NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

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**STO TECHNICAL REPORT** **TR-SAS-097**

# Robots Underpinning Future NATO Operations

(Robots étayant les futures opérations de l'OTAN)

Final Report of Task Group SAS-097.

Published May 2018

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# Robots Underpinning Future NATO Operations

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Final Report of Task Group SAS-097.

Edited by:

Václav Hlaváč and Michal Reinštein

Czech Technical University in Prague

Czech Republic

# The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

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

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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# List of Acronyms

| | |
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| AISBL | Association Internationale Sans But Lucratif |
| ATR | Automatic Target Recognition |
| CAFR | Center of Advanced Field Robotics |
| CBRN | Chemical, Biological, Radiological and Nuclear |
| CCW | Convention on Conventional Weapons |
| C-IED | Countering Improvised Explosive Devices |
| CMRE | Center for Maritime Research and Experimentation |
| CoE | Center of Excellence |
| CTU | Czech Technical University in Prague |
| EC | European Commission |
| EOD | Explosive Ordinance Disposal |
| EU | European Union |
| HIL | Human-In-the-Loop |
| HOL | Human-On-the-Loop |
| HOOL | Human-Out-Of-the-Loop |
| HRI | Human-Robot Interface |
| ICRA | International Conference on Robotics and Automation |
| ICRAC | International Committee for Robotics Arms Control |
| IEEE | Institute of Electrical and Electronics Engineers |
| IROS | International Conference on Intelligent Robots and Systems |
| JAPCC | Joint Air Power Competence Center |
| LAR | Lethal Autonomous Robot |
| LAWS | Lethal Autonomous Weapons Systems |
| LTA | Long Term Aspect of requirement |
| LTCR | Long Term Capability Requirement |
| M&S | Modelling and Simulation |
| NIFTi | Natural human-robot cooperation in dynamic environments, EC project FP7-ICT-247870 |
| ONRG | Office of Naval Research (Global) |
| R&D | Research and Development |
| S&T | Science and Technology |
| SOTA | State-Of-The-Art |
| STO | Science and Technology Organization |
| TARDEC | Tank Automotive Research, Development and Engineering Center (United States Army) |
| TRADR | Long-Term Human-Robot Teaming for Robot Assisted Disaster Response. EC project FP7-ICT-609763 |
| TRL | Technology Readiness Level |

| | |
|---|---|
| UCAV | Uninhabited Combat Air Vehicle |
| USAR | Urban Search And Rescue |
| UxS | Unmanned system; x for aerial, ground or underwater |
| | |
| WS | Workshop |
| | |
| xSAC | System with autonomous capabilities, x stands for operational domain as G (ground), etc. |

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- All collaborators who contributed to SAS-097 activities. Most of them are mentioned in this report.
- Members of NATO STO SAS Panel for their kind advice.

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# Robots Underpinning Future NATO Operations

## (STO-TR-SAS-097)

# Executive Summary


Robots have become the reality in defence, on the ground, in the air, in water, in space. Robots will likely constitute one of the key changing factors in future warfare. The related technology is there, especially if the robot is remotely driven by a human. The robotics background is wide on the scientific and technological levels. A substantial amount of our children get excited by science/technology through robotic toys. Consequently, there is a large pool of future robotics experts, on our side and also on the side of potential enemies. Most industries have been using robots.

In this report, robots are understood as a physically-embodied, artificially intelligent autonomous device, which can sense its environment and can act in it to achieve some goals. Robotics is the discipline aiming at creating such autonomous machines. Robotics integrates outcomes of several scientific and technological areas. Deploying robots and integrating them in the military context is an issue. The gap between the robotic technology and its operational use constitutes an important limitation.

The most important concept opening new horizons for robots is the autonomy. The autonomous machines sector has been boosted in the last decade by the attempt to create a self-driving car. The key car manufacturers, the new ones as Tesla, and informatics industrial giants as Apple and Google have been investing tremendous amount of money in autonomous cars. Universities follow the development too. The situation has changed in the life-time of SAS-097 substantially. The defence sector will benefit from the achievements in self-driving cars.

The NATO SAS task group SAS-097 acted from January 2012 to January 2015 and during its tenure, it:

- ***Analyzed the gap between operational requirements and technological possibilities (relationship to the NATO LTCR/LTAs) –*** The group conducted a trends analysis in Autonomous systems (AxS) in the areas of CONTROL, SENSORS and PLATFORM, completing an analysis of Operational Requirements, analyzing the EU Perspective and completing analysis of research into Human-Robot Cooperation.

- ***Bridged the gap between cutting edge of technology and military operational needs –*** The group participated in NATO exhibitions and exercises, cooperated with other NATO research organizations and center of excellence, and participated in numerous other NATO and EU symposiums, demonstrations and workshops.

- ***Provided experimentation support for robotics concept development and testing*** – The group conducted joint experiments between the Czech University of Defense and United States Army Tank Automotive Research, Development and Engineering Center (TARDEC), worked on multipurpose platform development – Project TAROS, supported real mission deployments and joint exercises with National entities and engaged with the academic community by participating in numerous academic conferences and publishing journal articles.

- ***Organized and Supported NATO Workshops (WS), symposium and conferences.***

- ***Created and supervised bidirectional working links to the European Commission R&D activities in dual-use of robotics.***
- ***Opened possibilities for the new robotics research motivated by military needs and funded by third parties.***

# Robots étayant les futures opérations de l'OTAN

## (STO-TR-SAS-097)

# Synthèse

Les robots sont devenus une réalité dans la défense, à terre, dans les airs, dans l'eau et dans l'espace. Ils constitueront probablement l'un des facteurs évolutifs clés de la guerre du futur. La technologie correspondante existe, en particulier si le robot est piloté à distance par un humain. Le contexte de la robotique est vaste au niveau scientifique et technologique. Beaucoup de nos enfants s'enthousiasment pour la science et la technologie par le biais de jouets robotiques. Par conséquent, il existe un grand vivier de futurs spécialistes en robotique, de notre côté et également du côté d'ennemis potentiels. La plupart des industries utilisent des robots.

Dans le présent rapport, on entend par robot un appareil autonome doté d'un corps physique et d'une intelligence artificielle, qui peut percevoir son environnement et agir dans celui-ci pour atteindre des objectifs. La robotique est la discipline visant à créer des machines autonomes de ce genre. La robotique intègre les découvertes de plusieurs domaines scientifiques et technologiques. Le déploiement de robots et leur intégration dans le contexte militaire sont une véritable question. Le fossé existant entre la technologie robotique et son utilisation opérationnelle constitue une limite importante.

Le concept le plus important qui ouvre de nouveaux horizons pour les robots est l'autonomie. Le secteur des machines autonomes a été stimulé au cours de la dernière décennie par la tentative de créer une voiture sans conducteur. Les constructeurs automobiles clés, les nouveaux comme Tesla et les géants industriels de l'informatique comme Apple et Google, investissent des sommes considérables dans les voitures autonomes. Les universités suivent également ce développement. La situation a sensiblement changé au cours de la durée du SAS-097. Le secteur de la défense bénéficiera des réalisations dans le domaine des voitures sans conducteur.

Le groupe de travail de l'OTAN SAS-097 a été actif de janvier 2012 à janvier 2015. Pendant son mandat, il a :

- ***Analysé l'écart entre les besoins opérationnels et les possibilités technologiques (relation avec les LTCR / LTA de l'OTAN)*** **–** Le groupe a mené une analyse des tendances des systèmes autonomes (AxS) dans le domaine du CONTRÔLE, des CAPTEURS et des PLATEFORMES, réalisé une analyse des besoins opérationnels, analysé la perspective de l'UE et achevé l'analyse des recherches sur la coopération entre humains et robots.
- ***Comblé le fossé entre les technologies de pointe et les besoins opérationnels militaires*** **–** Le groupe a participé à des expositions et exercices de l'OTAN, coopéré avec d'autres organismes de recherche et centres d'excellence de l'OTAN et participé à de nombreux autres colloques, démonstrations et séminaires de l'OTAN et de l'UE.
- ***Apporté un soutien à l'expérimentation concernant le développement et l'essai des concepts de robotique*** **–** Le groupe a mené des essais communs à l'université tchèque de la défense et au TARDEC (*Tank Automotive Research, Development and Engineering Center*) de l'armée de terre des Etats-Unis ; il a travaillé au développement d'une plateforme polyvalente, le projet TAROS ; il a appuyé des déploiements en mission réelle et des exercices interarmées avec des entités nationales et

s'est impliqué auprès de la communauté universitaire en participant à de nombreuses conférences de chercheurs et en publiant des articles dans les revues.

- ***Organisé et soutenu des séminaires, colloques et conférences de l'OTAN.***
- ***Créé et supervisé des relations de travail bidirectionnelles avec les activités de R&D de la Commission européenne dans la robotique à double usage.***
- ***Ouvert des possibilités pour les nouvelles recherches en robotique, motivées par les besoins militaires et financées par des tiers.***

# Chapter 1 – INTRODUCTION

**Michal Reinštein**
CZECH REPUBLIC

## 1.1 STUDY CONTEXT

The growing use of robotic systems in present day military operations and their expected increased introduction over the coming decades raises questions such as how to assess advances in robotic technology within the context of NATO operations and identify critical areas where Science and Technology (S&T) exploration will be required. Future operating environments will be more complex and uncertain, and future robotics systems will offer enormous potential. Robotic systems will redefine the way modern warfare will be conducted and may render existing capabilities obsolete.

There is an obvious shift in the paradigm. Current (military) robots are mostly controlled by humans remotely. Robots in the future will be (more) autonomous. The full autonomy, seen in self-driving cars already today, induces requirements to change the widely accepted principle of a human decisions/ responsibility in the chain of command.

The key opportunity is in autonomous behavior of man-manned systems, including robots. There has been a great progress in this direction both on scientific and technological level. The autonomous machines sector has been boosted in the last decade by the attempt to create a self-driving car. The key car manufacturers, new ones as Tesla and informatics industrial giants as Apple and Google have been investing tremendous amount of money here. The situation has changed in the life-time of SAS-097 substantially. The defence sector will benefit from the achievements in self-driving cars.

Robotic applications embrace a number of necessarily interlinked subject areas. The challenge is the lack of system theories allowing holistic analysis of the overall systems, involved processes and their interactions. Thus, better theories are needed for conceptual evaluation of robotic systems in operations. These theories will, by necessity, require exploration in the following areas:

1) The growing relationships between humans and machines and interactions between physical and emotional features that have moral, ethical and legal aspects have not yet been sufficiently defined. Robots and other intelligent devices need to perceive their surroundings during military operations. Planning and control of robots is based, in most cases, on the perception-action cycle. The goal will be to develop new perception algorithms applicable to defence and embed them into a cognitive framework.

2) Self-localization and navigation of robotic systems will be important for semi/fully autonomous and intelligent behaviors. Robotic systems rely mainly on uncertain information processing from on-board and other sensors. Self-localization and navigation capabilities together with building up a proper machine representation of the operating environment can enable autonomous activity planning as well as safe and collision-free guidance. The requirement will be to develop advanced data fusion methods capable of handling uncertain and incomplete information.

3) Homogenously teamed unmanned robots boost capabilities and reliability over that of a single robotic system. Heterogeneous groupings incorporate humans as team members sharing common knowledge with the robotic systems while assists each other in a complementary way. This will require mechanisms, algorithms and new technologies for coordinated operations performed by heterogeneous teams of Unmanned Systems (UxS), unattended sensors and human operators. The cornerstone concept of functionality planning and coordination will be agent-based computing and multi-agent systems.

4) Design methods and technologies will need to be tested on a scalable, high-fidelity computational simulation. The goal will be to investigate the methods of agent-based simulation and modelling and to perform validation on deployment of real hardware platforms.

5) The aforementioned research fields are targeted on both single and multi-robot (teamed up) setups of unmanned vehicles operating in large real indoor and outdoor environments. Robotic military applications will include rescue missions, inspection and surveillance robotics, autonomous assistive systems and many other defence/safety/security missions.

## 1.2 STUDY OBJECTIVES

The objectives of SAS-097 were as follows:

- Analyze the gap between operational requirements and technical possibilities (relationship to the NATO Long Term Capability Requirements / Long Term Aspects of Requirements (LTCR/LTAs)).
- Bridge the gap between cutting edge of technology and military operational needs.
- Provide experimentation support for robotics concept development and testing.
- Organize a NATO supported workshop, symposium or conference.
- Create and supervise bidirectional working links to the European Commission Research and Development (R&D) activities in dual-use of robotics.
- Open possibilities for the new robotics research motivated by military needs and funded by third parties.

## 1.3 STUDY ACHIEVEMENTS

The achievements of SAS-097 as related to the study objectives are outlined below:

- ***Analyze the gap between operational requirements and technical possibilities*** (relationship to the NATO LTCR/LTAs):
  - Completed an analysis of trends in Autonomous Systems (AxS) in the areas of CONTROL, SENSORS and PLATFORM (conceptual, technological and operational aspects of the new trends).
  - Completed an analysis of Operational Requirements through a SAS-097 Workshop in 2013 with NATO COEs: JAPCC, EOD, C-IED and M&S.
  - Completed an analysis of the EU Perspective through participation in the euRobotics Forum in 2014.
  - Completed analysis of research into Human-Robot Cooperation through participation in NIFTi (2010 – 2014) and TRADR (2014 – 2018) EU-FP7-ICT projects.

- ***Bridge the gap between cutting edge of technology and military operational needs:***
  - Participated in the Future Soldier 2012 Exhibition during NATO days in Ostrava, Czech Republic.
  - Initiated cooperation with the Center for Maritime Research and Experimentation (CMRE) through an exchange of visits in 2013.
  - Conducted cooperation with NATO COEs − Joint Air Power Competency Center (JAPCC), Explosive Ordinance Disposal (EOD), Countering Improvised Explosive Devices (C-IED), Modelling and Simulation (M&S).

- Participated in the Multinational Capability Development Campaign (MCDC) AxS Workshop in Prague, Czech Republic.
- Participated in the Meeting of Experts on Lethal Autonomous Weapons Systems (LAW) in Geneva, Switzerland.
- Provided speaker to the 1st Counter IED Technology Workshop in Madrid, Spain (Prof. V. Hlavac).
- Provided speaker to the 2014 NATO STB Symposium on Autonomous Systems in Bratislava, Slovakia (Dr. M. Reinštein).
- Provided speakers and robotic demonstrations to the Future Forces Exhibition and Conference in Prague, Czech Republic (Prof. J. Mazal, Dr. L. Preucil and Prof. V. Hlavac).

- ***Provide experimentation support for robotics concept development and testing:***
  - Conducted joint experiments between the Czech University of Defence and United States Army Tank Automotive Research, Development and Engineering Center (TARDEC).
  - Conducted work on multipurpose platform development − Project TAROS.
  - Urban Search And Rescue (USAR) − real mission deployment in May 2012, Mirandola, Italy, project NIFTi.
  - Cooperation with Italian fire brigade, joint exercise in Pisa, Italy, September 2014.
  - Regular participation in robotics conferences (Institute of Electrical and Electronics Engineers (IEEE) International Conference on Robotics and Automation (ICRA), IEEE International Conference on Intelligent Robots and Systems (IROS).
  - Published journal articles (IEEE Transactions on Robotics, IEEE Transactions on Mechatronics, Journal of Field Robotics).

- ***Organize a NATO supported Workshop (WS), symposium or conference:***
  - WS in Prague in 2012 to kick-off the Study Group:
    - Building-up task groups, planning and coordination; and
    - Invited guest from Office of Naval Research (Global) (ONRG).
  - WS in Paris in 2013 with participation from NATO CoEs.
  - WS in Prague in 2013 − participation of SAS-097 representatives in the organization of a workshop on “The use of robotic and autonomous systems in the Army of Czech Republic”, questionnaires regarding operational requirements and technological possibilities were collected and analyzed from more than 30 Czech Army high command representatives.
  - WS in Rome in 2014 in association with MESAS’14 − Participation of SAS-097 representatives in the organization of the workshop MESAS 2014 on “Modelling & Simulation for Autonomous Systems” as Scientific Committee members, May 5-6, 2014, Rome, Italy, in association with the NATO M&S COE. http://mesas2014.org/.

- ***Create and supervise bidirectional working links to the European Commission R&D activities in dual-use of robotics:***
  - Czech Technical University (CTU) member of the euRobotics Association Internationale Sans But Lucratif (AISBL).
  - Participated in the euRobotics forum in Rovereto, Italy, 2014, Vienna, Austria, 2015.

- Contributed to the Multi-Annual Roadmap (MAR) document.
- Explored potential of dual use of robotics in the fields of:
  - Search and rescue robotics;
  - Human-robot interaction; and
  - Manipulation with soft materials.

