carried out. Because thermal resolution of the images is 1 °C (one digital value), differences of temperature between pixels of ±1 °C have been neglected.
- Areas of the target that meet the above condition are marked out.

6. RESULTS.

The results of the analysis applied to two of the targets tested are presented in figures 1 to 14.

Figures 1 and 2 show the importance of acquiring images from different points of view, in order to properly characterize the signature of a target. Figure 1 is a front view of a power generator. In that image no significant areas are seen. Figure 2 is a rear view of the same target. Although the geometrical shape of both images is nearly the same, in image 2 the engine and exhaust system are clearly displayed. These parts have a thermal contrast with respect to background, high enough to allow detection. In figure 3 is marked out in red, and evaluated, the corresponding area.

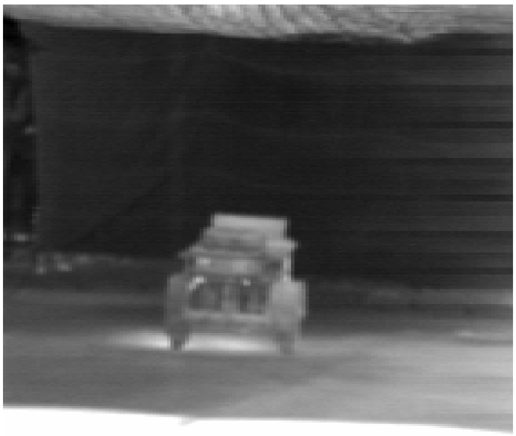

Figure 1. Power generator. Front view.

Figure 2. Power generator. Rear view.

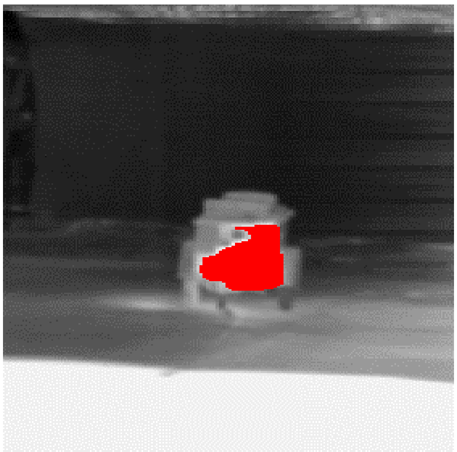

Figure 3. Power generator.
Rear view. Pixels with thermal contrast above threshold, in red. A= 1.5 m².

Figure 4 is a front view of the power generator with a camouflage net installed. The thermal contrast of this image is lower than that of figure 1; so, the net seems reduce the vulnerability of the power generator. Figure 5 is a rear view of the generator with the net installed. There is some improvement with respect to the case shown in figure 2, but the net is clearly insufficient to mask the exhaust system. So, detection of the target is still possible, even with this camouflage net installed. Figure 6 shows in red the high contrast area.

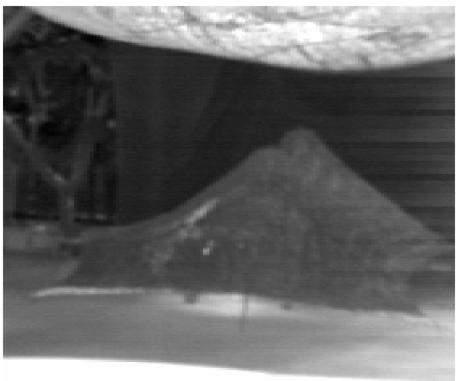

Figure 4. Power generator. Front view. Camouflage net installed.

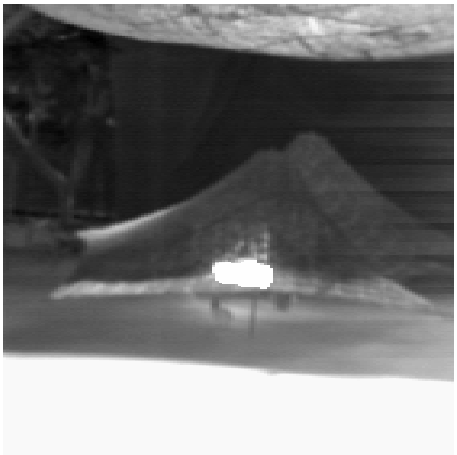

Figure 5. Power generator. Rear view. Camouflage net installed.

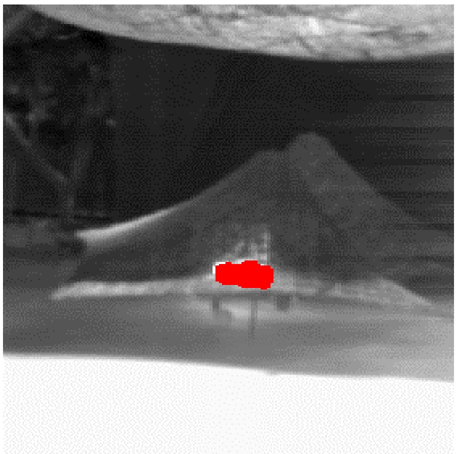

Figure 6. Power generator. Rear view. Camouflage net installed.
Pixels with thermal contrast above threshold, in red. A= 0.5 m².

Figure 7 displays a left view of a truck in a day condition. Hot parts corresponding to the engine and the exhaust system are clearly viewed. These parts could allow detection, but not recognition, because their shape is not distinctive. However, a texture analysis reveals, areas of constant temperature having circular patterns. Figure 8 shows some of these areas in red. This allows recognition, because circles are typical of a wheeled vehicle like the one considered.

Figure 7. Truck. Left side view. Day condition.

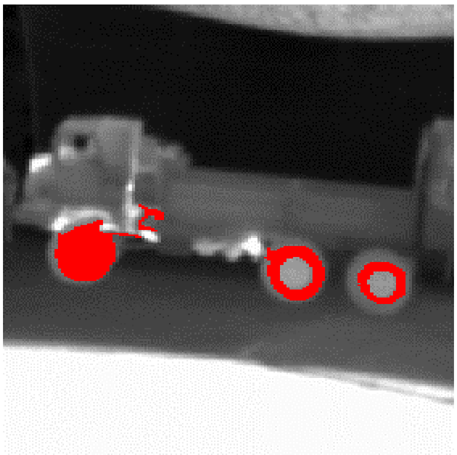

Figure 8. Truck. Left side view.
Day condition. Areas of constant temperature, in red. A= 2.3 m².

Figure 9 shows the same truck in a night condition. Circular patterns are visible as displayed in figure 10; so, recognition at night is possible.

Figure 9. Truck. Left side view. Night condition.

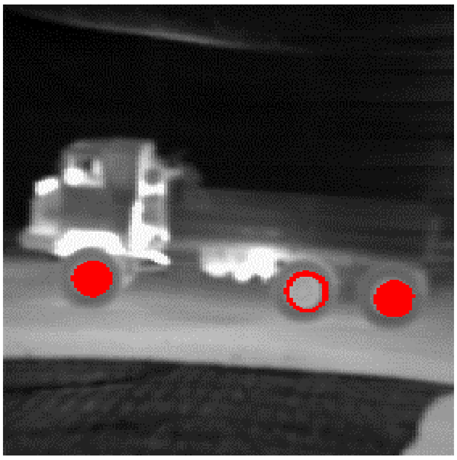

Figure 10. Truck. Left side view.
Night condition. Areas of constant temperature, in red. A=1.1 m².