- ***Open possibilities for the new robotics research motivated by military needs and funded by third parties:***
  - Established the Center of Advanced Field Robotics (CAFR):
    - Founded by 4 Czech universities: CTU in Prague, Brno University of Technology, Technical University of Ostrava, military is represented by the University of Defence and one industrial partner – VOP.
    - The aim of the CAFR is to bring together organizations in the Czech Republic that are engaged in R&D in the field of advanced robotics and autonomous systems.
    - Applied research primarily in the civil, security, industrial, and military domains.
    - Currently seven projects are in progress.

## 1.4 STRUCTURE OF THE REPORT

This report is structured to follow the Study Objectives roughly. It will commence with an examination of the operational requirements for robotic systems. This examination takes the form of reviewing the findings of a Study Group Workshop held together with several CoEs to explore operational requirements. This is followed by an assessment of the technological possibilities in three areas: reasoning, control, sensors and platform. Chapter 2 looks at Human-Robot Interface (HRI). Chapter 3 deals with the instruments for assessing the development and application of robotics technology. Chapter 4 examines the application of robotic technology to military operational needs in the areas of control, sensors and systems. Chapter 5 looks at Lethal Autonomous Weapons Systems (LAWS) and the findings of the Meeting of Experts of the Convention on Conventional Weapons (CCW). Chapter 6 assesses how autonomous robotic systems could be deployed in the future and some of the sensitivities surrounding the use of lethal force by these types of systems. Chapter 7 explores how the mission accomplishment, the environment and the utility should be considered in human-robot interactions. Annex A provides the Mission-To-Task decomposition for missions where robotic systems would be of best potential. Annex B lists standing NATO agreements related to robotics, Annex C lists capability areas where development of robotic capabilities could have significant impact. Annex D provides references to literature related to SAS-097, and finally, Annex E is an article prepared in parallel with the Study Group that provides a description of tools that are designed to assist operators of remotely controlled robotic systems.

# Chapter 2 − ANALYSIS OF OPERATIONAL REQUIREMENTS

**Mark Tocher**
CANADA

## 2.1 ANALYSIS OF OPERATIONAL REQUIREMENTS

### 2.1.1 Notes on Findings from SAS-097 Workshop in Paris[1]

Advances in technology in the areas of human-machine interfaces, networks, sensors, computing, security and power systems will enable associated improvements in the capabilities of robotic systems. Robotic systems will see wider use in areas such as surveillance, infrastructure support (e.g., ports), transportation, mine hunting/removal, disaster response, consequence management, medical, space, strike/engagement and casualty evacuation (Annex A provides a breakdown of possible tasks for robotics related to a broad array of missions). The importance of being aware of possible use of robotic systems against NATO forces by the enemy was also highlighted.

Currently, within the EOD community, robots are being used to detect, identify, access and mitigate hazards from explosives. Some challenges include using remote-control in urban areas (distance, interference from building and other radio sources), the development of more sensitive detection assets (multisensory, night/day capability), increased tactical flexibility through modular robot design (configuration, tools), and increased mobility over different terrain. The need was stressed to develop concepts of operation for robotics and standardization across the DOTMLPFI components. Increasing levels of autonomy should be developed to eliminate the need for continuous navigation control of robots. They should be given instructions to move to a location and then be capable of determining and executing the most efficient routing.

Cooperative robots, inspired by swarms in the nature, were examined with some highlighted advantages: robust to failure as no critical command unit, scalability, speeds the accomplishment of the task and allows the access to a broader set of sensors and tools. Cooperative robots could combine the advantages of both UGVs and UAVs. One significant military task would be convoying vehicles.

Manipulators on robots were discussed. We focused on the requirement for manipulators to be more intelligent. This would include the ability to determine the proper course to a target and to return back with the target. These methods are also attractive for medical robotics (robotic surgery). Once established, this capability would enable operators to simply point at an object (a bomb or a wire within the fusing device) and then allow the robot to make decisions on how to approach the task.

Within modelling and simulation, the similarities between modelling complex environments and tasks involving multiple robots were highlighted. These include the possibility for emergent behavior from systems following simple rules and self-organization/synchronization.

The French Military Academy (St. Cyr) has done considerable work in the area of developing concepts for the employment of robotic systems. Their research extends into areas such as legal issues, technologies, psychology of human-robot relations, ethics and tactics. The French Army has four robotic priorities:

1) Enhancing intelligence capabilities (observation inside buildings, subterranean networks, and pipes);
2) Improving the capability to detect, identify, neutralize and destroy mine/explosive threats;

[1] SAS-097 Workshop in Paris 2013 with NATO COEs: JAPCC, EOD, C-IED, M&S.

3) Complementing destructive capabilities in fire delivery and the use of weapons (retaining a human in the loop for lethal decisions); and

4) Participating in forward logistics.

The importance of robotic systems being able to operate at the speed of the unit that they support was highlighted. Some emerging issues were raised: the risk of dehumanization of war, risk of confusion between armed drones and surveillance drones in public perception, legal accountably resulting from robot autonomous actions, and the right to self-defence and laws of armed conflict. Recommendations for future systems included the need for consumable robots (cheap, disposable, not over-specified), modularity to be useful for many types of missions, anticipation of advances in sensors, and leveraging technological innovation from civilian uses of robotic systems. Chapter 6 provides an overview of some of the considerations proposed by this author.

The JAPCC (Joint Air Power Competence Center) is examining the use of UAVs in contested airspace. Recent experience has been limited to use of UAVs where friendly forces have air superiority and adversaries have very limited anti-air capabilities – this cannot be expected for all future operations. To address this, there are really two ends of the spectrum – inexpensive, disposable robots and expensive, survivable robots. Exploring this issue takes a holistic approach that examining the entire system – aircraft, payload, human element, control element, data link, and support element.

Overall, the growing familiarity with robots increases their effective employment. The applications of game controllers for 'driving' robots has reduced training and improved usage. Interoperability is an issue in the theatre. The electronic interference is becoming an issue as is the lack of commonality of parts within the growing number of different types of robotic systems.

Findings:

- Need to develop concepts of operation for robotics across DOTMLPFI (doctrine, organization, training, material, leadership, personnel, facilities and interoperability).
- Need to develop standards for testing, communications links, interfaces, parts such as manipulators and other tools, etc. (Annex B lists the current STANAGs related to robotics and shows considerable areas where new STANAGs could be developed).
- Need for open architectures to allow technology insertion (Annex C lists the current Science and Technology Priorities related to robotics).
- Increased requirement for autonomous navigation to reduce operator work load − determine the proper course to a target and then to return to the starting position.
- Need to standardize terminology.
- Highlighted the importance of robotic systems being able to operate at the speed of the unit that they support.
- Need to clarify issues in the areas of the right to self-defence and laws of armed conflict related to robotics.
- Need to address the transport of robots in the design of combat vehicles:
  - The volume of data transmitted over existing networks is increasing.
  - Need to define the right level of information at the correct echelon of command.
  - Frequency spectrum saturation issue.
  - Low probability of intercept communications – IR or light.
- Need to operate Beyond Line of Sight.

- Modularity is critical − one robot for many missions to reduce space, training and service requirements:
  - Better to have two 8 kg components that one 16 kg robot to lessen burden on dismounted troops.
- Requirement for sufficient clarity of vision and recording capability to capture biometrics, tool marks, electronic components for identifying and profiling IED builders and emplacers.

## 2.2 ANALYSIS OF THE CONCEPTUAL, TECHNOLOGICAL AND OPERATIONAL ASPECTS OF THE NEW TRENDS IN ROBOTICS FROM DIFFERENT PERSPECTIVES: CONTROL, SENSORS, PLATFORM

Annex D provides a literature search of the STO Library and other EU sources.

*Source: NATO STB Symposium on Autonomous Systems 2014.*

### 2.2.1 Control Perspective

#### 2.2.1.1 Conceptual Aspects

Growing number of deployed UxV increases demands on human operators and communications, which are still the bottleneck – despite the sophistication in UxS. Effort should be made in effective exploitation and cyber protection of data links. Even if successfully transferred, it is impossible for human operators to process the amounts of data generated by UxS, therefore online processing, simulation and modelling plays a crucial role. Deep learning methods are an example of an approach designed for *Big Data* processing.

#### 2.2.1.2 Technological Aspects

The emerging phenomena of Big Data collected from online battlefield require not only effective means of processing, but also − comparably challenging – distribution of relevant information back to command that can draw from databases of experience. This experience together with other information can be intuitively presented in virtual or augmented reality, which is becoming a standard tool of HRI.

#### 2.2.1.3 Operative Aspects

Regarding HRI, progress in PC gaming industry should not be ignored, know-how concerning control of virtual avatars can improve situation awareness and overall performance of the human operator.

### 2.2.2 Sensors Perspective

#### 2.2.2.1 Conceptual Aspects

Progress in sensor miniaturization together with power-efficient system-on-chip controllers drives development of networks of cheap smart sensing devices. This space-based approach is natively decentralized while can covering large areas by required sensing modalities. Current focus of the electronics industry on the internet-of-things (e.g., smart refrigerators that keep track of its contents and order missing items) brings more attention to problems associated with networks of sensors such as standardized protocols, data management or control. The smart sensors do not have to be necessarily passive devices, swarms of micro-robots can be equipped with various sensors as well and benefit from bio-inspired algorithms of multi-agent systems.

Development of wearable technology offers various sensors that can be integrated into standard equipment and perform some tasks for a soldier automatically such as health or ammunition supplies monitoring.

#### 2.2.2.2 Technological Aspects

While miniaturization already allows deep-integration of wearable technology, research is required in the area of energy sources (e.g., kinetic and thermal energy harvesting), battery life. Spectrum saturation and spectral signatures of the smart sensors need to be addressed as well.

#### 2.2.2.3 Operative Aspects

Networks of smart sensors together with other systems with sensing abilities generate large amounts of data which need to be adaptively filtered based on current frequency spectrum saturation and relevance and then distributed based on command demands.

### 2.2.3 Platforms Perspective

#### 2.2.3.1 Conceptual Aspects

- Highly sophisticated platforms for robotic-aided surgery.
- Major trend in multipurpose and modular design easy to replace, reducing space, training, and service costs.

#### 2.2.3.2 Technological Aspects

- Brain-machine interface research robotic prosthetics, robotic exoskeletons.
- From a single platform to distributed sensing and shared intelligence.
- Research motivated by minimal radar and heat signature, min. GPS dependency autonomous navigation based on 3D mapping and multi-modal data fusion.

#### 2.2.3.3 Operative Aspects

- Operational requirements for logistics supported by robots.
- Operational requirements for platforms engaged in symmetric warfare.

## 2.3 ANALYSIS OF RESEARCH INTO HUMAN-ROBOT INTERFACE (HRI)

*Source: NIFTi[2] (2010-2014) and TRADR[3] (2014-2018) EU-FP7-ICT projects.*

### 2.3.1 Motivation

Advances in technology of the recent decade have allowed mobile robotics (i.e. robots that move around by their own means) to leave controlled laboratory environments and to start seeking for real-live deployments. This search is not unilateral, there are real-life problems that explicitly require such robotic technology – the Fukushima power plant is planned to be decontaminated by means of mobile robots, exploration of our neighbor planet Mars is performed (among others) by robotic rover nicknamed Curiosity that is capable of

[2] http://www.nifti.eu.

[3] http://www.tradr-project.eu.

collecting and examining rock samples. Development of powerful and efficient mobile CPUs allows robots to process various data collected on board immediately and use them to plan their actions in order to accomplish their goals. Complementary, with the rapid advance in sensor technology, it has been possible to embed richer sensor suites and extend the perception capabilities and thus increase the environment awareness.

Such sensor suites provide multi-modal information that naturally ensures perception robustness, allowing also better self-calibration, fault detection and recovery. However, without sufficient data processing on the side of the robotic system the burden lies on human operator who is required to interpret the sensor data (video stream is probably the most suitable for human operators) and decide what actions should the robot take. Of course in that case, a stable broadband data link (wired or wireless) is necessary to transmit the data to the human operator and that is often found challenging or impossible due to real-life environments. Self-localization combined with mapping, kinematic assistants adapting the robot to current terrain or segmentation and labeling of visual information can lighten the amount of data transmitted or even make the human operator unnecessary if the robot can plan and execute actions by itself.

Experience with our robotic platform (developed during the EU FP7 NIFTi project and used within the TRADR project) confirms these claims – thanks to end-user evaluations with Italian and German fire brigades (Corpo Nazionale dei Vigili del Fuoco, Das Institut für Feuerwehr- und Rettungstechnologie der Feuerwehr Dortmund) and one real deployment in Mirandola[4], we have realized that combination of challenging environment and limited data link implies need for these assistants that run on-board and that are capable of exploiting as many sensors as possible.

### 2.3.2 NIFTi and TRADR Project Experience

#### 2.3.2.1 User-Centric Design

Input from the target user plays a vital part in the research and development cycle of any project that involves human-robot interaction. Therefore, the methodology of user-centric design has been adopted throughout the entire R&D cycle of both projects with imminent impact on robotic system capabilities, user interface design, sharing and presentation of mission data and other aspects of the system. For example, the original design of the terminal for the human operator included touch-screen interface which also implemented steering of the ground robot. It became immediately clear during the end-user evaluation that this is not acceptable since the firefighters wear protective work gloves that make steering of the robot impossible. Solution is a joystick that can be operated even with gloves.

#### 2.3.2.2 Shared Autonomy

Finding balance between autonomy of a robotic system and trust of its user is another problem that emerged. According to our evaluations, end-users have tendency to ignore or turn off high-level autonomous functions of the robotic system if they are not absolutely confident about their reliability. Therefore, effort should be made to design such functions that the end-users accept and benefit from. For example, a system assisting with setting optimal configuration and stiffness of caterpillar tracks of the ground robot has been developed. It removes some burden from the human operator of the robot, acts automatically and is easily acceptable by the operator.

#### 2.3.2.3 Persistence, Situation Awareness

In context of the TRADR project, we define persistence as *using a system level memory, making experiences outlive the process that created them, for gradual improvement of performance.* In other words, the system is expected to store mission data and gradually build models that can be exploited afterwards. If we expect the end-users to work with the robotic system as one team, it is necessary for the whole team to maintain a

[4] http://europa.eu/rapid/press-release_MEMO-12-620_en.htm.

common knowledge of the status of the mission. Situation awareness is key for successful accomplishing any rescue mission, either for the mission commander or in-field rescuer. Making the mission data persistent during the whole mission is a necessary condition for situation awareness supporting functions of the system.

# Chapter 3 − ANALYSIS OF TECHNOLOGICAL POSSIBILITIES

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For analysis of technological possibilities, we have identified a promising source of relevant information – the *MAR* document published by *euRobotics AISBL*[1]. *euRobotics AISBL* is a Brussels based international non-profit association for all stakeholders in European robotics. One of the association's main missions is to collaborate with the European Commission (EC) to develop and implement a strategy and a roadmap for research, technological development and innovation in robotics, in view of the launch of the next framework program Horizon 2020. *euRobotics AISBL* publishes annually the *MAR* document[2], which provides its reader with:

- Identification of market sectors for robotic applications.
- Examination of technology clusters to identify current and future capabilities (and their impact), descriptions of general system abilities of robots.
- Identification of similarities and gaps in research and development of technologies.
- Understanding of the potential areas (markets) of applications.
- Understanding of the level of current / future robot capabilities from the user perspective.

Since *MAR* provides a detailed analysis of the development and application of robotics technology, European research development and innovation funding is derived from the MAR as a part of the annual review cycle. The document is structured into three main sections:

- Market Domains;
- System Abilities; and
- Technology Clusters.

Section **Market Domains** focuses on specific needs and requirements of these domains: manufacturing, healthcare, agriculture, civil, commercial, transport and logistics, consumer and military. It summarizes which technologies each domain offers and which technologies are needed for the given domain to proceed with utilizing robotic technology. Section **System Abilities** investigates distinct aspects of the overall performance of a robotic system. In the defined set of abilities, each is discussed with emphasis on the current State-Of-The-Art (SOTA) and improvements to be achieved. The last section focuses on distinct **Technologies** that are involved in robotics, it treats them in a similar fashion as the previous section, it analyses the current SOTA and plots targets to be achieved to improve or allow new system abilities.

To give a common ground to its findings, MAR defines the TRL − *Technology Readiness Levels* for robotics:

- Level 1 − Basic Principles Observed – Idea.
- Level 2 − Technology Concept Formulated.
- Level 3 − Experimental Proof of Concept.
- Level 4 − Technology Validated in Laboratory.
- Level 5 − Technology Validated in Relevant Environment.

[1] http://www.eu-robotics.net/.

[2] http://www.eu-robotics.net/downloads/downloads/.

- Level 6 − Technology Demonstrated in Relevant Environment.
- Level 7 − System Prototype Demonstration in Operational Environment.
- Level 8 − System Complete and Qualified.
- Level 9 − Actual System Proven in Operational Environment.

These TRLs help the reader to make a clear picture of the referenced robotic systems and abilities.

# Chapter 4 − ROBOTIC TECHNOLOGY FOR MILITARY OPERATIONAL NEEDS

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In this chapter we address the possible future direction of robotic technology by analyzing the current operational requirements and technological possibilities from the three main aspects: control, sensors, and systems. We performed a thorough literature search and analysis of the state-of-the-art with respect to the military needs and focusing our efforts primarily on the following topics of interest:

1) Long-term capability requirements;
2) Future emerging technology trends;
3) Uninhabited military vehicles: human factors issues in augmenting the force; and
4) Nanotechnology for autonomous vehicles.

The results of this analysis are structured notes that allowed us to formulate the conclusions and important claims presented in the previous two chapters. These results and conclusions were presented on the NATO STB Symposium on Autonomous Systems (in Bratislava, Slovakia, September 15, 2015).

These notes are structured in three main sections: control, sensors, and systems. Each of these sections, if possible, concludes the major important points categorized either as military operational requirements or the current technological possibilities in robotics. These major points are grouped according to the four topics of interest as mentioned above. Since we are not the original authors of all of these points, we reference the original sources and recommend reading them when seeking more detailed information about a given topic.

## 4.1 CONTROL

### 4.1.1 Long-Term Capability Requirements

#### 4.1.1.1 Analysis of Operational Requirements

- *Area Access Control* − must deny area access, must discriminate about intruders, be capable of monitoring across all environments ([1] - A4).
- *Communications Services for Networking and Information Infrastructure* − need to be: robust, ubiquitous, easily accessible, agile, flexible, securely available, capable of multicast and broadcast, end-to-end quality of service, self-healing and self-adaptive ([1] - A10).
- *Counter Naval Mines* − must allow for rapid deployment, faster detection and identification of naval mines, against all types of naval mines, should allow for the conduct of covert and in stride counter mine activities, the detection, localization and disposal capabilities must be effective against naval mines in all water ([1] - A16).
- *Cyber Warfare Capability* − must allow the Alliance to protect information resident in its computer systems and networks, need appropriate planning and direction ([1] - A22).
- *Improved Modelling and Simulation* − the value of computer models for combat depends on their ability to accurately represent the range and variability of human behavior, asymmetric conflict... Improved interoperability among simulations and between simulation tools and C4ISR will enhance training and collaboration ([1] - A28).

- *ISR Processing, Fusion and Exploitation* − need to provide strategic, operational and tactical end-users with relevant, accurate and timely information and intelligence products. The processing, fusion, and exploitation capability must encompass the ability to collate, evaluate, analyze, integrate, and interpret in an appropriate manner large quantities of diverse imagery, data, information, and intelligence ([1] - A36, A37).
- *Planning and Decision Support* − needs to be repeatable, timely, accurate, complete, adaptable and relevant to the operational context, be in compliance with the principles of command and recognized organizational principles and applicable SOPs, will require significant timeline compression in future operations and must overcome information overload ([1] - A43).
- *Service Management and Control Services* – to undertake operations is dependent upon linking sensors, decision makers and weapon systems in a seamless, collaborative, planning, assessment and execution environment ([1] - A44).
- *Space Capability Preservation* − requires the capability to counter opponent's space denial operations, and hence preserve a space capability/situational awareness for NATO assets, reliance on space based capabilities for communication, geo-positioning, and intelligence collection ([1] - A46).
- *Systems Analysis and Knowledge Development* − need to exploit multiple information sources and use collaborative analysis, in a continuous and dynamic manner, to build timely, coherent, relevant knowledge and so enhance decision making ([1] - A50).

#### 4.1.1.2 Analysis on Technological Possibilities

- *Area Access Control* − methods are indiscriminate, removal is difficult, capability provides a means of preventing individuals from entering controlled areas ([1] - A4):
  - Potential systems − electronic fence, radiation, pattern recognition, image analysis … ([1] - A4).
- *Communications Services* − must support multiple smaller, modular, multinational force structures with force elements, a variety of transport mechanisms and provide a single information transport network. NATO communications are also vulnerable to disruption from various environmental phenomena, such as magnetic activity from sunspots ([1] - A10):
  - Potential systems − Commercial standards and protocols for QoS, IP-encryption devices and key management infrastructure, next generation IP, Voice Over IP, protocols … ([1] - A11).
- *Counter Naval Mines* − Naval mines can be difficult to detect and if unmoored, their location may be unknown even to the emplacing party, they are relatively inexpensive and simple means of damaging ([1] - A16):
  - Potential systems − Advanced sensors for local and wide-area threat detection and location sensor fusion, water space management systems, improved automation, advanced signal processing … ([1] - A16, A17).
- *Cyber Warfare Capability* − the Alliance relies heavily on computer systems and networks to store, process and transfer information ([1] - A22):
  - Potential systems − Artificial intelligence, computer systems, forensics … ([1] - A22).
- *Improved Modelling and Simulation* − has the potential to provide better collateral damage prediction, as well as near real time operations research and analysis during all phases ([1] - A28):
  - Potential systems − advanced and interoperable simulation architectures and languages, integration with C4ISR and other systems for deployed in-unit training … ([1] - A28).

- *ISR Processing, Fusion and Exploitation* − Timely processing, fusion and exploitation of imagery, data, information and intelligence provided by all-source capabilities. Ensuring seamless information sharing enables access to large quantities of archived and near real time ISR data ([1] - A36, A37):
  - Information processing and management, artificial intelligence, cognitive and behavioral sciences … ([1] - A36, A37).
- *Planning and Decision Support* − to satisfy the requirements of the commander, superior and subordinate formations, and other organizations, will allow large quantities of data received by HQs to be processed, fused and presented ([1] - A43):
  - Artificial intelligence, modelling and simulation, and training environments, cognitive and behavioral sciences, ... ([1] - A43).
- *Service Management and Control Services* − information systems and communication network permitting the timely and secure exchange of information, systems and infrastructures that have to be integrated in NEC will present particular challenges for the active monitoring, management and control of the network ([1] - A44):
  - Dynamic federated Service Level Management, Enterprise Application Integration technologies, Information Assurance, Information Security ([1] - A44).
- *Space Capability Preservation* − radar absorbing materials/signature reduction technology, advanced armors, unmanned space platforms, robotics ([1] - A46).
- *Systems Analysis and Knowledge Development* − goal is to present options, in the form of specific actions that can be taken against specific nodes, to assist decision-makers at strategic, operational and tactical levels in focusing capabilities to achieve desired effects ([1] - A50):
  - Information processing and management, artificial intelligence, human network analysis, cognitive and behavioral sciences … ([1] - A50).

### 4.1.2 Future Emerging Technology Trends

#### 4.1.2.1 Analysis of Operational Requirements

- *Computing* ([2] - 11-13):
  - The continued progress of Moore's Law will require another foundational material or new manufacturing techniques (the molecular structure of silicon at the atomic level will eventually present a limit to the number of transistors that can be added to computer chips).
  - Parallel computing where the target problem is deconstructed and analyzed by parallel computer chips may be part of the solution.
  - Holistic knowledge bases − will require sufficiently dense data gathering capabilities to bring the required information into the knowledge base.
- *Artificial Intelligence* ([2] - 23-24):
  - It is driven by several factors: the acceleration of computational capability; the greater investment in – and wider adoption of AI; and advances in ubiquitous computing, database management, cloud computing, smart algorithms, and increasingly powerful software.

#### 4.1.2.2 Analysis on Technological Possibilities

- *Computing* ([2] - 11-13):
  - Development of materials such as graphene will allow the continued growth of computing speeds.

  - Carbon nanotube field effect transistors that can operate at higher speeds − will support improved computational power and the concomitant improvements in military systems.
  - Chips to communicate within a network many functions that currently require human initiation will be done autonomously in the future.
  - Quantum computing − computers will be able to handle multiple, simultaneous computations resulting in significant enhancement in computer speed, possibly reaching or exceeding the exa-flop barrier.
  - Network hardware − applications will reside off-site on another server and be rented rather than be locally owned and maintained, it will eliminate the need for hard drives and local servers.
  - Web applications will reach much increased levels of power and complexity.
  - Contextual programming will allow search engines to find more than just the searched keywords.
  - Holistic knowledge bases − will make physical demands on bandwidth, software and underlying algorithms.
  - Web tools such as bots and spiders will allow real-time monitoring and gathering data to ensure that the knowledge base is kept current.
- *Artificial Intelligence* ([2] - 23-24):
  - The field of AI is reaching a mature stage that integrates machine learning, vision, navigation, manipulation, planning and reasoning, and natural language processing into a general framework.
  - AI would have the distinct advantage that once it learns something it can transfer it anywhere to another digital intelligence in seconds or minutes.
  - AI is making predictions, based on large data sets, about how people will behave.
  - AI will exceed human intelligence in many dimensions – speed, memory, multitasking, and bandwidth.

### 4.1.3 Uninhabited Military Vehicles (UMVs): Human Factors Issues in Augmenting the Force

#### 4.1.3.1 Analysis of Operational Requirements

- *System of systems* ([8] - 143-211):
  - Command and control: human information processing and trust in the delayed systems ([8] - 144-168):
    - Human Information Processing (HIP) Capabilities, Limitations, and Detractors ([8] - 144-150):
      - The challenge is no longer the lack of information, but instead finding the required information at the right time.
      - The environment UMV operators may be embedded in could adversely affect cognitive performance, subsequently degrading C2 decision making.
      - It is established that whole body vibration in the range from 2 – 12 Hz can affect human performance including decreased fine motor skills, fatigue, accident proneness and health hazards.
      - The concern is that motion induced fatigue has shown a positive correlation with degraded sense of well-being and lack of motivation.

    - User-Centric Information Management Concepts for Autonomous UMV Command and Control ([8] - 150-157):
        - Systems, displays, and technologies need to be developed to aid in task execution while accommodating cognitive processing of an operator.
    - Trust in Time Delayed Systems ([8] - 157-161):
        - This system presents important time delays; cognitive needs introduced by the evolving aspects of the environment are thus associated with latency.
        - We can define a response delay, an information delay and a feedback delay. Each of them has a specific influence on the conduct of robotic systems.
        - From the operator's point of view, an information delay can be added by itself to the response delay.
        - The presence of information delay increases the production of errors.
        - There is an obvious deterioration of performance when time delay happens, because of the lack of synchronization between the operator's time and the process time.
        - The use of research mode strongly depends on the existence of a free resources span.
    - Uninhabited Military Vehicles and Trust ([8] - 161-165):
        - System with all the inherent time delays creates spatial and temporal uncertainties for the operators.
        - Time delays eliminate the effect of certainty such as uncertainty would do, because time delays carry part of risk, which leads to uncertainty.
        - Anticipations require relatively powerful system of internal and external representation.
        - Time delays in a system leads to some difficulties of building and maintain relevant mental representations with respect to a given objective.
        - Intention and understanding are closely linked: understanding a situation consists in building a coherent representation of the world for the goal to achieve.
        - Problems related to the building of an operative system representation in an environment, leads to a progressive loss for the operator's understanding over his controlled/supervised system.
    - Future Research ([8] - 165-168):
        - An examination of the potential benefits of multimodal interfaces to mitigate the effects of visually induced motion sickness in provocative environments while allowing the operator to remain effective in performing C2 tasks.
        - The future research issue is to devise an autonomous UMV swarm – operator feedback loop that allows the operator to understand what, how, and why a swarm behaves like it does.
        - Little has focused on the C2 domain, and virtually no research has been done on operator-autonomous swarm interaction.
- Migration of operator control: human factors and teaming issues ([8] - 169-192):
    - Migration of UAV Operator Control ([8] - 170-172):
        - The higher the LOI, the more costly the equipment and the more specialized the training required.
    - Reasons for Migrating Operator Control ([8] - 172-182):
        - Many current human-machine operations are continuous in character and the nature of these operations often precludes a temporary shutdown because of economical or other constraints.

        - Some military endurance UAVs currently operate at great distances from the control station, necessitating beyond-line-of-sight communications.
        - Latencies greater than one second mean real-time feedback necessary for effective manual control is not available.
        - Many UMV operators are dependent on real-time imagery from cameras mounted on the remote vehicle in order to manually control the vehicle.
        - Data link constraints can result in limited temporal resolution, spatial resolution, colour, and field of view of imagery irrespective of on-board sensor capabilities.
    - Important Issues in Control Migration ([8] - 187-190):
        - Implicit in the concept of migration of operator control is the assumption that there is complete interoperability of both systems and personnel.
        - Migrating control between dissimilar systems is particularly difficult because of issues of system synchronization.
        - May require initiation and alignment of systems, one or more data and communications links, and possibly even cryptologic equipment.
        - Systems should be designed to provide immediate and unambiguous feedback to operators regarding the state of control transfer, whether gaining or releasing.
        - In order to safely migrate operator control, it is imperative the operator gaining control have at least the same level of SA as the operator releasing control.
        - Important to facilitate information sharing during UMV handoffs:
            - It can involve voice communication, text message exchange, graphical display exchange or alignment of system information.
    - Future Challenges ([8] - 190-192):
        - It is advisable to accept a moderate level of task conflict, but to train members in conflict management techniques or to create a problem solving protocol.
        - As part of the restructuring of military hierarchies to self-organizing teams, it may be advisable to move away from a process-outcome view of groups.
        - Verbal interactions among remote and co-located participants were found to be significantly retarded when participants were engaged in challenging tasks.

- Artificial cognition and co-operative automation ([8] - 213-292):
    - The work process and conventional automation's solution ([8] - 216-223):
        - Perspectives of Future Automation ([8] - 225-231):
            - Automation complexity can be seen as the most critical issue.
            - Advanced automation shall not displace the human operator in a work system, but share the tasks in a close-partner work relationship.
            - Coordination and communication with an automation system shall be supported on all performance levels.
            - Requirements for this (the Cockpit Assistant System CASSY , the Crew Assistant Military Aircraft CAMA, and the Tactical Information and Mission Management System TIMMS) class of systems:
                - It must be ensured the representation of the full picture of the flight situation.

            - A situation with overcharge of the cockpit crew might come up even when situation awareness has been achieved by the pilot crew.
        - Design principles for human-machine co-operation in the context of human centered design:
            - The human operator must be − actively involved; adequately informed; and able to monitor the automation assisting him.
            - The automated systems must be predictable; and also be enabled to monitor the human operator.
            - Every intelligent system element must know the intent of other intelligent system elements.
    - Technological Challenges ([8] - 231-233):
        - The various technological challenges to be borne in order to implement such a system:
            - Comprehensive situation perception: in principle the human operator on-board has access to information which is offered to him in addition to the information from his vehicle systems:
                - To facilitate cognitive behavior in a machine system the ability to perceive the environment has to be ensured.
                - Cognitive capabilities: the next step after a successful perception of the world will be the deduction of rational behavior on the basis of the gathered information.
                - Human-machine interaction: having an intelligent unit within the work system, which is enabled to gather and understand the entire situation, to make decisions and to exhibit rational and goal-oriented behavior.
                - Level of automation and authority: like with human teams, the question of the allocation of tasks and authorities has to be answered for human-machine teams, as well as for machine-machine teams.
                - Paradigm shift: users, consumers, designers, companies, procurement officers, and customers, have to reconsider the issue of the evolution of personal, social, and economic factors.
- Applied system approaches ([8] - 247-292):
    - Autonomous Decision Making for an Underwater Unmanned Vehicle ([8] - 281-290):
        - Will require the UUV to possess the capabilities to perform all the tasks to be performed, from navigation, power monitoring/management, threat identification and avoidance and payload delivery.
        - The traditional teardrop shape is the most efficient, from a drag minimization point of view, but this is not appropriate for very shallow waters (here, a thinner, flatter, more Ray-like profile is more appropriate, with a higher power consumption as a result).
        - The 3 risk factors of primary concern here are those relating to communication, workload and unpredictability.
        - The underlying requirement is for a system that can provide for dynamic, context sensitive adaptiveness, so as to engage each task at the appropriate level of autonomy.
        - Agents using any autonomy model must comprehend the concepts of 'self' and 'others'.
        - To achieve this, each agent must possess its own environmental model, such that it can understand the implications of the information it is receiving for any of the other agents and act accordingly.

        - In a fully autonomous system, without recourse to guidance from a human operator, all of the problems that may be encountered must be resolved on-board and an appropriate decision made in all cases.