Figures 11 to 14 show the truck at day and night with a camouflage net installed. Hot parts are still visible, but the texture analysis does not reveal characteristic shapes; so, recognition is not possible when the net is installed.

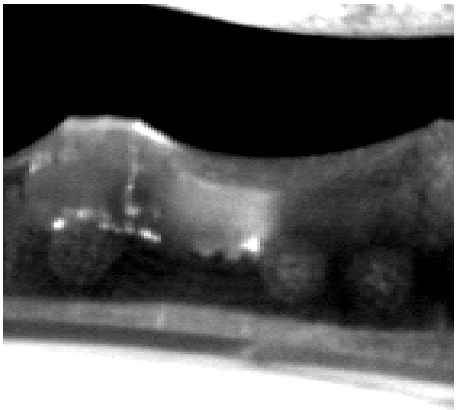

Figure 11. Truck. Left side view. Day condition.
Camouflage net installed.

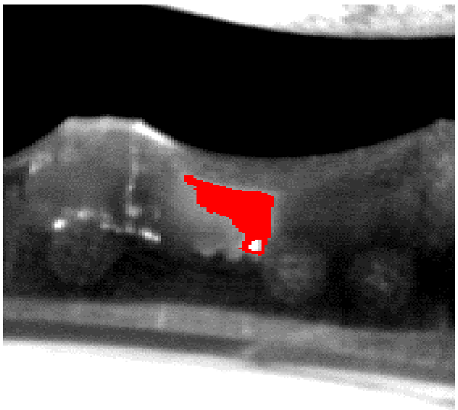

Figure 12. Truck. Left side view. Day condition.
Camouflage net installed. Areas of constant temperature, in red. A= 1 m².

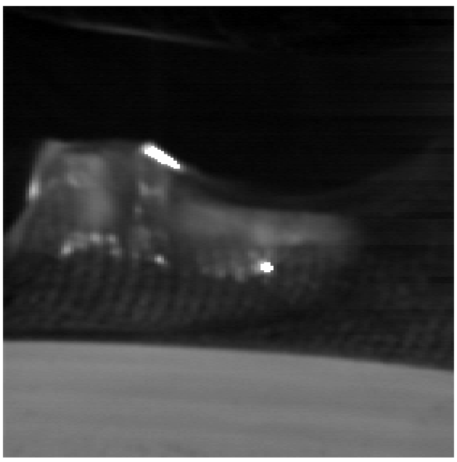

Figure 13. Truck. Left side view. Night condition.
Camouflage net installed.

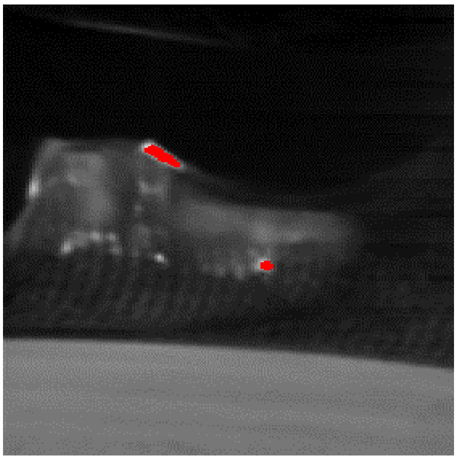

Figure 14. Truck. Left side view. Night condition.
Camouflage net installed. Areas of constant temperature, in red. A= 0.2 m².

7. CONCLUSIONS.

The susceptibility of a surface-to-air missile system to surveillance and target acquisition sensors operating in the infrared has been analyzed by testing.

To carry out a complete analysis factors like: waveband of interest, target orientation relative to the imager, thermal state of the target, environmental conditions and camouflage systems; must be considered.

Hot parts of the targets are clearly seen in the infrared, and could give place to detection at day or night conditions. This is specially true for certain orientations of the target.

Camouflage nets not always can mask hot parts; so, detection could be possible with the net installed.

Recognition of the target is made looking for characteristic patterns. These patterns are not necessarily associated to the hottest areas of the target. Camouflage nets give place to non regular patterns; so, they could be more effective to avoid recognition than detection.

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AVTP Trial Series 05: Security from Detection.

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Assessment of the Effectiveness of the Integrated Air Defense of Multinational Peacekeeping Crisis Reaction Forces

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1. The Specific Nature of the Organisation of the Air Defense of Multinational Peacekeeping Forces (MPF AD).

MPF AD should be organised in accordance with the UN mandate (UN Security Council Resolution). The UN mandate states:

- The objectives defined for MPF and their AD;
- The basic methods of task execution;
- The restrictions on AD and MPF air force actions in the airspace;
- The limits applying to airspace use by air force of the contending parties and contiguous countries in peacekeeping regions and some other regions.

Among the main objectives assigned to MPF AD are the following:

- Control over airspace in the peacekeeping regions and in the air safety zone (ASZ),
- Coordination of airspace use,
- Organization of cover for MPF and for the units they protect.

Control over airspace in peacekeeping regions is a complicated organizational and technical goal. The complicated character of the goal is due to the requirement for guaranteed all-altitude control in the zone under MPF AD jurisdiction and also the need for 24hr radar surveillance and the extremely limited time frame for reaction to possible attacks in the airspace. In some cases the multinationality of the peacekeeping forces is also a significant factor.

The requirement for all-altitude control (1) over the zone under MPF AD jurisdiction ($\mathbf{H}_{\mathbf{ad}}$) is determined by the necessity to control airspace at all altitudes available to aircraft of all types ($\mathbf{H}_{\mathbf{max}}$) at the disposal of the contending parties as well as at the disposal of neighboring countries.

$$H_{ad} \geq H_{max} \qquad (1)$$

There are complications concerning the requirement for 24hr duty on airspace surveillance. They are as follows:

- First, the demand for several specialist groups which would replace each other and thus provide twenty-four-hour maintenance of the equipment.
- Second, the necessity to carry out the task of control over a long period of time. Overcoming conflict is a slow process, and the moment of final reconciliation of the parties is often protracted which is why the peacekeeping operation could last as long as the process of negotiation. In isolated cases, the peacekeeping operation forming part of one and the same UNO mandate might continue for several months or even years. The mission of constant airspace control has to be carried out throughout this period.

Paper presented at the RTO SCI Symposium on “System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces”, held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

At the same time some peacekeepers return home after completion of their military service and new peacekeepers must undergo the appropriate course of training and take the place of their predecessors. Over a certain time span they undergo a commissioning procedure for peacekeeping units including MPF AD elements. This hinders the effective use of radar devices and the accomplishment of the airspace control task.

Third, the limited operating characteristics of radar equipment. The equipment should regularly undergo maintenance if it is not in battle mode operation; if the equipment operational date has expired it should be replaced. Therefore, it is hardly possible to operate with only one radar station for MPF AD, even if the station is capable of detecting air targets in the peacekeeping region. There should be at least two radar stations.

With reference to MPF AD units we can conclude that there should be more radars than the design specification for the single coverage of the zone under MPF AD jurisdiction.

Looking at this problem in the light of tactics we should take into consideration possible cadre casualties as well as losses of armament units used for radar control over the airspace. These losses might be a consequence of force implementation by one of the contending parties against the peacekeepers. Predictable losses due to participation in military actions can be compensated for by timely creation of facility and force reserves. Otherwise, if there are no reserves, theoretically and practically there are several options for filling a gap in the radar field of the MPF AD:

- For a period of a few hours the task can be carried out with the help of aircraft and helicopters for radar patrol provided that meteorological conditions are satisfactory;
- If several days coverage are required ship radar assets can be used in the coastal regions;
- Over a prolonged period of time the task can be accomplished by new radar reconnaissance units which include one member from every MPF country in accordance with an additionally coordinated agreement.

Thus, 24hr airspace control can be accomplished under the following conditions:

- Location of a sufficient quantity of reliable radar installations in the field and the necessary battle crews for 24hr operation,
- Deployment of the required number of radars to create a solid radar field in the peacekeeping region and in the air safety zone if such are established,
- Timely creation of adequately trained staff reserves and constitution of armament reserves to compensate for probable losses due to participation in military actions,
- Timely maneuver of the radar intelligence forces assembled for peacekeeping operations. At the same time it is necessary to allow for the possibility of using radar reconnaissance assets installed on troop carriers and ships in the coastal area.

Organization of co-operation with the air defense capabilities of neighboring countries whose peacekeeping contingent forms part of MPF or where such countries agree to occasional participation in the task of radar control of airspace in peacekeeping regions.

It is acceptable, for airspace control, to use certain radar ground reconnaissance assets at the disposal of peacekeeping crisis reaction forces. Nevertheless, this does not fully solve the existing problem due to the limited capacities of these radar assets with regard to the range and altitude of detected targets.

The most significant factor in the organization of MPF AD is the time limit. The small amount of time that the joint air defense has at its disposal is first of all dictated by the limited area of the peacekeeping operation and high airspeeds of the aircraft.

Let us take for instance Kosovo, (KFOR peacekeeping operation) the territory of which is some 11 00 square kilometers in extent. If we consider the territory of Kosovo as a square then we can obtain a linear measure, i.e. a square side along which, hypothetically, an intruder can infringes the order of airspace use. The length of one square side is approximately 150 km. Supposing that the whole of the air safety zone is controlled by MPF AD, then the complete course of an aircraft from the moment of its detection at the edge of the air safety zone to its exit from the peacekeeping region would be 130 km. Even at subsonic airspeed (Vi ≅ 300 meters per second) its presence in the zone of impact would be no more than 7,2minutes.

A somewhat more favorable time balance can be achieved for MPF AD when the intruder is a helicopter at low airspeed (Vi ≅ 75 meters per second). In this case its presence in the zone of impact would be approximately 29 minutes. The calculation is made for ideal conditions when the air target is constantly detected throughout its course. Nevertheless, time balance with respect to the intruder is practically minimal. I.e. time available for impact ($\mathbf{T_{disp}}$) and time needed ($\mathbf{T_{need}}$) 12.

$$T_{disp} \approx T_{need} \tag{2}$$

This kind of time balance means zero tolerance of all possible unjustified losses of time in major MPF AD units. Losses can be avoided or significantly reduced in four areas:

1) In the control system, by automation of the control procedure on the use of airspace by civilian and military aircraft and also by automation of the whole control cycle for air defense reconnaissance and combat assets. Here, great emphasis is placed on dynamic elimination of weaknesses in knowledge of the active control language of control by the C2 officers in the MPF AD for whom this is a foreign language. Similarly, this can be applied to the handling of automated control equipment used by specialists at standard work stations;
2) In radar reconnaissance systems by realizing realization of all the potential capacities of radars for target detection at maximum range. This can be achieved by automisation of detection procedures, modernization of locating devices and constant target tracking in intensive natural noise. In isolated cases intensive jamming can be applied;
3) In short and medium range SAM units by optimal positioning for maximum target shoot-down capability and by organisation of operating procedures.
4) In the MPF air force, by reducing the necessary number of radar patrol aircraft required in order to reconstruct the radar field and its development in the directions of potential threat. Scheduled patrols of airspace by interceptor crews can be organised when there are no other assets capable of acting in a certain part of a zone under MPF AD jurisdiction or in case of necessity.

Special attention should be given to the multinationality of MPF AD. Let’s take as an example the air defense assets of the Dutch and Belgian airmobile brigades which are recruited and trained for peacekeeping missions.

The 11th airmobile brigade (Holland) has 3 platoons of portable SAM batteries at its disposal. In every platoon there are 24 Stinger type man-portable guided missile (MPGM) units, making in all 72 Stingers. The Belgian brigade has a battery of MPGM containing 18 “Mystral” type MPGMs. In the peacekeeping brigade of the Russian Federation, which acts as part of the multinational division “North” in Bosnia and Herzegovina, air defense forces also consist of MPGM subunits.

The maximum range of this kind of device does not exceed 6 km and the maximum altitude is no more than 3500 m. Air intruders are unattainable for air defense systems used for the self-defense of mobile peacekeeping brigades at heights of over 3500 meters.

The Dutch and Belgian brigades are members of the multinational airmobile division “Center”. According to the media, the primary problem of equipment support for the Division “Center” is the variety of armament and military equipment models. Despite the efforts made by NATO on standardization during the last 30 years, at the present time the division is equipped with:

Helicopters – 6 types,

Artillery – 6 types,

Small arms – 9 types,

Antitank weaponry – 7 types,

Military vehicles – 10 types.

In addition, each type may have up to 4 modifications. Air defense armament is approximately in the same situation.

Thus, various types of armament of similar class and mission are widely used in MPF. They can significantly differ in their battle capacities from one to another. In addition to this, the quantity of armament of similar class available to military units and formations of equal level can be totally different. These two things are objective factors which complicate organization of MPF AD.

The next conclusion concerns the absence of proper radar intelligence assets in airmobile brigades; their availability would enable build up of the required radar field. These brigades do not have short and medium range SAM units which are essential for MPF AD to combat especially dangerous intruders and in particular the transports used for delivering military supplies to the contending parties.

The absence of the above mentioned air defense assets in the peacekeeping brigades demands means that they should be incorporated into multinational peacekeeping divisions or into units that are subordinates at a higher level, i.e. at the level of international security forces commander. The latter option seems to be the most rational from the organizational and economic points of view.

2. Influence of the Phased Deployment of MPF in the Peacekeeping Region.

In accordance with the Military-technical agreement between the international security force (KFOR) and the Governments of the Federal Republic of Yugoslavia and the Republic of Serbia, 72 hours after the entry-into-force day (EIF) of the agreement, all the forces and assets of FRY AD are to be completely withdrawn from Kosovo and other parts of Serbia, i.e. outside the 25-kilometere air safety zone. At the same time, the complete withdrawal of all Federal Republic of Yugoslavia forces from Kosovo is to be completed by the end of the 11th day, which is 8 days later than the EIF. The speed that the MPF should use when deploying is calculated on the principle of “avoiding any vacuum in security issues”. This fully concerns the deployment of MPF AD.

Consequently, there should be advanced air defense units in the leading columns entering the peacekeeping region; the radar should be deployed simultaneously or even before removal of the radar station of the departing government forces.

Cover of the MPF from the air threat during the initial phase of deployment is theoretically possible in three ways:

- With the help of AD assets for immediate cover of both organic and attached units at low and limit low altitudes;
- With the help of interceptors from one or more of the MPF countries, based on aerodromes of neighboring countries and capable of performing duties in the air or on the depot aerodrome. Interceptor control is carried out from the air command post (airborne warning and control system**,** AWACS);

- With the help of SAM systems within the altitude and range zone of neighboring countries and subordinate to the international security commander, provided there are necessary agreements that meet the demands of international law.