#### 4.1.3.2 Analysis on Technological Possibilities

- *Military Relevance* ([8] - 41-91):
    - Military relevance for Uninhabited Aerial Vehicles (UAVs) ([8] - 82-91):
        - Interaction (Control) Characteristics: ([8] - 89):
            - Due to the physical separation, the only possible interaction is what's designed to occur.
            - The character of control may vary over time, but typically it's a question of a time-dependent reduction of the possibility to interact.
            - Character of control is a tool used to handle situation uncertainty.
            - The characteristics of the interaction may be described with its intensity, level of abstraction and possibility of adaptation.
- *System of Systems* ([8] - 143-211):
    - Command and control: human information processing and trust in the delayed systems ([8] - 144-168).
        - Human Information Processing (HIP) Capabilities, Limitations, and Detractors ([8] - 144-150):
            - The increased cognitive demands associated with a dependence on large complex data sets have been hypothesized to result in information saturation.
            - Human information processing models provide insight into cognitive process that occur when an individual perceives information from the environment, acts on that information, and responds to the environment.
            - The HIP flow:
                - Begins in the sensory stage when a sense organ encounters a stimulus that is within its capabilities and of sufficient intensity to initiate processing.
                - If attention is diverted from the stimulus, it is stored in a Short-Term Memory Store (STSS).
                - When a stimulus is attended to, it enters the perception stage where meaning is attached to its attributes to aid in detection, identification, and recognition of the stimulus.
                - After perception, processed information then enters the decision making and execution stage.
            - The momentary direction of one's attention may be described in terms of selective attention.
            - Dimensional system of resources consisting of distinct stages of processing, sensory modalities, WM processing codes, and response modalities.
            - Workload can be described as the relationship between resource supply and task demand.
            - When parallel processing is supported through the utilization of multiple modalities a rich data environment can be realized, leading to a system design approach.
            - In information rich NCO environments, effective information management will be multi-variant in nature accounting for cognitive capabilities and limitations, environmental stressors.

- User-Centric Information Management Concepts for Autonomous UMV Command and Control ([8] - 150-157):
  - In depicting information using spatial or graphical representations, visualization techniques use the human visual system to facilitate comparison, pattern recognition, change detection, and utilize various cognitive skills.
  - Augmenting information via other modalities may greatly enhance HIP.
  - The goal of multimodal interaction paradigm is augmenting traditional visual interaction with auditory cues to substantially enhance cognitive information management capacity.
  - Leverage available user senses, adapt to specific user's perceptual and cognitive needs, and respond to such needs by facilitating intuitive interaction with users.
  - Participants processed nearly 3x more information when it was distributed across various sensory systems as compared to stimulating a single sense.
  - Cues can be processed simultaneously with minimum interference because such information activates distinct brain regions utilized by different HIP resources.
  - SEAS should exploit human's capacity to attend to a wide variety of different sound dimensions.
  - Realizing the full potential of multi-modality means not limiting the dimensions of HIP processing to the verbal-spatial dichotomies typically associated with sensory and working memory processing codes, and extending beyond vocal-manual response modalities.
  - SEAS uses earcons, auditory icons, and data auralization to semantically map information to particular sound parameters or environmental sound cues to convey intended messages.
  - The objective of the SEAS auditory cues in this study was a reduction in operator attentional and visual perception bottlenecks, while also assessing how many autonomous UMVs a single operator could effective control.
  - The data also revealed that subjective assessment of workload was perceived as lower with the use of the multi-modal SEAS interface than the baseline purely visual interface.
  - Many studies have shown cognitive performance decrements for certain tasks when using 3D displays as compared to traditional 2D displays.
  - Data fusion provides UMV operators a comprehensive tactical picture that is requisite for effective battle management by fusing the data sources.
  - In the C2 domain, uncertainty and time pressure are elements in the decision making process and therefore, decision aids must provide autonomous UMV operators the ability to comprehend the battlespace and how various decisions may affect the future.
  - A critical design element of the sensitivity analysis capability is a data presentation user interface.
  - Automation brittleness is the concept that automated decision-support algorithms are typically fixed in code in initial design phases, and therefore unable to resolve unforeseen circumstances.
  - Higher levels of automation are not recommended for dynamic decision making environments like C2.
  - Associate concept − decision aid is able to assess the external and internal situation, make decisions based on a common view of the mission goals and plans and operator intent, and execute tasks in accordance with these goals.
  - Four levels of authority:
    - Manual: The associate system may never propose a plan on its own.

        - Permission: The associate system may propose a plan, but may not activate it without explicit permission from the operator.
        - Veto: The associate system may propose a plan and may activate it if the plan is not explicitly rejected by the operator within a given timeframe.
        - Autonomous: The associate system may propose and activate a plan.
- Trust in Time Delayed Systems ([8] - 157-161):
    - The operator's actions are combined with the process dynamic and he is not alone in this process.
    - Operators show a certain form of adaptation to time delays by using specific strategies allowing them to reach a certain performance in their activity, while accepting a lowering system dynamics.
    - Wait for the feedback before beginning a new move ("Move and Wait"):
        - Strategy allows operators to limit the incoming of unstable and unwanted movements, but without excluding them.
        - The task is considered, by the operator, as divided into various intermediary goals; the fluidity of the movement is then particularly affected.
        - The late perception of system responses leads the operator to modify his instruction.
    - Use of delayed feedbacks shows some characteristics:
        - It shows up after a great number of trials.
        - It is rather the exception than the rule.
        - It's only use during in mastered activity.
        - The operator tries to predict only the success or the failure of the action.
    - The presence of the screen provokes by itself a change in the control space.
    - Certain alterations of the perceptive mechanisms implicated in visual research.
    - Being in a downgraded situation will tend to select a strong and statistically sure mode in order to carry out this task of targets research.
    - From a certain control, it becomes possible to release some resources from the time delays management to prevent a "cognitive overload", and thus to restore a certain confidence in the system.
- Uninhabited Military Vehicles and Trust ([8] - 161-165):
    - The cognitive requirements related to the UMV management are fulfilled by the creation of an internal representation of the system, its evolution, and the action plans.
    - Information for the operator presents some specific deformations of the vehicle environment.
    - Two different notions can define trust: self confidence and trust in the system − it is their ratio which indicates the level of acceptable risk for the operator.
    - The flexibility of adaptation to the context, resulting from confidence, cannot be directly associated with the know-how.
    - The operator can take more risks in exchange of a greater adaptability in his task.
    - Operators use automatic modes in accordance to their previous level of confidence, the probability of failures and their skills in manual control.
    - In the case of system which presents failures, the operator can judge his own capacity to manage it manually less reliable and riskier than in an automatic mode due to workload increase.

        - The certain researchers consider that man, in his interaction with an artificial system, reproduces the same behaviors of management of trust as those observed in social situations between individuals.
    - Future Research ([8] - 165-168):
        - The goal of augmented cognition is to develop a cognitive feedback loop between operator and system that allows the system to sense when an operator is experiencing unacceptable levels of cognitive workload, mental fatigue, and/or stress.
        - The goal of augmented cognition is to increase the amount of information that operators can process and utilize in decision making, reduce manpower requirements, and improve selective attention during stressful battlefield conditions.
        - Aiding from closed-loop augmented cognition significantly improves autonomous UMV operator performance on both primary and secondary C2 tasks.
        - In conjunction with sensor development is the improvement of techniques for processing the sensor data and selection of appropriate user interface augmentations.
        - The chat application and the information contained in the chat messages dominated operator attention allocation while performing time sensitive retargeting of tactical tomahawk missiles.
        - Participants of experiment became fixated on the chat application despite explicit instructions that time critical retargeting was the highest priority task and answering chat queries was the lowest priority task.
        - Humans will continue to be needed in autonomous swarm networks to ensure safety and monitor progress toward an intended effect as part of the supervisory control and decision making loops.
- Migration of operator control: human factors and teaming issues ([8] - 169-192):
    - Migration of UAV Operator Control ([8] - 170-172):
        - Levels of Control:
            - Level 1: Reception and transmission of secondary imagery or data.
            - Level 2: Reception of imagery or data directly from the UAV.
            - Level 3: Control of the UAV payload.
            - Level 4: Control of the UAV, without take-off and landing.
            - Level 5: Full function and control of the UAV to include take-off and landing.
        - LOI (Levels Of Interoperability) allowing a user more control of the system has the potential to enhance mission execution by decreasing the number of intermediary personnel.
        - Types of changeovers include:
            - Time transfer (the operators are identical in skill and function and control is transferred because the endurance of the vehicle exceeds that of the operator).
            - Function transfer (function transfer implies the operators must accomplish different tasks during the same mission, possibly in another system-mode or even at a different part of the system).
            - Skill transfer (the operators are trained differently and the transfer is required as the vehicle performs different tasks).
        - A vehicle transfer implies operators transfer control of the vehicle to include the following:
            - Vehicle command and control.

        - Navigation.
        - Voice communications.
        - Vehicle safety and emergency responsibility.
        - Payload control.
        - Data transmission link control and monitoring.
    - If a large area must be covered or objects of interest are mobile, a high degree of coordination is required between the vehicle and payload operators in order to keep the UMV path within sensor constraints.
- Reasons for Migrating Operator Control ([8] - 172-182):
    - Future military and civil UMV systems are projected to operate for durations of days to months at a time.
    - A critical problem for such endurance UMV systems is the predictable decrements experienced by individuals continuously performing cognitive tasks for sustained periods.
    - UMV operations are not immune to fatigue-related operator performance decrements.
    - Increased automation (e.g., supervisory control) and predictive displays have been utilized to mitigate the effects of control latency.
    - Functional migration of control also occurs in some military tactical UAVs where responsibility for take-off/landing and enroute control is divided between two operators.
    - It should be expected that tasks requiring the sustained attention of UMV operators will be susceptible to degraded performance and increased risk for operational errors.
    - Migration of operator control plays a potentially critical role in the maintenance of optimum operator performance and decreasing risk for operational errors.
    - UMV crew is limited only by data transmission link accessibility.
    - Experience improves operators' cognitive throughput, allowing them to devote limited attentional resources to future problems while automatically attending to immediate perceptual and motor tasks.
    - Rather than training all operators to handle emergencies, specialty teams could be trained to take control of the vehicle and troubleshoot a malfunctioning or damaged UMV.
    - Functional specialization allows for increased training program efficiency since all personnel do not need to receive equal training.
    - Operator performance controlling a single vehicle is significantly degraded when heavy demands are imposed by payload operations.
    - A study examining control of multiple retargetable missiles found operators could effectively control 8 - 12 missiles, but performance degraded with 16 missiles.
    - Migration of control may be utilized as a workload mitigation strategy.
    - Operators became focused on the targeting function to the detriment of situational awareness and vehicle control.
    - If vehicle control is adequate for the task using some form of supervisory control, it may only be necessary to handoff payload control to a more proximate control station, potentially eliminating the need for full control stations in forward locations.
    - Migration of control may well constitute a critical and potentially high workload phase for UMV operators.
    - Controller performance was markedly decreased over the first 5 minute period following assumption of controller duties.

  - Breakdowns in team performance, cooperation, and communication have been shown to be a contributing factor in military UAV mishaps.
- Effects of Control Migration on Concept of Teams ([8] - 182-187):
  - Teams are behaviorally distinct from groups on the dimensions of performance requirements, interdependence, and accountability.
  - Teams may be classified according to four general structures: traditional work teams, long-term project teams, network design structures, and parallel teams.
  - As the relationship of human and computer interaction evolves, the notion of what has constituted a human member team must be changed to include nonhuman entities.
  - Coalition operations require the coordination of dynamic and culturally-diverse teams.
  - Three types of adaptive social processes virtual teams' experience: technological, work, and social adaptation.
  - Understanding the organizational processes at the supra and micro system levels becomes more critical for virtual teams.
  - Cultural differences across team members: on the dimensions of learning style, thinking style, teamwork experience, functional expertise, uncertainty threshold, and intelligence − it may create barriers to building trust and consequently retard the development of team cohesion.
  - High satisfaction of team members varies directly with team commitment and committed team members are critical for operational success.
  - Virtual teams are highly influenced by establishing organizational norms for communication media choice, providing appropriate training, and managing team member relationships.
  - Teams will likely benefit from training in conflict management, uncertainty avoidance, learning to select appropriate communication channels, and how to design appropriate messages.
  - Pilots who were trained in teamwork behaviors were better prepared to deal with complex problems using team competencies.
- Important Issues in Control Migration ([8] - 187-190):
  - Information exchange can be facilitated by the preparation of a mission folder containing the flight plan, tasking, handover location, datalink parameters, other system settings, and emergency or contingency plans.
  - Three levels of SA: perception of the elements in the environment, comprehension of the current situation, and prediction of the future status of one's own situation and the surrounding elements.
  - UAV mission may include SA of a very broad array of issues:
    - System status: fuel status, power settings, etc.
    - System degradations: missing functionality and its consequences for flight continuation, vehicle performance, etc.
    - Datalink status: coverage, frequencies, cryptologic settings…
    - Vehicle parameters: position, speed, attitude, intentions, and future flight path.
    - Airspace: restricted areas, danger zones, and both current and predicted weather.
    - Position of other elements in the environment: traffic, threats, cooperative elements, and coalition assets as well as their intentions and predicted future status.
    - Mission objectives: tasking(s), commander's intent, target information…

    - Future Challenges ([8] - 190-192):
        - Some general recommendations to consider for future work and research include:
            - Conceptualize work process and structure as sequences of communicative actions which coordinate the activities of members.
            - Develop trust and cohesion by incorporating face-to-face meetings early in the team creation process.
            - Evaluate which tasks are appropriate for virtual teams, etc.

- Artificial cognition and co-operative automation ([8] - 213-292):
    - The work process and conventional automation's solution ([8] - 216-223):
        - The Hierarchy of a Conventional Guidance and Control System ([8] - 219-223):
            - Sheridan’s notion of manual control, being unaffected by automated control loops, is to some extent impaired by the current technology of control configured vehicles.
            - A major performance feature of an educated, trained, and well skilled operator is the capability of transforming this work order into a desired work result.
            - There are a couple of restraining factors for the remote operation of the vehicle:
                - The remote operation heavily relies upon the availability, the performance and integrity of some specific guidance functions, such as auto-land, otherwise requiring manual interactions.
                - Insufficient downlink bandwidth and/or incomplete sensor coverage, with respect to the task.
                - The availability of data link, i.e., the ability to monitor or control the vehicle remotely may be disturbed.
    - Problem definition ([8] - 223-234):
        - Shortfalls with Conventional Automation ([8] - 223-225):
            - Erroneous human action is the predominating factor in aviation accidents − many of these human errors are caused by over-demands on the pilot’s resources.
            - The introduction of automation was most beneficial in many situations, which otherwise could not be handled.
            - The most critical design factors are complexity, brittleness, opacity, and literalism.
            - In particular under the assumption of increasing complexity of automation, the human operator is almost completely separated from the underlying process.
            - Conventional automation will usually not be able to recover from undesired situations induced by malfunctions, faulty operations or just the unexpected.
            - Conventional automation is not at all capable of performing any higher decision loop in the sense of supervisory control.
        - Perspectives of Future Automation ([8] - 225-231):
            - As soon as the human is involved as the tasking and monitoring element, which is always the case, the human will be part of the work system.
            - Automated part-tasks, such as autopilot functions, working independently from human intervention likewise, are considered to be automatic.
            - If a vehicle operates fully automatically, it can only react to situation changes, which were foreseen by the operator.

        - As an alternative to full autonomy without human intervention a configuration, where an artificial cognitive component in addition to the human operator might be introduced into the work system.
        - Cognitive automation − it would notice ground or traffic proximity, or maybe exposure to enemy radar.
- Approaching cognition ([8] - 234-245):
    - Model of Human Performance ([8] - 235-237):
        - Rasmussen's model became the probably most common psychological scheme within the entire engineering community.
            - Distinguishes between three levels of human performance, the skill-based, the rule-based, and the knowledge based behavior.
        - On the rule-based level most of the everyday conscious action that we perform takes place in a strict feedforward control manner.
        - The knowledge-based level will be entered in situations, where there are no applicable rules available in order to recognize objects or to determine the selection of action.
    - Modelling Approaches for Intelligent Machine Behavior ([8] - 237-240):
        - From a very global standpoint there can be identified two fundamentally different approaches:
            - One strongly influenced by the idea of mimicking the human implementation of cognition in the brain.
            - The other being based upon models taken from information technology.
        - Besides those two main streams, early human factors research offered modelling approaches on the basis of control theory.
        - While the processor is almost independent from the task, the functionality is encoded in the knowledge persistent to the memory.
        - To characterize the activity of the cognitive processor:
            - On each cycle, the contents of Working Memory initiate associatively-linked actions in the Long Term Memory, which in turn modify the contents of Working Memory, setting the stage of the next cycle.
        - The so-called production systems − the knowledge is stored in the rule base, the long-term memory of the architecture.
        - Two approaches − symbolic cognitive architectures meant to model intelligent performance:
            - ACT-R is used to model different aspects of human cognitive behavior, i.e., to implement human-like behavior.
            - SOAR [10,4] is used to model an agent's intelligent capabilities, i.e., to implement rational behavior.
        - Some of the most prominent approaches:
            - BDI (Belief-Desire-Intent)-Agents: are software constructs situated in a certain environment and interacting with it autonomously in order to achieve specific individual objectives.
            - RCS (Real-time Control System): is a reference model architecture, suitable for real-time control problem domains, and therefore closely related to robotics.