The border air defense zone of neighboring countries can be viewed both as a means of organization and as an objective for their air defense, i.e. to cover a part of the MPF in the peacekeeping region during the initial phase. Air defense systems of this kind are not only multinational but intergovernmental. This affects the organization of MPF AD. The system must have the required communication channels and data transfer links to ensure this type of control. It is reasonable to incorporate coordinator officers into the operation groups of the MPF headquarters and of neighboring country AD headquarters.

During the following phases of the MPF AD peacekeeping operation, it is possible and expedient to continuously cooperate with the air defense border zones of neighboring countries.

From the outset, i.e. the crossing of the state border or the peacekeeping region border, international security forces should have cover from the air threat. During the initial phase of the peace support operation, (PSO) due to the lack of absolute control over the situation it is highly probable that armed conflicts between the contending parties might suddenly break out and all kinds of armament might be used, including air attack.

At such times, the commander in chief of the MPF is under great pressure when controlling the peacekeeping forces entering designated areas and he can not devote all his time to air defense objectives at the expense of the major objective, i.e. control of peacekeeping force deployment. Nevertheless, air defense missions still exist; and they tend to be rather complicated when the contending parties have small numbers of air attack assets at their disposal due to the limited volume of reliable data on the air situation.

The control objectives of MPF AD are specific and their accomplishment demands special training and appropriate control skills from the corresponding officials, which is why is it preferable and expedient to place all responsibility on one of the deputy commanders in chief of the MPF or even better with a deputy commander in chief for air defense issues. The post of deputy commander in chief of MPF on air defense issues is therefore an essential one during the initial phase of PSO.

The rule which has emerged from practical experience demands top-priority entry and deployment of joint air defense forces in the PSO region and demonstrates the necessity of having a basic MPF AD unit at the disposal of the commander in chief of MPF. The objective of the basic MPF AD unit is to provide the commander in chief of the MPF with reliable radar data on the air situation and to frustrate possible plans of the contending parties to have armed conflicts in the airspace or to attack peacekeeping forces.

A basic MPF AD unit for a PSO region with a total territory of 10-15000 km 2 might be configured as follows: one radar reconnaissance battalion (or advanced company), 2-3 SAM battalions of short and medium range and a CAM system (computer aided management system) for the MPF AD to ensure interoperability of the air defense assets belonging to the national peacekeeping contingent.

It is expedient to detach the basic air defense unit from one country or from a regional military organization. The head of the basic MPF AD unit completes a course of professional training as deputy commander in chief of MPF for air defense issues. Following the full-scale deployment of MPF and the decline of the air threat level in the PSO region, it is reasonable to take a new decision on the organization of MPF AD including the configuration of its basic unit.

Control of MPF AD in the peacekeeping region might be complicated due to double subordination of separate national peacekeeping contingents. With regard to administration they are subject to national command, with regard to operation control they are subordinate to the commander in chief of MPF. In isolated cases, direct operational subordination is conditional. In order to carry out a decision it is necessary to get not only the order from the commander in chief of the MPF but also confirmation from the senior national military commander in the MPF headquarters. Naturally, this complicates the system of control.

There are other factors that complicate control of MPF AD:

- Heterogeneity of the applied air defense assets;
- Peculiarities of the national legal system on questions of peacekeeping actions;
- Problems of reliable linguistic support for peacekeeping operations and peculiarities of the national psychological mentality of the peacekeepers in terms of multinationality.

The specific nature of MPF AD control places high demands on its automation, on reduction of the number of control levels to a reasonable amount especially in cases of tactical problem solving. Therefore, on completion of full-scale deployment of MPF and despite the expected decline in the air threat level the mission of direct control over air defense forces should be carried out by the deputy commander in chief of MPF for air defense issues. This is why the post on the MPF control staff should be maintained until complete elimination of the air threat.

The deputy commander in chief of MPF AD should have a battle control group to plan application of all MPF AD forces and control them during peacekeeping operations. Among the members of the battle control group should be the officers of those countries that have committed their sub-units to the MPF AD and where complicated legal standards on national peacekeeping contingent participation are in force. Naturally, if there is no air threat there is no need to maintain the post of deputy commander in chief of MPF AD and the appropriate specialist staff.

The nature of resistance during peacekeeping operations (high dynamism and transiency, incomplete data and increased level of threat from even one ASSU (air and space strike unit) is practically the same as against aircraft in the course of normal combat operations. This is why the joint air defense of the MPF must be of the same quality that of a national air defense. This requires high effectiveness, stability, mobility, flexibility, and the capability to solve the unexpected problems. All these qualities need to be evaluated in order to improve the MPF air defense system.

3. Purpose and Tactical-Technical Basis of the Interactive Model System for MPF Joint Air Defense.

The system of interactive models (CIM) is intended for the design of complicated real time technical systems including the solution of problems of planning, organization and preparation of the joint MPF air defense and research into its effectiveness. The principal questions that can be formulated with the help of the CIM are armament, build up and functioning of the joint MPF air defense and its sub-systems and sub-units. Moreover, common and special problems of air traffic control (ATC) in the peacekeeping region can be solved with the help of the CIM.

At the present time there are still ongoing on peacekeeping operations in many regions of the world. In some of them there is still a serious air threat to the peacekeepers as well as to their efforts in supporting peace. This threat can come from contending parties or from third countries that support one of conflicting parties and deliver military supplies to it by air.

The sources of air threat sources are the ASSU’s that are being constantly modified. In response to this, new air defense assets are designed and the old ones modified, and new ways and methods of employment are being actively worked out. Development of operating means and methods for ASSU’s and AD significantly influences air defense organization for peacekeeping operations.

Under these circumstances the effectiveness of MPF AD at the required level is an acute and extremely complicated problem which demands well-grounded decisions and considerable financial resources.

In order to exclude unjustified expense and to save UNO resources, it is necessary to have highly efficient decision making tools for joint MPF AD organization issues in the designated peacekeeping region. At this point it is necessary to choose the most rational combination of air defense assets from all the possible units that can be submitted by national armed forces for inclusion in the MPF AD structure.

In the event of any alteration of the UNO mandate, the command and the staff of the MPF AD should prepare a new decision on joint air defense as quickly as possible; this is to be accomplished with the help of the appropriate hardware and software; it should be put into practice in variants to suit the new circumstances of the evaluation of all-round effectiveness of the modified AD.

The specially designed interactive model system (IMC) of the combat activities of different forces and air defense assets enables this kind of possibility. The IMC is a new software product which makes it possible to design the following, in the Windows system:

1) Mathematical models of ASSU equipped with any possible variant of combat airborne weapon. There is a hypothetical variant that for research aims a random set of onboard equipment and armament can be chosen.
2) Mathematical models of ASSU actions. Actions of various scale and intensity are designed and they range from single airspace object action to delivery of massive air and missile attack.
3) Mathematical models of air defense assets (radar stations and systems, air defense missile systems, fighter-interceptor, electronic command post automation system, etc.)
4) Mathematical models of air defense units of random composition and configuration.
5) Mathematical models of bilateral combat actions formed entirely of software blocks that simulate ASSU unit employment processes and reciprocal actions of air defense units.