        - Subsumption Architecture, representing the field of behavior-based robotics, almost fully dismisses the notion of a mental world model. Instead, this architecture is strongly behavior oriented.

    - The Cognitive Process as Approach to Cognitive Automation ([8] - 241-244):
        - The concept of a piece of automation being a team-player in a mixed human-machine team, or even a machine taking over responsibility for work objectives to a large extent.
            - Promotes the approach of deriving required machine functions from models of human performance.
        - Conventional automation – in particular in the avionics domain, it mainly acts on a level which might be compared with the skill-based human performance level.
        - In order to achieve a system engineering framework, the main idea of Rasmussen's model, namely rule- and knowledge-based performance, is mapped into the so-called Cognitive Process (CP).
        - There are two kinds of knowledge:
            - The 'a-priori knowledge', which is given to the CP by the developer of an application during the design process.
            - The 'situational knowledge', which is created at run time by the CP itself by using information from the environment and the a-priori knowledge.
        - The following steps are performed by the CP in order to generate behavior:
            - Information about the current state of the environment is acquired via the input interface.
            - The input data are interpreted to obtain an understanding of the external world.
            - Based on the belief, it is determined, which of the desires are to be pursued in the current situation.
            - Planning determines the steps, i.e., situation changes, which are necessary to alter the current state of the environment in a way that the desired state is achieved.
            - Instruction models are then needed to schedule the steps required to execute the plan, resulting in instructions.
            - These instructions are finally put into effect by the appropriate effectors of the host vehicle.
        - It is desirable to reuse not only the inference mechanism, but also knowledge in different applications.

- Cognitive systems architecture – realization ([8] - 245-247):
    - How to implement an Artificial Cognitive Unit (ACU) on the basis of the proposed theory:
        - The starting point is the human operator as operating element in a work system.
        - As a next step of the development of a cognitive system, the realization of an Artificial Cognitive Unit (ACU) has to be accomplished.
    - COSA is composed of four building blocks:
        - The kernel implements the theory of the CP and does not contain any application-dependent information. Its only task is to generate behavior from knowledge.
        - The application is formed by several COSA-compliant application components, which correspond to packages.
        - The front end provides tools for the developer of an application, which help him to model the knowledge for the application.

        - The distribution layer is responsible for the communication among the modules of COSA. It ensures that components and modules can run on different computers in a network.
- Applied system approaches ([8] - 247-292):
    - Artificial Intelligence (AI) Methods Perspective ([8] - 248-256):
        - UAVs have significant potential to enhance a force's ability to project combat power.
        - Removing the human from the aircraft's cockpit enables more efficient and cost-effective platform designs.
        - Micro-UAVs (MAVs) are supposed to be man-portable and expendable, hence a fully-autonomous architecture is not required.
        - UAVs such as X-45A:
            - Are capable of taking off and landing automatically, and following waypoints to a target.
            - Can relay surveillance data to a controller for target acquisition and designation, and deploy ordnance to destroy a soft target.
        - Autonomous UAV/UCAV have to undertake some of the following actions:
            - System monitoring.
            - Airmanship tasks.
            - Health monitoring/diagnostics.
            - Take-off.
            - Formation.
            - Ingress / routing to target.
            - Carry out mission.
            - Egress.
            - Landing.
        - No single AI technique is appropriate for all areas of autonomous operation.
        - The Airmanship process would be a Knowledge Based System − would continually monitor the state of fuel levels, weapons and sensors, and the position of the aircraft with respect to flight levels and so on.
        - A mission planning system − for the Route Planning process − take the current mission objective and abstracted RASP from the mission manager and; with knowledge of airspace regulations, the platform's capabilities, knowledge of the terrain for masking purposes, and ROE; produce a flight plan.
        - The Mission Manager is in overall control of the aircraft − can use a hybrid technique with inputs from all the other processes feeding a KBS or fuzzy system
        - A human will still be in the loop somewhere, most likely monitoring the UAV/UCAV as part of a system of systems from a ground station, and possibly taking tactical decisions about the overall mission plan.
        - No single technique was a panacea for complete platform autonomy, however certain methods can be applied to particular areas, which might be self-contained should the goal of complete autonomy be judged unobtainable or undesirable.
        - Autonomous flight management might be accomplished with a hybrid system comprised of a controlling fuzzy system fed by a neural network.
        - AI techniques could also be more confidently employed in areas where less capability is required.

- Intelligent, Adaptive Help System Design ([8] - 256-281):
  - "Intelligent" software is built using Knowledge-Based Systems (KBS), which imitate human reasoning.
  - The process of applying Common KADS to build a help system involves the specification of the following six models:
    - Organization model − the primary emphasis of that phase is to examine organizational or business processes that could benefit from the implementation of a knowledge system.
    - Task model − is created primarily as part of the organizational analysis and feasibility assessment and focuses on high-level tasks and goals of agents in the system.
    - Agent model − is developed during the initial feasibility phase. It is used to identify the participants in the itemized tasks so that their responsibilities can be incorporated into any resulting knowledge system.
    - Knowledge model − contains a detailed enumeration of all knowledge required by the system to perform its tasks it has three categories: "domain," "inference" and "task" knowledge.
    - Communication model − the purpose is to describe communication that must occur among agents in the knowledge system. Communication is broken down using a transaction model.
    - Design model − examines hardware and software issues related to the construction of the knowledge system.
  - It is recommended that Common KADS systems should be implemented in an Object-Oriented (O-O) environment.
  - The final step in constructing the Design Model is to create a detailed plan for implementation of the Application Model, Views and Controller, as well as the tasks, inferences and domain knowledge within the Knowledge Model.
  - The IDEF standards provide a set of guidelines for analyzing processes, activities and information needs within organizations.
  - One of the drawbacks of UML is that it is inflexible in representing temporal relationships and constraints among those elements.
  - IDEF3 permits flexible modelling of temporal concepts.
  - IDEF5, which, provides specifications for ontology modelling. It has five steps:
    - Organizing and scoping.
    - Data collection.
    - Data analysis.
    - Initial ontology development.
    - Ontology refinement and validation.
  - Explicit Models Design (EMD) is a development approach that seeks to make explicit the knowledge required by intelligent software systems. It is compartmentalizes software knowledge into five distinct, interacting models:
    - Task Model, containing knowledge about tasks being performed.
    - System Model, consisting of the system's knowledge about itself and its abilities.
    - User Model, comprised of knowledge relating to the user's abilities, needs and preferences.

  - World Model, representing knowledge about the world relevant to the purpose of the software.
  - Dialogue Model, containing knowledge related to communication among human and software agents.
- Explicit Models Design:
  - The Task Model contains knowledge relating to the tasks being performed by the user, represented as a hierarchy of actions, goals and plans.
  - The System Model is composed of the system's knowledge about itself, its abilities and the means by which it can assist users.
  - The User Model is comprised of knowledge about the user's abilities, needs and preferences.
  - The World Model contains the software's knowledge about the external world: the objects that exist in the world, their properties and the rules that govern them.
  - The Dialogue Model contains knowledge about the manner in which communication takes place among user and system agents.
- Plan Recognition − ability to recognize user plans is an important element in EMD and enhances the system's "awareness" of what a user is trying to accomplish.
- It should occur in the context of a system of rules to classify user activities according to a set of criteria that identify whether the user is carrying out the current task:
  - Correctly, completely, consistently, efficiently, safely.
- Plan Generation is the process by which the system develops strategies for accomplishing its goals to assist the user.
- The concept of feedback is important in EMD for establishing mutual understanding and support between the user and the system, enabling one agent to inform another of its goals, plans and knowledge.
- Explicit feedback can occur in the form of dialogues among agents.
- Another theoretical approach recommended for use in help system design is Perceptual Control Theory (PCT).
- The ways in which PCT contributes to help system design fall into two basic categories:
  - Performing hierarchical goal analyses.
  - Using PCT principles in the algorithms of the system.
- A method has been proposed for Hierarchical Goal Analysis (HGA) using principles from PCT, and that technique has the potential to produce a robust and complete task and goal decomposition for help system implementation.
- PCT systems can be implemented as a hierarchy of control loops, wherein the output of the higher levels determines the reference signals at the levels below and the perceptions at lower levels feed the inputs at the levels above.
- The system's decision to offer help is based in part on an assessment of user needs according to whether tasks are being carried out in compliance with the five criteria (correction; completion; consistent; efficient; safety).
- The plan generator should take into account the magnitude of the error signal in determining the optimal behavior for providing assistance under the circumstances.
- An autonomous software agent is a program with the ability to sense its environment and to act on that environment over time.

- The agent-oriented development paradigm offers several advantages, including:
  - Increased modularity.
  - Enhanced reusability.
  - Improved organizational effectiveness.
  - Increased speed.
  - Increased reliability.
  - Better distribution.
- A Multi-Agent System extension of the Common KADS methodology was developed to add specific agent-related constructs, including those associated with:
  - Inter-agent communication.
  - The division of tasks among individual agents.
  - The implications for implementation of multi-agent systems.
- Explicit Models Design (EMD) recognizes the roles of the User and System as agents and can accommodate both multiple human users and system agents, each represented by its own User or System Model.
- Hierarchical goal analysis offers the same benefits described earlier: a thorough decomposition of the goal-plan-action hierarchy with stability and information flow analyses.
- Ecological Interface Design (EID) examines how humans interact with their surroundings.
- Integrated Methodology for Help System Design is composed of elements from the following design approaches:
  - Common KADS (CK) – a knowledge management and engineering methodology.
  - IDEF Standards – a complement to the Common KADS methodology through its more effective support for temporal modelling and ontology construction.
  - Explicit Models Design (EMD) – a methodology for building models that identify and compartmentalize the knowledge required by intelligent systems.
  - Perceptual Control Theory (PCT) – a feedback control system model for goal-directed behavior in a system.
  - Software Agent Paradigm – a software design approach that supports enhanced modularity, reusability and efficiency.
- Generalized Principles of Help System Design:
  - Combine principles from Common KADS, IDEF Standards, Explicit Models Design, Perceptual Control Theory and agent-oriented development to design and implement the system.
  - Use the results of the user needs analysis to develop plans that provide optimal help given the system's on-going knowledge of the user.
- The Five-Part Taxonomy for Plan Recognition in the "Perceptual Control Theory" section:
  - Correctly − There are a few possible scenarios when the system observes a user perform an action that is not the expected next step in the currently inferred plan. Such scenarios provide opportunities for the system to offer clarification on the correct approaches.
  - Completely − Incomplete execution of plans also can be associated with a variety of scenarios. In some cases, it may be desirable to present a reminder about the unfinished task.

    - Consistently − User consistency with task execution can be determined by comparing steps taken to achieve a particular goal with those taken by the user to satisfy that goal in the past.
    - Efficiently − A simple rule for identifying inefficiency in user actions would compare the current plan with alternate plans for achieving the same goal. The presence of another plan with fewer steps suggests that the user should be informed of the simpler alternative.
    - Safely − Safe execution of tasks will not be a critical issue in all applications, but in some domains, the safety of humans and equipment can be a deciding factor.
- Description of help needs as they fall within the five-part taxonomy:
    - Correctness − if a plan is being pursued incorrectly, it is likely that the user should be informed about it promptly.
    - Completeness − an incomplete plan can be the result of a user omitting a required action during its execution and, as such, it is important to inform the user of that omission.
    - Consistency − some inconsistent behavior on the part of a user may indicate confusion as to how to achieve current goals, it will be more appropriate to use a less overt form of help, such as waiting for a pause in a user's activities before presenting information.
    - Efficiency − the efficiency criterion usually is not associated with problems in completing the current task and, therefore, an inconspicuous or delayed form of help is appropriate.
    - Safety − the safe execution of tasks is associated with a high priority for conveying help to the user, help information relating to safety will necessitate immediate notification of the user in a conspicuous manner.
- Plans for Providing Help:
    - A "wizard" interface to guide the user through a complex process, such as creating a workspace and configuring its contents.
    - Tutorials tailored to a user according to what the system believes the user knows.
    - Interactive tutorials, whereby the system steps through a description of a procedure while the user carries it out.
    - Tutorials providing guidance on how to solve an application-specific problem that a user is confronting.
    - Presentation of a question asking if the user would like assistance or a question asking for clarification of a user's intentions.
- The wizard interface approach offers a number of advantages:
    - It simplifies tasks for users.
    - Incidental learning occurs when users are guided through procedures for achieving high-level goals.
    - By stepping a user through a well-defined procedure.
    - Given the built-in constraints on task execution, there will be fewer opportunities for plans to violate any of the help system criteria.
- Audio Wizards – consideration should be given to the creation of a wizard interface that uses an audio dialogue between the user and system.
- A high-level description of control loop goals is as follows: to perceive (believe) that:
    - The user is performing the current task sufficiently well and does not require help.

        - The user is performing the current task efficiently.
        - There are no plans with fewer steps available to achieve the current goal.
        - There are no more efficient plans of the same length to achieve that goal.
        - The user is performing the task correctly.
    - Agent-based objects are to include all standard interface elements, such as windows, buttons and menu items, as well as application-specific objects.
    - A need exists for users to be able to specify their requirements of the system.
    - The system should intervene, based on:
        - System beliefs that the user possesses relevant knowledge.
        - Feedback from the user in response to each help offer from the system.
        - General feedback from the user on preferred types of help, based on online.
        - Historical system knowledge of techniques that have been most effective at conveying information to that user in the past.
        - State of completion of the current task, so as to avoid unnecessary disruption.
- Autonomous Decision Making for an Underwater Unmanned Vehicle ([8] - 281-290):
    - The free swimming UUVs tend to be very small, of limited endurance, with a single specific task, such as inspection of underwater objects.
    - It is useful to simplify the different levels of tasks into 3 groups, namely system health monitoring, mission control and strategic control.
    - The aim in improving the ability of an autonomous vehicle to handle higher level functions and tasks and environments with significant levels of uncertainty associated with them, can be expressed directly in terms of increasing the PACT level of tasks from that currently attainable.
    - The sensible agent, which participate in a two phase process prior to engaging in tasks, namely:
        - A decision-making phase, during which sub-tasks designed to carry out the goal are identified and agreed upon.
        - A task allocation phase, during which the various agents are assigned actions and tasks, in accordance with the decisions made.
    - The work on UCUV artificial intelligence engine development has two facets:
        - The development of a knowledge based system for “inside-the-envelope” decision making.
        - The development of a Bayesian based learning techniques for “outside-the-envelope” decision making.
    - The robustness of the Bayesian approach itself and also significant promise for the application of the ‘abstract and simplify’ approach adopted here, in the context of noisy, information-poor environments.

## 4.2 SENSORS AND OTHER INPUTS

### 4.2.1 Long Term Capability Requirements

#### 4.2.1.1 Analysis of Operational Requirements

- *Battle Management System* − needs to provide timely and accurate information, must be lightweight, robust and relatively inexpensive, function in all weather and environmental conditions ([1] - A7).
- *C-EID (Counter Improvised Explosive Device)* − must allow the interception of constituent IED parts, it must monitor IED construction information available from open sources, must permit the interception of constructed IEDs, must work in all weather conditions and across all relevant military domains ([1] - A13).
- *Information Assurance Services* − NATO's capability to undertake operations is dependent upon linking sensors, decision makers and weapon systems in a seamless, collaborative, planning, assessment and execution environment involving dynamic risk and vulnerability assessments. Have to be ubiquitous, distributed and accessible by each user/agent from the highest level down to mobile and distributed military units in the field ([1] - A31).

#### 4.2.1.2 Analysis on Technological Possibilities.

- *Battle Management System* − effective force monitoring must reduce the occurrences of both types of fratricide, maintain accurate location and status information ([1] - A7):
  - Potential systems − electric power cells, nanotechnology, integrated microsystems… ([1] - A7, A8).
- *C-EID* − IEDs pose a lethal hazard to all personnel, the devices are inexpensive to produce, can be placed in a variety of locations, ability to counter IEDs in a timely manner would prevent death or injury ([1] - A13):
  - Advanced sensors, data fusion, advanced pattern recognition, directed energy and acoustic weapons… ([1] - A13).
- *Information Assurance Services* − increases confidentiality, integrity, availability, authentication and non-repudiation by developing an adaptable and verifiable environment for information services:
  - Automated reaction tools, key management, dynamical, role-based, policy-based, ... ([1] - A31, A32).

### 4.2.2 Future Emerging Technology Trends

#### 4.2.2.1 Analysis of Operational Requirements

- *Communications* ([2] - 18-20):
  - Evolution of three key technologies: wireless communication, sensors and semantic technologies within computer science.
  - C2[1] − heavily depends on telecommunication upgrades, construction of fiber-optic lines and worldwide upgrades to digital switching has improved the reliability, security, and speed of national and strategic C2 communications.
  - The use of GPS in contemporary MCD represents the initial step toward using sensors to track the motion of users and provide geo-location data.

[1] "Command and Control."

    - The necessary connectivity will be provided by deployable wireless networks that attach to vehicles, UAVs or aerostatic balloons supported by some form of mesh network.

- *Sensors* ([2] - 24-26):
    - Applications are being developed that will remove heat signatures so that they are undetectable by thermal-imaging devices through introduction of new materials or cooling systems.
    - As sensor technologies become more prevalent, they will generate increasing amounts of data, with the associated problems of storage and processing.
    - Sensors usually consist of microwave and/or millimeter wave radar, thermal imagers operating in the mid- and long-wave infrared bands, laser range finders, ultraviolet receivers, and television systems operating in the shortwave infrared and optical bands.
    - Increased national research on passive covert radar technology is promising a low-cost air surveillance solution, with the potential for improved low-level surveillance and enhanced detection of low-observable targets.
    - A wide variety of spectrally specific sensor applications only need implementation as ruggedized equipment.
    - Work is being done on algorithms that could potentially automatically track vehicles and even people over the whole viewing area.
    - Types of expert systems will be necessary to analyze the significantly increased amount of digital data that will be collected by these advanced electro-optic sensors over time.

#### 4.2.2.2 Analysis on Technological Possibilities

- *Communications* ([2] - 18-20):
    - Open use networks and cloud computing will allow multiple users and uses to leverage shared information from a network of hardware, software applications and databases.
    - Mesh networks – will provide inexpensive and robust means of passing data, will be able to expand automatically and efficiently as the number of devices on the network increases ([2] - 18/19).
    - Mobile Communications Devices (MCD) – will be integrated with on-board technology able to “sense” the behavior, attitude, issues and needs of the user.
    - These developments will lead to the ‘internet of things’ wherein most objects will have a connection to the internet to share/receive information. This will support initiatives such as Smart Cities.
    - MCDs will be increasingly versatile. Speech recognition will replace conventional keyboards as the primary interface with these types of devices.
    - Augmented Reality (AR) – will become the norm in the coming decades. Personnel will be able to view information while maintaining visual contact with the surrounding environment.

- *Sensors* ([2] - 24-26):
    - Sensors will provide unprecedented access to information about the environment and potentially increase our ability to influence and control it, as well as improve detection and monitoring of changes.
    - Mesh networks and low-energy wireless communication technologies will allow sensors to communicate their data.
    - Smart dust is essentially a fixed passive system once deployed.
    - Speckled computing combines the concept with that of swarm robotics to allow for intelligent reorganization and reprogramming of the sensor network.

- Low cost night vision equipment will be available for sale on open markets.
- Targeting ability of weapon systems in adverse environments will be increased using multi-spectral sensors and supporting algorithms.
- Element-level digitization, adaptive beam-forming and energy management is now well understood and operational in the naval and missile defence environments. This could be readily extended to the ground-based air-surveillance to provide the flexible detection of low-observable targets in complex electronic measures environments.
- Nanotechnology may support networks of very small persistent sensor that could be widely distributed through the operations area.
- Spectrally-sensitive technologies will detect targets in cluttered background and under camouflage. These systems will be aided by automatic target recognition.

### 4.2.3 Nanotechnology for Autonomous Vehicles

#### 4.2.3.1 Analysis on Technological Possibilities

- *Impact of nanotechnologies and novel technologies from other application areas* ([7] - 37-44):
  - Sensors ([7] - 39-41):
    - The big advantage of wireless sensor systems is that by removing wires and batteries, there is the potential for embedding sensors in previously inaccessible locations.
    - Nanotechnology has the potential to design sensors that are not only smaller, but also less power consuming, and more sensitive than micro or macro sensors.
    - For sensor applications, the cantilevers are coated with an application specific layer and placed in a sensor device. A liquid or gas is passed through them.
    - Nanotube-based physical sensors can measure pressure, flow, temperature, or the mass of an attached particle.
    - Sensors based on functionalized carbon nanotubes are expected to provide high sensitivity, large linear range, fast response, long lifetime and low detection thresholds for different (bio)chemicals.

### 4.2.4 Uninhabited Military Vehicles (UMVs): Human Factors Issues in Augmenting the Force

#### 4.2.4.1 Analysis of Operational Requirements

- *System of Systems* ([8] - 143-211):
  - Command and control: human information processing and trust in the delayed systems ([8] - 144-168):
    - Human Information Processing (HIP) Capabilities, Limitations, and Detractors ([8] - 144-150).

### 4.2.5 Long Term Capability Requirements

#### 4.2.5.1 Analysis of Operational Requirements

- *Counter Threat to Low Altitude Air Vehicles* − must reduce the losses of and damage to low speed / low altitude air vehicles, must encompass the ability to search for and detect, identify and track potential and active threats ([1] - A19).

- *Land Engagement Capability* − needs to be lighter, faster, have higher availability / lower maintenance, and possess greater operational range and greater engagement. Must have the survivability, lethality and range to successfully perform future NATO missions ([1] - A38).
- *Vehicle Mobility and Survivability* − needs to significantly improve the mobility and survivability of vehicles used on deployed operations, should in general be lighter, faster, have longer range, increased payload, must also be capable of operating in all terrains, all weather ([1] - A51).

#### 4.2.5.2 Analysis on Technological Possibilities

- *Counter Threat to Low Altitude Air Vehicles* − low speed and low altitude aircraft are particularly vulnerable to low technology weapons, high performance aircraft are also vulnerable during take-off and landing [1 - A19]:
  - Sound damping, armors, materials, sensors to detect threat, lower signature… ([1] - A19).
- *Land Engagement Capability* − allow operation in all terrains including littoral zones to support amphibious operations, capable of integration into the overall NEC ([1] - A38):
  - Hybrid vehicles, directed energy weapons, multiple fuel power sources, helicopters, … ([1] - A38).
- *Vehicle Mobility and Survivability* − Vehicles with increased mobility in a range of terrain and climates will enable operations in all threat environments ([1] - A51):
  - Autonomous vehicles, multi-fuel capable, alternative propulsion, New armor technology, charged-coupled devices, ... ([1] - A51).

### 4.2.6 Future Emerging Technology Trends

#### 4.2.6.1 Analysis of Operational Requirements

- *Fossil Fuels* ([2] - 42):
  - Technology has also supported greater production of oil in many areas.
  - Capture and sequestration of carbon dioxide emitted from fossils will be particularly important.
- *Alternative Energy* ([2] - 43):
  - The full life-cycle plant-based fuel alternatives are still not fully understood, particularly the degree to which they cause, directly or indirectly, changes in land use around the globe.
- *Solar Power* ([2] - 43):
  - Though the installed infrastructure for fossil fuels would take a long time to replace and would not be without significant upfront costs.
- *Other Alternatives* ([2] - 44):
  - Hydrogen does not have the energy density of fossil fuels and is difficult to transport in large amounts.
  - Once the production of hydrogen can be accomplished through renewable means – primarily solar – it will become much more feasible.
  - The accompanying issues of storing nuclear waste and decreasing stocks of uranium would still need to be resolved, though both could be addressed by using waste nuclear material as fuel.
  - Osmotic power commercial use has been limited due to the low generating capacities offered by innovation in nanotechnology.

- *Battery Technology* ([2] - 44-45):
  - The use of renewable energies have a continuing challenge of ensuring that power supplies are maintained when sources are intermittent.
- *Resources* ([2] - 45-46).

#### 4.2.6.2 Analysis on Technological Possibilities

- *Efficiency* ([2] - 41-42):
  - Smart grids and smart cities will allow for more precise monitoring and consumption of energy.
  - Smart grids would also have stronger protection against cyber-attacks on its Supervisory Control and Data Acquisition (SCADA) – the components of systems that are controllable via the internet.
- *Fossil Fuels* ([2] - 42):
  - A viable alternative to fossils fuels may come in the form of electrically driven cars provided the electricity is generated in some renewable or energy-efficient fashion.
- *Alternative Energy* ([2] - 43):
  - Second- and third-generation bio refineries could produce more tractable, higher octane fuels from the non-edible portions of plants and faster growing biomass or algae.
- *Solar Power* ([2] - 43):
  - Solar power has potential to solve many of the problems associated with fossil fuels.
  - The energy efficiency of solar is 100-200% higher than other alternatives and improving at a similar rate as Moore's Law through new materials and nanotechnology.
  - There is also progress being made in producing solar energy at night through capture of infrared waves albeit at much lower levels.
- *Other Alternatives* ([2] - 44):
  - Hydrogen could become a viable energy source.
  - The future of energy may lie in a nuclear reactor small enough and safe enough to be installed in groups of homes.
  - Other possible examples of alternative power sources include methane hydrates and osmotic power.
  - Osmotic power plants generate electricity from the difference in the salt concentration between river water and seawater.
- *Battery Technology* ([2] - 44-45):
  - Nanotechnology has shown significant progress in the development of improved batteries.
  - Wireless power transmission is demonstrating some potential over short ranges, but could see major improvements in the future.
- *Resources* ([2] - 45-46):
  - Nanotechnology is developing filters for reverse-osmosis water generation that requires a fraction of the energy needed today to push water through a filter.
  - Renewable energy sources and emerging technologies will make desalination of ocean water a more viable means of supplying fresh water.

- New water retention technology is being developed that will retain a greater proportion of available water.

### 4.2.7 Nanotechnology for Autonomous Vehicles

#### 4.2.7.1 Analysis of Operational Requirements

- *Rapid and Effective Response* ([7] - 19):
  - Flexible, adaptable, technologically advanced forces.
  - Deplorability and Sustainability.
  - Light / medium weight. Low logistics burden.
  - Precision effects / minimum collateral damage.
- *Network Enabled Capability* ([7] -19):
  - Information Dominance. Real-time decision making.
  - Novel Sensors – detection and identification.
- *Protection and Survivability* ([7] -19]):
  - Personal protection. Equipment protection.
  - Low observability. Combat identification.
  - Autonomous Systems.
- *Interoperability* ([7] - 19).
- *Autonomous vehicles* ([7] - 67-73):
  - Mems and nanotechnology for controlling UAV aerodynamics ([7] - 70-73):
    - Passive aerofoil-shape change for multipoint optimization needs: Exploration of membrane wing concept, which may allow passive means to reduce effect of low Reynolds number on lateral stability, combining with RF control, weight reduction, and other multi-functions...

#### 4.2.7.2 Analysis on Technological Possibilities

- *Autonomous vehicles* ([7] - 67-73):
  - Nanotechnology applications to UAVS ([7] - 67-70):
    - Micro and nanotechnologies will enable the development of materials for enhanced sensor performance and novel sensing capabilities.
    - (Micro) radar for personal use and for unmanned miniaturized vehicles, thermal IR sensors with enhanced sensitivity, …
    - Possibilities in long term: enhanced surfaces treated with anti-corrosion, hardware, and frictionless coatings, stealth coatings, adaptive camouflage, electronics...
    - As for weight and hardness, Toyota started using nano-composites in their bumpers making them 60% lighter and twice as resistant to denting and scratching.
    - Nano-composite is scratch-resistant, light-weight, and rust-proof, and generates improvements in strength and reductions in weight, which lead to fuel savings and increased longevity.

    - The treatment of surfaces to make them into Super-hydrophobic structures have implications on sensors and electronic materials and (sub) systems packaging which need to be operational and functional in highly humid environments.
    - Improved energy utilization is also the premise of nanotechnology, to modify the combustion profile in order to deliver more useful work from each combustion cycle for a given quantity of fuel.
    - Nano-cubes made of organometallic network materials, currently being analyzed for their properties by BASF researchers, could prove a suitable storage medium for hydrogen.
    - In essence, the current advancements in the field of nanotechnology will impact all aspects of defence applications, including autonomous vehicles.
  - Mems and nanotechnology for controlling UAV aerodynamics ([7] - 70-73):
    - Potential benefits: Reduced system complexity/weight, velocity/pressure distribution control...
    - The benefits of flow separation control are: Increased performance, reduced cost, reduced size, reduced weight, reduced maintenance costs, reduced signatures.
    - Control of attached flows can be achieved by: Use synthetic jets, which are distributed over aero surfaces. Improve aerodynamic performance to reduce drag, avoid separation and optimize circulation.
    - MEMS and nano-enabled materials have the potential to improve performance of aerostructures.

### 4.2.8 Uninhabited Military Vehicles (UMVs): Human Factors Issues in Augmenting the Force

#### 4.2.8.1 Analysis of Operational Requirements

- *Military relevance* ([8] - 41-91):
  - Military relevance of human factors of UMV systems ([8] - 41-82):
    - Operational Benefits of UMVs: ([8] - 48-63):
      - Failure rates in urban terrain are relatively high with a mean-time between failures on average of between 6 – 20 hours.
      - UGVs are mostly operated by remote control, requiring robust, compact and portable operator control stations, with relatively simple control and display interfaces.
      - EOD/IED operational environment involves complex problem solving and high levels of operator situational awareness → requires high levels of operator and team skills and experience.
      - In the military underwater domain research has been characterized by a desire for a direct route to behaviorally simple, but fully autonomous, Uninhabited Underwater Vehicles (UUVs).
      - Free swimming UUVs tend to be very small, of limited endurance, with a single specific task.
      - The closer the UUV is driven to the beach, the greater the sensing, navigation, communications and control problems become.
      - Retaining and managing power is an important UUV task, and a strong candidate for automation.

- Important question is: “can I do the mission and return to my recovery point on my power reserves?” this base-lining of the projected energy consumption for the whole mission.
- Challenges of UAVs: interoperability of systems, vulnerability, insatiable demand for bandwidth …
- Believes that future UAV systems will have the ability to control several vehicles with one UCS.
- Believes that a UAV must respond to commands in a timely way, similar to manned aircraft.
- Current UAVs have limited sense and avoid capability.
- Curran believes that all classes of UAVs will have the following core capabilities:
  - Networked systems-of-systems using the Future Combat System (FCS).
  - Embedded autonomous flight control and navigation, and safe flight protocols.
  - Unprecedented reliability, maintainability and operational availability.
  - A reusable platform durable against environmental effects.
- Autonomy is needed so that degraded communications, whether caused by sunspots or jamming, must not impair the aircraft functionality or the system’s ability to complete missions.
- System must within a large area of interest image any details with the Synthetic Aperture Radar (SAR) mode.
- In the Moving Target Indicator (MTI) mode it must detect, track and classify moving targets.
- The Stand Off Surveillance and Target Acquisition System (SOSTAS) demonstrator is intended to perform all the required functions of the full scale model, including the simultaneous interleaved operation of SAR and MTI, but has a small antenna size to reduce cost.
- Decision making, modelling, learning, and attack planning have the highest risk/highest cost associated with their development in UAV systems, but they also support the greatest number of autonomous capabilities.
- An autonomous UAV operating within a network centric environment needs to behave with the same reliability and effectiveness as manned elements and ideally, should not require special handling.

- Command and Control ([8] - 63-65):
  - NATO Air Command and Control System:
    - UAV sorties must be included in the Air Task Order (ATO) along with manned aircraft sorties for maximum combined effectiveness.
  - Interoperability:
    - Is needed in Combined/Joint services operations to provide close coordination, the ability to task quickly available assets, and the rapid dissemination of resultant information at different command echelons.
- UMV Use Cases ([8] - 71-82):
  - An articulation of the context of use of UMV systems is needed in order to provide a military relevant reference basis for considering HF issues.
  - The selection of vignettes is important and entails the inherent risks of being unrepresentative → selectivity risks biasing analysis, by introducing irrelevant or limiting focus, and setting overly restrictive boundaries and limitations to thinking.

- The objectives which NATO air power must accomplish:
  - Neutralization of the internal air threat.
  - Radar support jamming.
  - Neutralization of the maritime threat.
  - Battlespace surveillance, airborne command and control and communications support.
- Special corridors will be needed for ingress and egress, with rendezvous with manned aircraft in pre-planned areas.
- UCSs will need to be integrated into the COMAO planning process. This will include consideration of:
  - Leaders.
  - Routing.
  - Reaction to threats.
  - Target area tactics and procedures.
  - Delay and cancellation procedures and options.
  - Communications and data link selection and de-confliction.
- Current COMAOs with manned aircraft require extensive pre-planning and have a degree of rigidity.
- As a cautionary observation, SAS-016 noted that UAV systems may lend themselves to micro-management from higher command levels.
- UAV tasks were identified for a COMAO mission to attack an airfield:
  - Ingress: Control, Guidance, Navigation, Re-plan, Communication, System management, Self-defense and Target location.
  - Over Target: Target registration, identification, verification, designation, Control, Guidance, Navigation, System management, Communication, Sensor management, Self-defense, Rules of engagement and Battle damage assessment.
  - Egress: Control, Guidance, Navigation, Communication, System management and Self-defence.
- The UUV VSW MCM (and EOD) task as comprising seven phases:
  - Deployment and distribution of assets.
  - Execution of a search strategy.
  - Detection of mine-like objects.
  - Classification and identification.
  - Neutralization.
  - Verification and certification of clearance.
  - Recovery of assets.
- The greater the autonomy given to the vehicle and the use of buoys will help to maintain the covert nature of the mission.