The IMC is a highly effective tool for short term problem solving for air defense. We consider the following to be at the top of the problem list:

- Assessment of the effectiveness of the deployed air defense units and exposure of their weak aspects;
- Substantiation of trends in new air defense facility design and modernization of outmoded air defense assets (electronic command post automation system, radar stations, air defense missile systems, radar intelligence and electronic warfare assets, etc.);
- Substantiation of nomenclature and procurement of new equipment for rearmament of air defense units;
- Design of new and modernization of existing air defense units in order to provide the required efficiency. The principal elements of the given system are:
  - choice of the armament and military equipment produced for air defense forces and assets in a specific region;
  - substantiation of the numerical composition of formations, units and sub-units of army branches and of specialized air defense troops;
  - build up of the air defense unit and its structural optimization depending on the problems set;
  - the choice of a rational control system for the air defense unit;
  - substantiation of methods and order of interaction between the different elements of the air defense unit;
  - substantiation of the combat order of units and sub-units of army branches in the air defense unit for the practical solution of specific air defense problems;

- Creation of different simulators and simulation systems for single operator training on separate systems, for reduced and full combat crew operating information and firing assets, and for combat crew operation of fighter-interceptor direction posts and command posts;
- The set-up and execution of command and staff exercises and war games in real time and for purposes of air defense and non-strategic antimissile defense;
- Planning of air force combat action to penetrate air defense and to deliver air attacks on designated targets;
- Creation of principal modeling systems (stands) and specific software for the design and testing of armament and military equipment available to the air defense unit.

Some examples of principal modeling systems are:

- A system of simulation models for assessment of the effectiveness of combat action, of the vitality and noise immunity of a radar reconnaissance system, and of a SAM defense and fighter cover air force unit;
- Simulation and analytical model system for assessment of the effectiveness of combat actions and of the vitality of electronic warfare units of AD;
- A research system for selection and debugging of optimal algorithms for solution of problems on combat action control and for radar data processing;
- A system for the calculation processing, during the combat action planning phase:
  - of operational and tactical capacities of air defense units
  - of combat estimated losses
  - of armament and military equipment nomenclature and their quantity in the air defense unit reserve,
  - of staff reserve.

The solution of any of the above problems is accomplished in accordance with the basic data conditions and limits set by the Customer and coordinated with the Executor.

IMC is aimed at researchers and specialists working on the problem of the opposition between air defense and air and space strike units, it is also aimed at designers of future air defense and air force systems, at air defense, air force staff officers and MPF staff. The IMC user interface is fairly simple and easy to master.

The principles of IMC design, structure, algorithms and the detail of its constituent parts operation are not confidential. The initial data and the results of the research may however be of a confidential nature.

4. Characteristic of the Modeling Subjects.

The basic subjects of modeling are bilateral combat actions between the air defense unit and the air adversary. They are modeled as a whole and in parts; at this point there is a possibility of termwise modeling of separate sub-systems (control system, radar reconnaissance system, air and space strike units, air defense aircraft unit, electronic warfare units and sub-units). The structure of the basic part of the IMC which includes models of ground air defense forces and assets is shown in figure 1 (appendix 1).

Modeling also concerns various types of air attack assets: airplanes, helicopters, ballistic missiles, aeroballistic missiles, cruise missiles, etc.

All types of air attack assets are characterized by basic parameters, by functional structure, combat operation logic and movement dynamics.

Command stations and control stations with automated systems, means of data provision (radar detection stations), ground and air fire power (FM) of different types, electronic warfare assets, shields against high-accuracy weapon and communication assets are modeled as elements of the air defense unit.

All types of information, fire control and other capabilities included in the air defense unit are characterized by basic tactical and technical parameters, by functional structure and by their combat operation structure.

Control stations (CS) are characterized by their functional structure, their control algorithm system, and by the logic of the battle crew work.

The structure of the air defense unit system of control is selected as a multilevel and can reconfigure during combat actions (dynamic structure), which helps to take into account the possible loss of air defense forces.

The additional modeling subjects are subjects under cover. All subjects under cover can be characterized by a number of parameters including the vulnerability factor.

IMC is suited to modeling not only in terms of time close to real time, but also for modeling on an accelerated time scale, which helps the command post to evaluate a number of MPF AD action variants and to choose the most effective when decision making on the interception of strike aircraft or against intruder actions in the peacekeeping region or in the air safety zone.

The simulation model system using Windows can be successfully installed in the MPF AD local or regional computing system for the creation of complicated air situations, so as to train air movement control operators or to train combat control officers at the command post. With its help it is possible to evaluate the aptitude for control of all officials in operational and combat groups at command posts. At the same time there is a possibility of defining any alteration in control quality due to the lack of skills and knowledge of operational control on the part of MPF control specialists for whom this language is not their native tongue.

This highly effective tool for assessment of the effectiveness of MPF AD, i.e. the interactive model system, has a wide sphere of application for peacekeeping goals as well as for detailed research into problems of opposition between air attack and air defense assets.

Conclusions

1. The design of joint MPF AD should be carried out in accordance with the rules of opposition in airspace between attack and air strike defense assets assumed for the purposes of air defense design in any given nation. The effectiveness of MPF AD at every stage of the peace support operation (PSO) should correspond to the problems posed and to the solutions envisaged.

2. One of the primary objectives of MPF AD is to control aircraft employment in the zone of responsibility. The solution of the problem at definite stages of the PSO can be fully committed to the MPF AD which should be taken into account when setting up joint air defense control and radar reconnaissance systems. Later, there is a possibility of using part of a nation’s air traffic control (ATC) assets for the joint execution of control function in the conflict region until such time as the problem can be transferred to the national air traffic control center.

3. All other things being equal, control of the MPF AD forces is extremely difficulty due to their multinational composition. The basic factors that affect MPF control are: type variety in the weapons applied, insufficient knowledge of the operational language of control by the specialists of certain national peacekeeping contingents, absence of the necessary skills in using the automated control system, differences in legal standards on peacekeeping activities, and negative manifestations of national psychological mentality in a multinational environment. The increased complexity of MPF AD control

makes it necessary to provide a post of deputy commander in chief of MPF on air defense issues and the appropriate specialist group in the command post staff.

4. It is impossible for MPF AD to solve all the problems it is faced with in accordance with the UNO mandate with respect to air defense crisis reaction forces, due to the lack of radar reconnaissance assets and cover assets against ASSU attacks carried out from 3500 m altitude. In the event of an air threat, the air defense assets at division level should be attached to the MPF or to the basic air defense unit directly subordinate to the MPF commander in chief, which has increased capabilities detected target range.

5. The initial phase of PSO, with deployment of MPF is a special element in the theory and practice of peacekeeping. During this phase there is still a high possibility of military confrontation between the conflicting parties and also a possibility of force application against the peacekeepers. This particularly applies to the air threat to MPF and to assets under their guard. The discrepancy between the maximum air threat and the lack of deployed and warfare capable MPF AD forces and assets at this stage can be resolved by full cooperation with the air defense and air forces of neighbouring countries, by cooperation between PSO participants and by obtaining the assistance of the air defense forces of the regional military organization which has provided the greatest number of peacekeepers to the MPF staff.

6. At the end of the initial phase of PSO, and provided there is enough control over the conflict situation, the air threat should decrease in the zone under MPF AD jurisdiction and this will lead to reconsideration of the quantitative organization of active air defense assets.

7. The effectiveness of joint air defense action can serve as an integral base criterion for initial and subsequent decisions on organization and improvement of MPF AD. Assessment of the all-round effectiveness of MPF AD with the use of different types of software and hardware will give the basis for decision making and efficiency. Interactive models of the processes of opposition between ASSU and AD in airspace are an example of future software devices of this type.

A Way to Control Medium and Low Range Weapons Systems in an Air Defense Artillery Command and Control System

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1 Summary

When an Air Defense Artillery (ADA) commander receive the order to defend an area o high value point he also receives the list of ADA units that can be employed. He will never receive the appropriate resources he would like to have.