#### 4.2.8.2 Analysis on Technological Possibilities

- *Military relevance* ([8] - 41-91):
  - Military relevance of human factors of UMV systems ([8] - 41-82):
    - Operational Benefits of UMVs ([8] - 48-63):

- UAVs have probably resulted in the most significant technical activity from a human factors perspective.
- Uninhabited Ground Vehicles (UGVs) have been particularly successful in support of space operations, such as the Lunar and Mars rover vehicles.
- UGVs have important military roles for reconnaissance and surveillance in support of urban operations, particularly for working in confined, restricted and dangerous environments.
- For military purposes, UGVs experience major challenges to mobility and maneuverability due to sensing and avoidance difficulties with unexpected ground obstacles and crevices, and due to terrains.
- Remotely controlled UGVs have a significant current role as tools for detecting hazardous and dangerous materials, and in particular for counter-mine.
- The current version of Talon is a semiautonomous unmanned vehicle capable of firing rifles, machine guns, grenade launchers and rockets.
- Benefits and issues of UGVs: removal of soldiers from hazardous and hostile environments, robot must prevail in competitive conflict, persistent attention…
- Future UGVs are envisioned for more complex and hazardous tasks, such as casualty evacuation, with more challenging technical requirements, complex safety issues, and potentially high levels of automation.
- Autonomous, networked and integrated robots may be the dominant fighting force by the year 2025.
- We have experience in using underwater Remotely Operated Vehicles (ROVs) in the oil industry for offshore support and UUVs have been used in varied environments for scientific work.
- Deploying sonars near enemy naval installations to track asset movement and even kill them with torpedoes.
- The dolphins locate the mines using endogenous sonar, then drop pingers to tag locations.
- Alternatives include large UUVs carrying a variety of sensors and deploying sensor arrays, and smaller vehicles firing torpedoes.
- As with current UAVs, UUVs will soon fire weapons on command, requiring reliable secure underwater communications systems.
- ALUV (Ariel Autonomous Legged Underwater Vehicle – a crab-like robot, for mine and obstacle neutralization) would secure itself to the mine and await a detonation signal, or deposit an explosive.
- It is believed that the ability of UAVs to perform their missions with autonomous capabilities will be a major step towards achieving flexible, efficient and interoperable military operations.
- Strengths of UAVs: dealing well with 3D tasks, ease of re-tasking, increase stand-off ranges for kinetic, and non-kinetic or cognitive attack …
- Table 2-1: Summary of UAV Classes, Roles and Control ([8] - 54-56).
- The UAV and payload control can be handed over to the CAOC or other sea-, land- or air-based tactical UCSs at any time during the flight.
- Joint Unmanned Combat System (J-UCAS) program seeks to exploit the potential of a networked system of high performance, weapon-carrying unmanned aircraft with the ability to penetrate and persist deep within the enemy territory.
- In the future may be achieved with the operators' tasking optimized for workload and mission-critical needs.

- Allied Ground Surveillance (AGS) is a method to support Peacekeeping and other military operations.
- Table 2-2: Summary of UMV Missions and Environments ([8] - 61-62).

- Command and Control ([8] - 63-65):
  - NATO Air Command and Control System:
    - UAV systems are currently not part of the NACCS and are not managed as part of a manned strike package.
    - Four entity types Combat Air Operations Center (CAOC), Air Control Center (ACC), Rapid Air Picture (RAP) Production Center (RPC) and Sensor Fusion Post (SFP) constitute the "core" of NACCS.
  - UMV Use Cases ([8] - 71-82):
    - Are tools for systems engineering, providing the basis for the mission analyzes used to develop understanding of system functions, information and user interface HF requirements?
    - UAV currently operate in segregated airspace physically separated from manned aircraft.
    - Different classes of UAV systems can undertake different types of mission/tasks dependent on payload, range and endurance, speed and survivability.
    - UAV systems can replace manned aircraft for various mission/tasks, placing fewer aircrew at risk.
    - For the mid-term, there will be no close formation flying because of technical limitations and aircrew mistrust.
    - In the MCM role, the UUV will be deployed from a platform, or a harbour, and transit to its operational area.
    - The UUV might follow one of the following tactical options:
      - Report the position of mines and wait for further instructions.
      - Autonomously decide no clear path through the minefield exists and search for an alternate route to the objective.
      - Dispose of mines along the swept path.
    - Once the mines have been located, each small UUV could position itself over a mine and drop a small detonation charge to neutralize the mine.
    - Table 2-3: Composite Scenario Tasks ([8] - 79-80).
- Military relevance for Uninhabited Aerial Vehicles (UAVs) ([8] - 82-91):
  - Platform Characteristics ([8] - 88-89):
    - Separation is done in time and space and the consequence are a change in the character of control, which may vary over time.
    - The character of the platform that states the type.

## 4.3 SYSTEMS

### 4.3.1 Long Term Capability Requirements

#### 4.3.1.1 Analysis of Operational Requirements

- *Assured Precision Strike* − must be persistent and responsive, capable of being rendered inert ([1] - A5).

- *Battlefield Medical Attention* − be able to quickly identify the requirement for medical attention, deliver the diagnosis, should provide prompt remedial treatment ([1] - A6).
- *Beyond Line Of Sight (BLOS) Communications Capability* − be flexible, robust, secure, reliable and affordable, users must be able to communicate covertly when required, must allow communication between C2 elements ([1] - A9).
- *CBRN* [2] − must detect, classify and quantify the full spectrum of CBRN agents, must be reliable and durable, needs to be fully integrated into the JISR[3] ([1] - A12).
- *Counter Rocket, Artillery and Mortar* − must successfully identify, track and engage in-flight threat munitions, must provide precise early warning of attack, systems must be able to act autonomously, coordinating actions on the point of origin and collecting data ([1] - A18).
- *Counter Underwater Threats* − ability to rapidly and reliably detect, identify, localize, track, and neutralize or destroy all types of underwater threats, need for an improved capability in analyzing and characterizing the underwater operating environment ([1] - A20).
- *Deployment and Mobility of Forces* − need to reduce the time required to deploy an effective force at strategic distances from Alliance territory, must meet future requirements as set forth in relevant operations plans ([1] - A23).
- *ISR Collection Capability* − JISR[4] collection capabilities should aim to minimize the risk to Alliance personnel involved collection operations and, when necessary, collection needs to be non-intrusive and covert ([1] - A34, A35).
- *Non-Lethal Capability* − must restrain, repel or temporarily incapacitate targeted individuals or groups with a low probability of fatality or permanent injury, or to disable equipment with minimal undesired damage or impact on the environment ([1] - A42).
- *Soldier Situational Awareness* − Needs to be lightweight, compact and robust. The system must withstand extreme conditions. Must also be clear and easy to understand. Needs enough available communications bandwidth to transmit and receive various formats of information and sufficient power to transmit in all terrains over various distances ([1] - A45).
- *Support Chain Management* − minimizing both the logistic footprint and drag during deployed operations, supply chain of military operations need to be highly flexible rather than highly optimized ([1] - A47).
- *Support to Insertion, Extraction and Resupply of Special Operations* − must safely insert and extract forces into the theatre of operations with a very low probability of detection from visual, aural, or any other electromagnetic spectrum detection means, the delivery of the supplies should be self-verified and, if required, should be neutralizable ([1] - A48).

#### 4.3.1.2 Analysis on Technological Possibilities

- *Assured Precision Strike* − problem to rapidly detect, identify, assess, track, and accurately attack. Locating and destroying the target ([1] - A5):
  - Potential systems − advanced sensors, precision guided weapons, warhead design, scalable, …. ([1] - A5).

[2] "Chemical, Biological, Radiological and Nuclear."

[3] "Joint Functional Component Command for Intelligence."

[4] "Joint Intelligence and Reconnaissance."

- *Battlefield Medical Attention* − potential systems − AI, Robotics, medical UAV[5], autonomous ambulances, autonomous diagnostics of patients, … ([1] - A6).
- *BLOS Communications Capability* − secure, robust, reliable, and affordable means of augmenting available capacity ([1] - A9):
  - Potential systems − Satellite communications technologies; high altitude, software defined radio technology, … ([1] - A9).
- *CBRN* − it is done at close range through collecting samples (this is undesirable). Advanced detection of CBRN agents enables planning for an appropriate response. Now, there is limited standoff capability for containerized biological/chemical agents ([1] - A12):
  - Potential systems − Biotechnology, chemical agents, materials, AI, laser sensors… ([1] - A12).
- *Counter Rocket, Artillery and Mortar* − radars and other surveillance assets can help locate sources of rocket, will reduce military/ civilian casualties and support successful NATO operations ([1] - A18):
  - Potential systems − Advanced radars, capable gun systems with advanced hit efficiency and destruction ammunition, … ([1] - A18).
- *Counter Underwater Threats* − small group of underwater vehicles is capable of conducting coastal defence or sea denial missions, detection of threats with sufficient warning, increase the likelihood of defeating threat torpedoes ([1] - A20):
  - Potential systems − Advanced decoys, advanced sensors for local and wide area high-precision underwater threat detection and tracking, advanced signal processing, … ([1] - A21).
- *Deployment and Mobility of Forces* − potential systems − High Speed Ships, Wing in Ground effect technology, larger cheaper air transport methods ([1] - A23).
- *ISR Collection Capability* − Such products need to cover the appropriate Political, Military, Economic, Social, Infrastructural, Informational aspects of opponents/neutrals and other relevant parties, identifying trends and developments. New technologies also offer the prospect of enhancing the efficiency of currently available capabilities e.g. reduction in manpower requirements ([1] - A34, A35):
  - Unmanned air, ground and underwater vehicles, robotics, meteorological assessment, … ([1] - A35).
- *Non-Lethal Capability* − individual or crowd control could prevent collateral deaths or injury and still allow Alliance military objectives to be obtained. Capturing individuals for further interview without injury or death may be more successful than through lethal means ([1] - A42):
  - Robotics, anaesthetics, lasers, behavior monitoring, pattern recognition, vehicle arresting systems, DNA tagging, … ([1] - A42).
- *Soldier Situational Awareness* − increased comprehension of the situation, a more accurate understanding of possible future events and more informed decisions by the soldier ([1] - A45):
  - Smart/functional materials, electric power cells, nanotechnology, integrated microsystems, human/technology interface, ... ([1] - A45).
- *Support Chain Management* − will result in increased asset visibility and availability in theatre ([1] - A47):
  - In-theatre visibility, transport tracking, in-vehicle system status technology, in-theatre production and fabrication of equipment, ... ([1] - A47).

[5] “Unmanned Aerial Vehicle,”

- *Support to Insertion, Extraction and Resupply of Special Operations* − Lighter forces covertly inserted into theatre may be more effective if complete surprise can be achieved. Would significantly reduce resource requirements and reduce the risk of delivering supplies ([1] - A48):
  - Chameleon camouflage, cloaking systems, artificial Intelligence, novel guidance and power systems, lightweight materials, ... ([1] - A48, A49).

### 4.3.2 Future Emerging Technology Trends

#### 4.3.2.1 Analysis of Operational Requirements

- *Computational Modelling* ([2] - 20-23):
  - AR techniques wherein actual imagery and video from the battle space can be registered with computer generated terrain data stored in geospatial databases.
  - Characterization of uncertainty – methods to track the propagation of uncertainties are required since they can lead to large uncertainties in the output of the simulation.
  - Exploratory analysis under uncertainty − an important research area is developing ways to use modern computer power to explore the space of simulation outcomes and to search for interesting regimes.
  - Explanation Capability − is important for field commanders, managers, and engineers. But it will have more general value and thus they may well be developed in the commercial sector.

- *Cyber Protection* ([2] - 26-28):
  - A lack of common legislation and policies directed toward curbing cyber threats and the cross-organizational nature of the threat has led to disjointed attempts at defending against the rising use of this dimension by criminals, non-state and state actors.
  - Defence against these types of threats will be expensive while attacks with cyber weapons will be cheap – essentially free.
  - Authentication of personnel and processes will be essential to keep networks safe from intrusion and attack.
  - User authentication technologies also show some improvement and password authentication should at some point be replaced by personal devices that are able to perform cryptographic operations, and could possibly include additional factors such as biometrics.
  - Methodologies will need to be developed to quickly instruct pieces of network hardware to drop connections or isolate computer systems when an attack is detected.
  - High potential cyber weapons require specific intelligence, major investments in research and development and long lead times.
  - Centralized network management systems will not be able to cope with new military challenges. To enhance capability, dynamic planning mechanisms based on artificial intelligence and learning systems will assist in the pro-actively provision of service delivery.

- *Robotic Systems* ([2] - 34-35):
  - Technological progress has been seen in key areas such as vision, positioning in terrain, communication, information sharing, environmental scanning and decision making based on some form of reasoning or heuristics.
  - Computer Vision is an important application as it will drive robot/human interaction and, when combined with accurate speech recognition/generation, will complete the communications loop.

- *Autonomous Systems* ([2] - 34-37):
  - Various enhancements to aspects of propulsion, data transfer, sensors, and computer vision will be necessary to field this capability.
  - Drones currently can be used most effectively in permissive airspace as they are limited by their lack of self-protection against a determined attack.
  - The endurance of UAS, and other related systems, will be increased over time with the advent of hydrogen and solar powered systems along with air-to-air refuelling.
  - Future ASSV (Autonomous Surface Sea Vehicles) propulsion systems will utilize environmental energy sources like sea motion and the broad range of alternative power sources.
- *Impact of Unmanned Systems Technologies on Military Operations* ([2] - 37):
  - These systems are prone to jamming and hacking. They will have to be appropriately protected.
  - The advent of unmanned combat vehicles is generating a need for smaller weapon systems to fit their reduced dimensions.
- *Implications of Robotic Systems* ([2] - 37-38):
  - Capabilities will also have to be developed that will disable or destroy systems that fall into enemy hands.
  - The software programs to support these types of systems will be extremely complex and likely written by teams of programmers where the overall complexity could lead to software errors and possibly to unforeseen emergent behaviors.
- *Space Systems* ([2] - 48-49):
  - Systems in future will demand that the Alliance counter with the ability to either move rapidly to alternative sources or operate without this information.
  - In some circumstances, aerostatic balloons or other lighter than air vehicles could be appropriate. Development of reliable over-the-horizon ionospheric backscatter radar may also be an alternative.
  - The development of an accurate and continuously updated library of global geospatial data capability would require development of enabling technologies in the areas of video storage and retrieval, holographic presentation and artificial intelligence.
- *Precision Guided Weapons* ([2] - 49-50):
  - Enhanced warhead technologies for precision munitions will include high energy density warheads, multi-mode warheads, hard target penetrator warheads, and powered sub-munitions.
  - Advances in shaped-charge design and production will continue to stress armor developers.
- *Other Systems* ([2] - 50-51):
  - As emitters utilize shorter radiation times, Low Probability of Intercept (LPI) signals and passive radars using signals from TV or radio stations, the following trends in technology will support progress in Electronic Support Measures.
  - The most serious effects of High Power Microwave (HPM) weapons will be on sensors working in the RF region, but infrared and electro-optical sensors also could be impacted.
  - Protective circuits will have to take into account the difference of ultra-wide-band pulses and natural Electron Magnetic Pulse (EMP) cases like lightning and nuclear.

- *Logistics* ([2] - 53-54):
  - Intelligent systems must be capable of gathering relevant information about their environment, analyzing its significance in terms of assigned functions, and defining the most appropriate course of action consistent with programmed decision logic.

#### 4.3.2.2 Analysis on Technological Possibilities

- *Computational Modelling* ([2] - 20-23):
  - The improved modelling of physical, environmental and human characteristics and behavior, and their incorporation into simulations, offers the potential for innovations and improvements in many fields.
  - In science and engineering, modelling is the formulation of mathematical representations, or ‘models’, of real-world phenomena and processes.
  - Expert systems will assess the quality of gathered data as well as sort and categorize it.
  - These systems will support the development of a comprehensive approach by allowing the construction of high fidelity models of individuals/groups, which capture intents, motivations, objectives, goals and strategy.
  - System modelling – will allow synchronization of actions with effects. This allows the identification of how to stress particular systems to achieve the goals of a campaign.
  - Cognitive modelling will allow information to be gathered, formatted and presented in such a way as to be more easily assimilated by operators.
  - Expert systems will be able to catalogue and exploit explicit information while providing tools to distil and disseminate tacit knowledge built up by experience garnered in operations and exercises.
  - Expert systems will also support areas such as risk analysis. Risk refers to the likelihood or probability for an adverse outcome.
  - Agent-based modelling, advanced simulation and systems dynamics will provide tools for developing appropriate responses to risk.
  - Serious games − are becoming a useful tool, particularly in problem solving, training and education, provide motivation to solve problems that seem less difficult than if presented in other media.