The most common problem arised to the ADA commander is to manage different kinds of weapons systems (medium, short and very short ranges) given for air defense purposes.

To integrate subordinate Fire Direction Centers (FDC,s) and the various weapons systems in a single ADA Command and Control (C2) Fire Direction Center (FDC) is a real problem.

Functions providing control of weapons require some ideas to be presented in this paper.

The national weapons systems integration can be easily managed.

Non national resources could be integrated if some software and communication problems could be solved.

2 Introduction

Air Defense employment principles are relevant in an ADA C2 system concept. Principles such as mass, mix, mobility and integration have been columns which support the system concept.

Integration, as an operational effectiveness maximizer, is the principle to which more pages are dedicated in this paper.

As System Concept, *mass* implies having an adequate number of weapons systems according to present engagement requirements and future needs.

The main constraints to this number come from communication performances and exchange information needs.

As System Concept, *mix* implies having a variety of weapons systems going from medium SAM (MSAM) to very short range (VSHORAD) systems, and subordinates ADA C2 FDC,s which have weapons systems mixture.

The term *control*, in this paper, should be interpreted as *target assignment to a weapon system*.

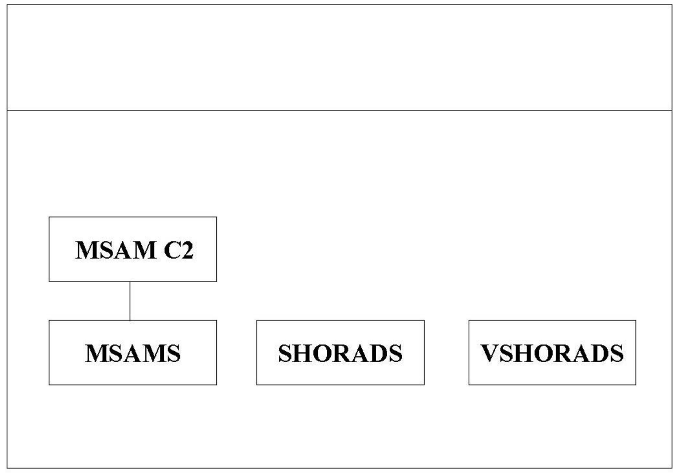
3 National historical perspective

National capabilities in terms of Air Defense Artillery history are explained below.

Very short range (VSHORAD) and short range (SHORAD) weapons systems have been in the inventory for a long time period.

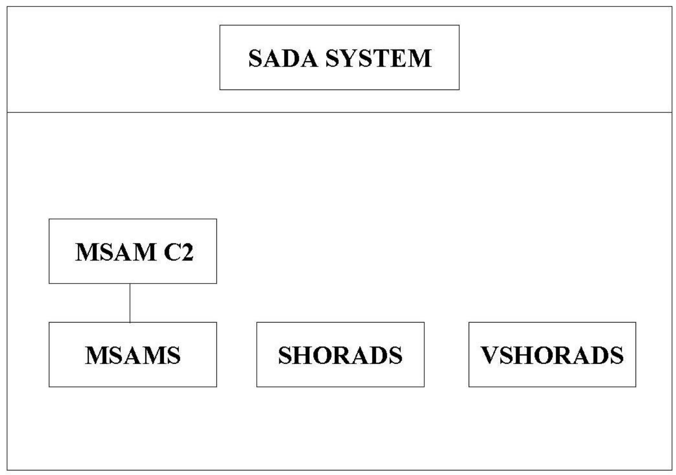
Paper presented at the RTO SCI Symposium on "System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces", held in Valencia, Spain, 22-24 May 2000, and published in RTO MP-063.

In 1965 Army ADA arrived to the medium range (MSAM) theater with integration capability (C2) to control this weapons systems.

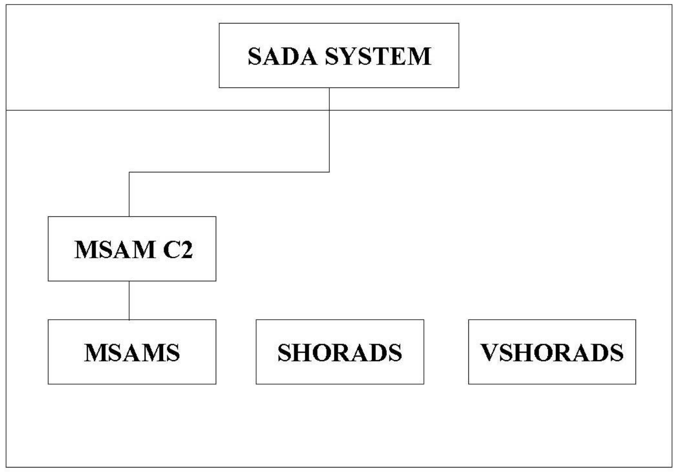


In 1972, Army ADA incorporated a long range unit and acquired integration capability (C2) to control this weapon system.

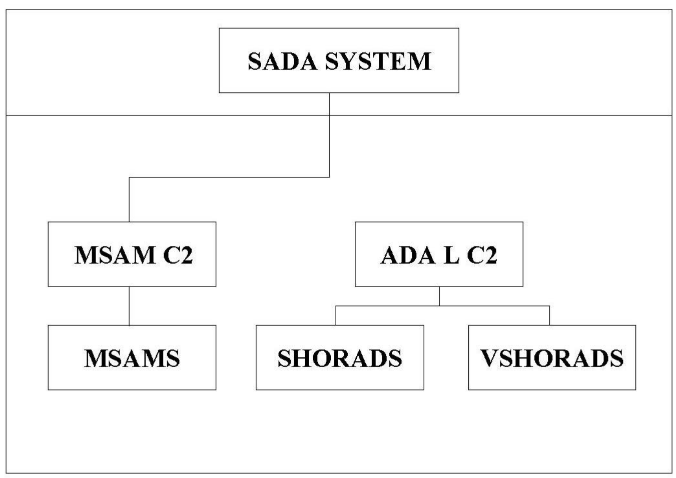
In 1975, Air Force finalized one phase of Combat Grande Program, which allowed to have an Air Defense Semiautomatic System (SADA) able to integrate ADA Command and Control Systems.



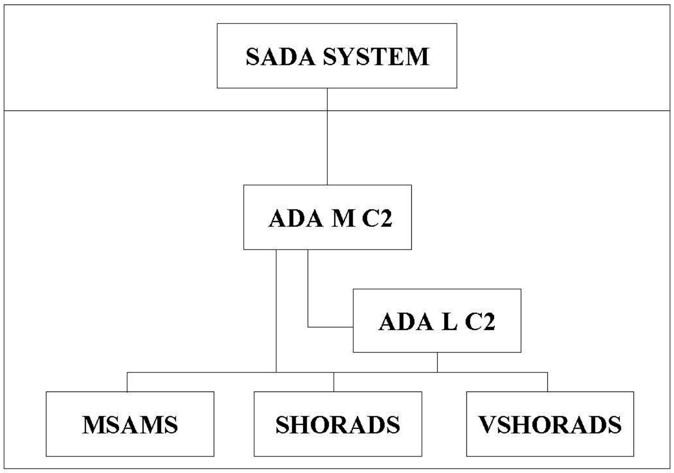
In 1984, Army ADA Command and Control Fire Direction Center for medium range was integrated by data link in SADA allowing to integrate MSAM units in the Air Defense.



In 1997, Army ADA Command and Control Fire Direction Center prototype for Very Short and Short Range Weapons Systems (ADA L C2- COAAASL) was delivered to Army Units for trials finishing in a serial production.



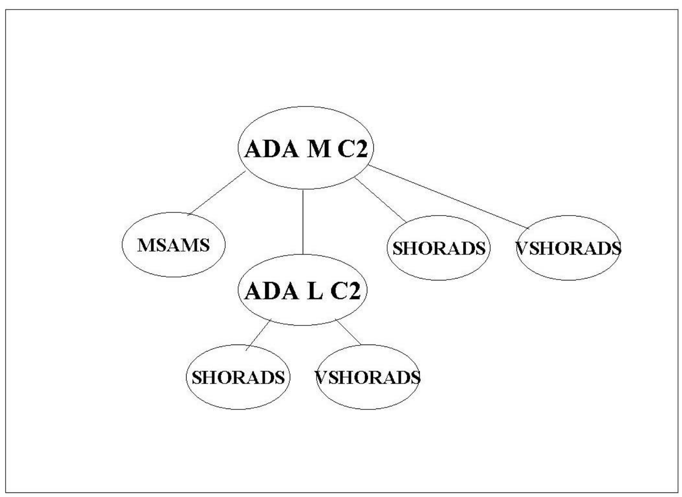
In 2000, Army ADA Command and Control Fire Direction Center prototype for Medium, Short and Very Short Range and ADA L C2 FDC (ADA M C2- COAAASM) will be available. At that moment any national weapon system in inventory will be integrated in Army ADA C2 and in Air Defense (SADA).



In the near term, interoperability between ADA M C2 and other non national Command and Control System will be achieved.

4 Problem presentation

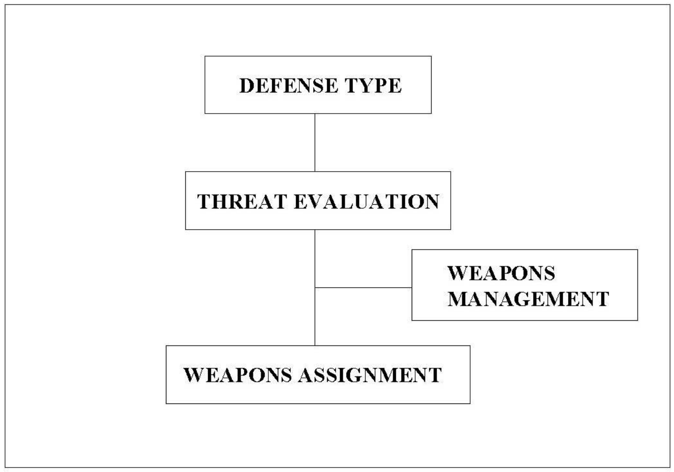
To control (engage a target by a fire unit) a mass/mix of weapons systems and subordinates ADA C2, is the problem at which this paper is dedicated.



5 The way to control

In order to implement the control of weapons systems the following main functions have to be addressed:

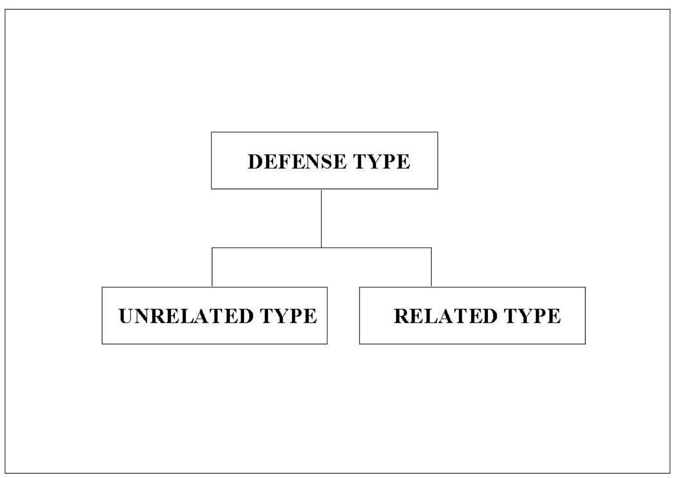
- Defense Type
- Threat Evaluation
- Weapons Management
- Weapons Assignment



6 Defense Type

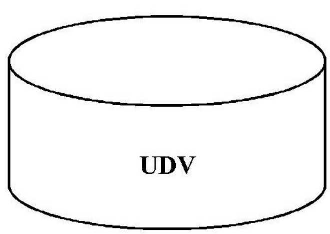
The primary decision is to standardize the types of defense the C2 must deal with. The family approach can be explored:

- Unrelated defense type
- Related defense type



6.1 Unrelated Defense

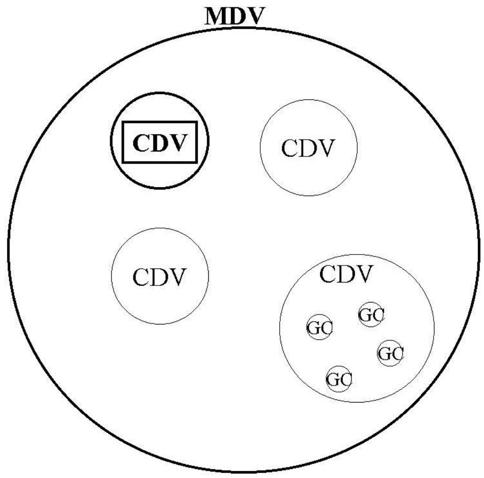
The Unrelated Defense is the airspace zone that can be associated to a sole volume (UDV).

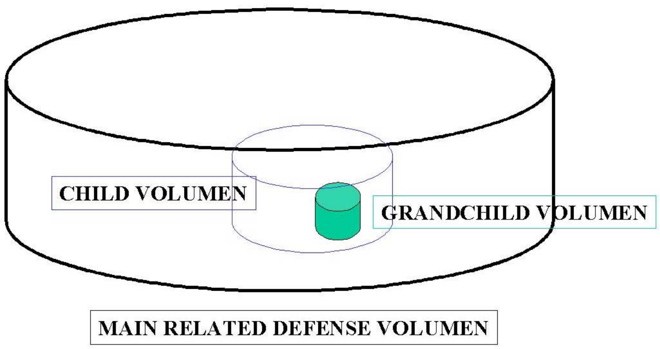


6.2 Related Defense

Airspace zones that can be associated to a family of volumes form the Related Defense. The family of volumes can be made up by:

- A Main Defense Volume (MDV)
- Several Child Defense Volumes (CDV,s) into each MDV
- Several Grandchild into each CDV (if required)





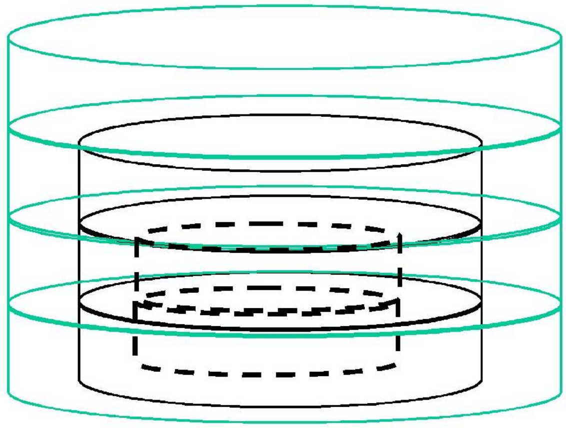
7 Threat Evaluation

The Threat Evaluation function shows how a target position in the airspace is threatening the defense type. Its process can be divided in two steps:

- To design Threatening Position Zones (TPZ)
- To define a Threat Priority List (TPL) of each Zone

7.1 Threatening Position Zone (TPZ)

According to the expected threat it is useful to design - around and inside the Defense Volume (sole or family) - airspace zones where the target positioning must be avoided. If a subdivision in altitude is taken into account, this design will provide a partitioned airspace where the threat is grows more threatening as it enters in the defense volume.



THREATENING POSITION ZONES

H4	TPZ				
H3	TPZ	TPZ	TPZ	TPZ	TPZ
H2	TPZ	TPZ	TPZ	TPZ	TPZ
H1	TPZ	TPZ	TPZ	TPZ	TPZ

The number of suggested zones for a Defense Volume is:

- Unrelated Defense Volume:
  - Several External Zones
  - One Internal Zone
- Main Defense Volume:
  - Several External Zones
  - One Internal Zone
- Child Defense Volume:
  - One External Zone
  - One Internal Zone
- Grandchild Defense Volume:
  - One Zone

7.2 Threat Priority List (TPL)

It is essential to obtain for each Threatening Position Zone (TPZ), the list of targets that are moving to occupy a position into the zone and listing them on a threat decision logic basis:

- Platform type and weapons associated
- Target cinematic
- Etc

8 Weapons Management

Weapons Management deals with a mass/mix of weapons systems. The most important lines of this function are:

- Weapons types to be employed
- Parameters to define this weapons
- Interchanged parameters by data link

8.1 Weapons types to be employed

In this context, a certain number of subordinate units:

- Medium range weapons
- Short Range weapons
- Very Short Range weapons
- Subordinates ADA C2 FDC,s

can be integrated.

8.2 Parameters to define weapons

Parameters associated to the Weapons Management function in order to obtain an Optimal Engagement Plan are as follows:

- Location and type of weapon system
- Primary and secondary TPZ,s
- Maximum effort permitted by TPZ
- Intercept volume
- Weapon speed
- Reaction time
- Compatible type of threat
- Maximum number of engagements

Subordinate ADA C2 can be transformed in a **Special Weapon** before becoming an engageable fire unit. The transformation can be made providing such a special weapon with values according to the SHORADS/VSHORADS under its control in the before mentioned parameters.

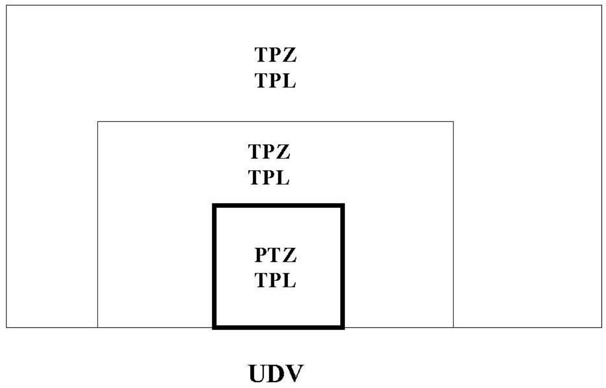
8.3 Interchanged parameters by data link

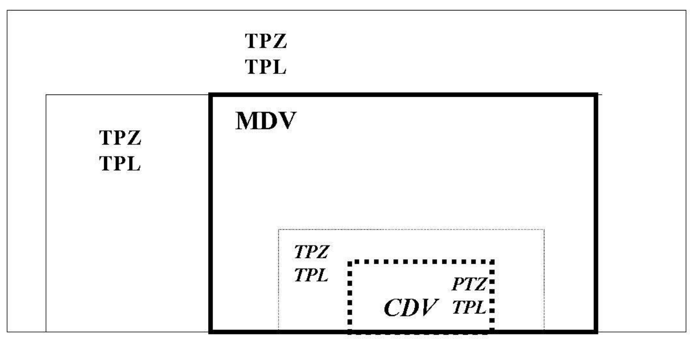
As a minimum, the following parameters are needed:

- Weapons status
- Weapons control status
- Fire control orders

8.4 Threatening Position Zones (TPZ)

Due to in that moment the commander knows the mass and the mix of weapons, he can redefine the Threatening Position Zones (TPZ) to a number more appropriate in order to reduce the amount of Threat Priority Lists (TPL) to play.

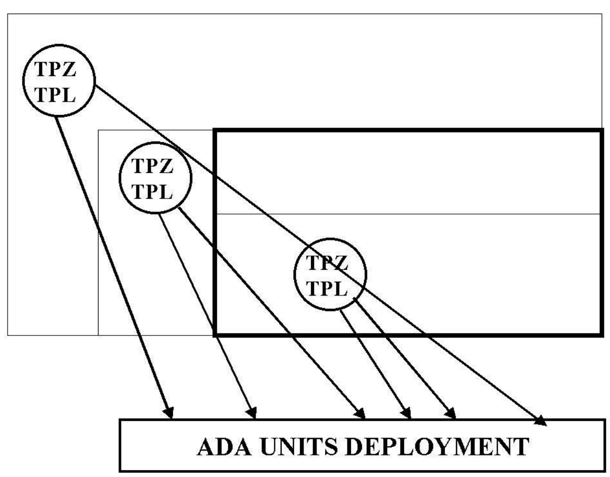




9 Weapons Assignment

In both defense types, the Engagement Plan for each Threat Priority List can employ the following process.

- To determine those weapons systems which are able to counter the threat
- To select the weapon system which can destroy the threat in the minimum time



10 National Weapons Systems

A Combat Net Radio (CNR) and Weapons Terminals provide for the integration of SHORADS and VSHORADS (for warning, cueing and weapons assignment).

A Combat Net Radio (CNR) and standard data links provide for the integration of MSAM Weapons Systems.

11 Non national Weapons Systems

The employment of the same CNR and Weapons Terminals would permit the integration of non-national SHORADS and VSHORADS without changes in doctrine and procedures (for warning and weapons assignment) adapting certain parameters in the weapons terminals (minor software changes).

If MSAM non-national units have the same standard data links, the integration of this type of weapons systems is also possible.

12 Conclusions

Integration of SHORAD and VSHORAD weapons systems (national or non-national) is a real capability at this moment.

Integration of national MSAM SHORAD and VSHORAD weapons systems (directly or through ADA L C2) is no longer a concern.

Integration of national Army Air Defense in Air Defense is no longer a concern.

Interoperability between ADA M C2 will be a challenge to be solved in the near term.

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(2) National Fire Directions Centers Programs bibliography

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Command and control	Weapon systems	
Information systems	Aerial reconnaissance	
Armed forces procurement	Threat evaluation	
Joint operations	NATO	Multinational forces

14. Abstract

The meeting proceedings from this symposium on “System Concepts for Integrated Air Defense of Multinational Mobile Crisis Reaction Forces” was organized and sponsored by the Systems Concepts and Integration (SCI) Panel of the Research and Technology Organization of NATO in Valencia, Spain on 22 to 24 May 2000.

The symposium's goal was to describe techniques and technologies viable for the lay-out and design of operational air defense systems that meet multinational requirements. The papers were presented under the following headings:

- Description of typical scenarios
- Enabling Technologies for Air Defense Systems
  - Sensors (IR, RADAR, UV, LASER)
  - Sensor Fusion
  - Pointing and Tracking
  - Soft Computing, Information Processing
  - High Level knowledge-based (KB) Automation
  - Data-Link, communication
- System Architecture and Mechanization
- Man-Machine Interface, Visualization techniques
- Interface with Weapon Systems and higher level Battlefield Management
- Systems Design for Interoperability

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