- *Cyber Protection* ([2] - 26-28):
  - As wireless technology and personal devices become more outspread, systems will increase both in dynamicity and diversity.
  - Low potential cyber weapons or malware can influence a system from the outside or remove information.
  - High potential cyber weapons penetrate a system and influence it from the inside.
  - Self-configuring − adapt automatically to dynamically changing environments, self-configuring components adapt dynamically to changes in the IT system.
  - Self-healing components can detect system malfunctions and initiate policy-based corrective actions without disrupting the IT environment.
  - Self-optimizing − Self-optimizing components will be able to monitor and tune resources automatically to meet system demands.
  - Self-protecting − to anticipate, detect, identify and protect against attacks from anywhere.

- *Robotic Systems* ([2] - 34-35):
    - Robotic systems have the attractive feature that they can be stored indefinitely until they are needed, thus reducing their overall operations, maintenance and other lifecycle costs.
    - Exo-skeletal suits will enable human soldiers to carry more equipment for longer distances and time.
    - Drones will provide surveillance over-watch and fire support.
- *Autonomous Systems* ([2] - 34-37):
    - The development of unmanned ground vehicles will support the delivery of the large volumes of material required to maintain a military force in the field.
    - Autonomous capabilities will allow more efficient movement of military supplies.
    - Autonomous systems communicate directly with each other allowing closer vehicle spacing at higher speeds.
    - Groups of relatively simple robots in all domains, with relatively simple and readily available autonomous control systems already have been shown to be able to co-operate to achieve quite complex goals.
    - Future Unmanned Aerial Systems (UAS) are designed to have reduced radar signatures, thus decreasing their probability of detection.
    - Measurements of 3D terrain imagery can be obtained from electro-optical and infrared sensors which would then be compared with a stored digital terrain elevation map database.
    - On-board radar and weapons systems have been incorporated with autonomous decision making abilities in order to defend against the possibly high number of fast, inbound targets that contemporary air defence systems need to defeat.
    - Current and developmental AUV (Autonomous Underwater Vehicles) applications include roles in mine detection, reconnaissance, underwater surveys and ocean data collection.
    - Scientists focused on the field of sensing and are developing extremely small sensors. Using a combination of water pressure and computer vision technology, the sensors allow the compilation of 3-D images of nearby objects and mapping of its surroundings.
- *Impact of Unmanned Systems Technologies on Military Operations* ([2] - 37):
    - Military forces are using robots to search tunnels, caves and buildings for enemy fighters and explosives.
    - Robotic detection and identification of CBRN material and post-event consequence management will be particularly important with the possible proliferation of weapons of mass destruction.
    - Robotic surgery on the battlefield, during transportation or closer to the front lines is also highly possible given advances in this area.
- *Implications of Robotic Systems* ([2] - 37-38):
    - Autonomous robots technology is advancing faster than the development of associated policy and legal considerations.
- *Space Systems* ([2] - 48-49):
    - Space systems with the ability to rendezvous with and investigate other satellites to determine their purpose could allow for intervention prior to the engagement of space-borne anti-satellite systems or even facilitate the repair of on-station assets.

- *Precision Guided Weapons* ([2] - 49-50):
  - Precision attack munitions are aimed at achieving a hit with an accuracy down to the level of from a meter to centimeter.
  - Hybrid GPS/INS will provide metric precision guidance reduced jamming susceptibility that will permit the use of low cost seeker-less missiles against fixed targets.
  - Microelectromechanical (MEM) technology will create more energy per weight.
  - Lasers could be used quickly against many inbound targets.
- *Other Systems* ([2] - 50-51):
  - The development of Anti-Ship Cruise Missiles (ASCM) with improved design features such as supersonic speed, evasive maneuvers, ballistic trajectories and advanced terminal seekers.
  - New construction submarines equipped with Air Independent Power (AIP) propulsion systems will constitute an increasingly greater percentage of worldwide launches and proliferation to new user countries.
  - The EMP effect is characterized by the production of a very short but intense electromagnetic pulse which produces a powerful electromagnetic field sufficiently strong to produce short lived transient voltages of thousands of volts on exposed electrical conductors.
- *Logistics* ([2] - 53-54):
  - Emerging intelligent systems will enable the deployment of advanced systems able to sense, analyze, learn, adapt, and function effectively in changing or hostile environments.
  - On a smaller scale, an intelligent system will be able to automate the resupply and replenishment process.

### 4.3.3 Nanotechnology for Autonomous Vehicles

#### 4.3.3.1 Analysis of Operational Requirements

- *Nanotechnology market sectors* ([7] - 26-28):
  - Fullerenes are still at the very beginning of their life cycle. Bulk production of fullerenes is starting to be established.
  - The major problems to be solved are production efficiency / cost price and safety / environmental issues.
- *Top down equipment* ([7] - 29-32):
  - Nano-imprinting ([7] - 29-30):
    - Important factor for the quality is the mask, usually fabricated by E-beam technology.
    - Monomer properties are important for the pattern quality and are an important aspect of the process selection.
  - Atomic Layer Deposition (ALD) ([7] - 30-31):
    - Is needed for capacitor dielectrics and metal electrodes when conformal deposition of extremely high-aspect-ratio structures is required.
  - Direct Writing ([7] - 31-32):
    - Not all materials can be patterned by the sequence of deposition, lithography and etching.

        - To overcome the disadvantage of the low deposition speed, the plan is to launch an array set for multiple processing (the dip-pen approach).

- *Physical chemical processing* ([7] - 32-33):
    - Powder/Particle Process Equipment ([7] - 32):
        - There are two approaches to produce small particles: either by milling down larger particles or by chemical reaction. In case of a chemical process, the chemical reactor design has to be such that the resulting nanoparticles do not get a chance to agglomerate.
    - Milling ([7] - 32-33):
        - Although scale work with smaller beads (down to 30 mu) has been carried-out in a lab environment, it will become increasingly difficult to separate bead from milled material.
        - Alternatives to bead milling, such as the use of ultrasonic vibration, has been proposed, although is not yet commercialized.
    - Chemical Reactors ([7] - 33):
        - To initiate and maintain the process, often high densities of energy are needed.
        - The energy can be added to the reactants by kinetic energy or by plasma.

- *Nanotube process equipment* ([7] - 33-34):
    - The length of the tubes is an important aspect, which suggests that controlling the purity of the products is a key factor in process technology and equipment manufacturing.
    - One of the principal difficulties in using carbon nanotubes to construct electronic devices lies in the means of manipulating such materials in a controllable fashion.
    - The major differentiator will be the possession of equipment and processes to produce large quantities of nanotubes at low cost and with high purity.

- *Bottom up processing* ([7] - 34-35):
    - Nano-manipulation ([7] - 34-35):
        - Any type of AFM may be used to manipulate atoms, however, it is challenging to develop a financially viable bulk fabrication process using such techniques.

- *Impact of nanotechnologies and novel technologies from other application areas* ([7] - 37-44):
    - Data processing ([7] - 38-39):
        - Faster processing power could enable to fly entire mission and take actions without human intervention.
        - It is expected that quantum processing will help with the cost, size and energy consumption.
    - Energy storage and processing ([7] - 41-44):
        - Fuel Cells ([7] - 42-43):
            - Using pure hydrogen gas for fuel directly allows the simplest and most efficient fuel cell, but transporting and storing the hydrogen can be troublesome.
        - Energy Harvesters ([7] - 43-44):
            - Typically capture only a very small amount of energy (although over a long period). Therefore they must also contain an energy storage subsystem in the form of a capacitor or rechargeable battery.

- *Nanotechnology based sensors for defence* ([7] - 45-66):
  - Nanotubes ([7] - 54-57):
    - Common defects of carbon nanotubes affect the adsorption of gas molecules on the surface of the nanotube.
    - Defects directly affect the sensing abilities of nanotube sensory devices.
  - Spectroscopic approaches ([7] - 65):
    - BioWatch is a very slow system – it cannot provide real time detection.
    - There are plans to develop faster devices based on BioWatch.

#### 4.3.3.2 Analysis on Technological Possibilities

- *Nanotechnology based products* ([7] - 26):
  - Nanomaterials will also have an impact on the processes used by and the products made by the microsystems industry.
  - This will happen in the area of sensors, where nanomaterials will open a wide new range of opportunities for sensors, especially in life science.
  - It will be in the area of energy systems, where nanotechnology will enable more efficient energy supply systems, creating opportunities for local small energy systems for miniature devices.

- *Nanotechnology market sectors* ([7] - 26-28):
  - Nanotechnology is used to create either the small features of the magnetic heads and/or the material for the storage medium.
  - Nanotechnology is one of the prime contenders for the next generation of data storage technology, together with holographic techniques and DNA based systems.

- *Top down equipment* ([7] - 29-32):
  - Nano-imprinting ([7] - 29-30):
    - The substrate is coated with a thin layer of monomer which, being a low viscosity liquid, spreads out easily onto the wafer; only a few nanoliters are required.
  - Electron Beam Tools ([7] - 30):
    - Multi beam processing tools aim to overcome the slowness of the single beam tools and are a candidate to replace light based aligners for high end semiconductor applications.
  - Atomic Layer Deposition (ALD) ([7] - 30-31):
    - This technology is mainly used for high end semiconductor processing to achieve sub 100 nm layers with well controlled thickness, high uniformity and good conformity, especially for barrier, seed and dielectric layers.
    - With an appropriate process sequence, it is also possible to create alternate layers of a different composition.
    - ALD is expected to replace current technologies to deposit copper seed and barrier films, ultra-thin nucleation layers for subsequent fill and gate dielectrics.
  - Direct Writing ([7] - 31-32):
    - An alternative approach could be direct mask-less lithography, circumventing the mask making process, or, even better, direct deposition of the material on to the device wafer.

        - An alternative approach is proposed by Micronics which uses micro-mirrors to expose the resist.
        - Currently the technology is not yet capable of operating in the nanotechnology area, however, research in this field is ongoing.
        - Another approach for the direct deposition of materials is that of "dip-pen" writing.

- *Physical chemical processing* ([7] - 32-33):
    - Milling ([7] - 32-33):
        - Is a well-known and proven process and technology to create smaller particles from bulk materials?
        - The small particles resulting from this process have the same chemical composition and physical properties as the original material.
        - The process of bead milling is based on the grinding of suspended particles by the impact and shear forces between moving grinding beads.

- *Nanotube process equipment* ([7] - 33-34):
    - Nanotubes have nearly perfect structures; they can achieve material values very close to their theoretical limits.
    - The unique physical, mechanical and chemical properties of nanotubes placed them into the position of one of the most promising materials in nanotechnology.
    - Their extraordinary mechanical properties make them also interesting as composite material for applications in the automotive and aerospace industry.
    - Carbon nanotubes have been demonstrated as enabling components for various electronic and chemical mechanical devices functional on the molecular scale.
    - Nanotubes with additional chemical groups, for instance, to make them water soluble, are available.

- *Bottom up processing* ([7] - 34-35):
    - Nano-manipulation ([7] - 34-35):
        - Photomask repair is currently the only application that rises above R&D status.
    - Molecular Self Assembly ([7] - 35):
        - Striking examples of the possibilities are found in nature: cells, natural self-replicating machines, form a variety of minerals, including magnetite and silica, under water, using chemical techniques four billion years old.
        - Calmec which focuses on the production of electronic devices and has developed an architectural concept for a 3-dimensional computer memory device aimed at replacing hard disks, flash memory chips, and computer mass storage media/systems.

- *Impact of nanotechnologies and novel technologies from other application areas* ([7] - 37-44):
    - Data storage ([7] - 37):
        - The reason for the end of the hegemony of the hard disk lays in the fact that when the magnetic domains on the disk become too small, they tend to become unstable.
    - Data processing ([7] - 38-39):
        - Although quantum computing is still in its infancy, experiments have been carried out in which quantum computational operations were executed on a very small number of qubits.

- Energy storage and processing ([7] - 41-44):
  - Batteries ([7] - 42):
    - It is possible to increase the power from a battery and decrease the time required to recharge a battery by increasing the surface of the electrodes.
    - One can also increase the shelf life of a battery by using nanomaterials to separate liquids in the battery from the electrodes.
  - Fuel Cells ([7] - 42-43):
    - Methanol based fuel cells have been given a boost by the development of nano-engineered membranes, preventing crossover of methanol.
    - Nanotechnology could play a role in creating more efficient catalysts to generate hydrogen for alkenes or alcohols.
  - Energy Harvesters ([7] - 43-44):
    - Energy harvesting is not a single technology but a broad approach that embraces many techniques.
    - When it comes to sensors for maintenance (corrosion, wear, etc.) there is no nanotechnology as yet foreseen.

- *Nanotechnology based sensors for defence* ([7] - 45-66):
  - Cantilevers ([7] - 45-49):
    - Numerous sensors have been implemented in cantilever architectures both at the micro and nano scales and have been demonstrated for various possible military defence applications.
    - Magnetostrictive micro-cantilevers have been shown for use in remote biosensor applications.
    - One uncoated cantilever, which is inert to target molecules, is used as a negative control group for detection measurements.
    - Adsorbed target molecules change the stress on the surface of cantilevers; the resulting stress is sensed with integrated piezoresistors.
    - Bimaterial cantilevers can also be used for standoff detection of surface residues of explosives.
    - Uncoated micro-cantilevers can be used for explosive detection.
    - Nanocantilevers have also been demonstrated to sense very fast displacements of nanoscale objects.
    - The nanoscale architecture leads to better sensor performance including higher sensitivity, more stable high quality factor, very fast response, and wide band width.
  - Nanocrystals ([7] - 49):
    - A sensing device that consists of a $CeO_2$ rod integrated with Pt nanocrystals on its surface has been demonstrated to be used as a gas sensor.
    - SnOx nanocrystals dispersed on the surface of amorphous silica ($SiO_2$) spheres are used to increase the performance of SnOx chemical sensors.
    - Semiconductor nanocrystal Quantum Dots (QDs) have been in general demonstrated for their possible applications in molecular biology.
    - QDs are alternative to fluorescent dyes; they potentially have long term stability and tunable broad wavelength.
    - QDs are used in biological bar-coding.

- Nano-fibrous membranes ([7] - 49):
  - Nano-fibrous membranes made of fluorescent polymers have been proposed for their capability to sense metal ions and nitro aromatic compounds optically.
  - Electrospinning method is utilized to fabricate nanofibrous membrane films, which have larger effective surface area than conventional thin films.
- Nanoparticles ([7] - 50-51):
  - Ru-Ni core-shell nanoparticles are utilized in biological sensors.
  - Spores are immunomagnetically captured on the EAM nanoparticles. Direct charge biosensor is then used to detect the collected spores.
  - $WO_3$ nanoparticles are coated on the surface of gate electrode. Due to absorption of target molecules, gate voltage changes which results the change in drain current.
  - Various metal nanoparticles can be used to increase the enhancement factor of the surface enhanced Raman spectroscopy.
- Nanopins ([7] - 51):
  - Nanopins consist of metal capped dielectric pile on a circle shaped metallic disc.
  - Nanopin arrays have some advantages such as strong enhancement of electromagnetic field and tunable resonant frequency.
- Nanorod[6] ([7] - 52-54):
  - $O_2$ affects the electrical properties of nanorod because of the electron transfer on the surface of nanorod between $O_2$.
  - SERS-active silver nanorod array substrates are proposed with their possible biosensor applications.
  - SERS-active substrate can be used to detect infectious pathogens.
  - ZnO nanorods can be used for intracellular pH detection.
- Nanotubes ([7] - 54-57):
  - Chemical nerve agents' strong electron donor property is employed for the detection mechanism.
  - Carbon nanotube transistor array can be used to detect DNA hybridizations.
  - IR sensors have been made from carbon nanotubes.
  - The photoelectric effect is demonstrated as the dominant stimuli for the IR photoresponse of SWNTs embedded in the insulating polymer matrix.
  - Single walled carbon nanotubes have been also implemented as a liquid flow detector.
  - SWNT device is proposed to operate as chemi capacitor.
  - Single walled carbon nanotubes' electrical properties are used to detect gas molecules.
- Nanowires ([7] - 57-62):
  - ZnO nanowire gas sensor can be built. The device uses conductivity change of nanowire for detection.
  - Enhancement of nanowire array decoration allows for stable linear response and lower threshold amount of target gas needed for detection.

[6] Babak Sadeghi (2012). Synthesis and Application of Nanorods, Nanorods, Dr. Orhan Yalçın (Ed.), ISBN: 978-953-51-0209-0.

    - The device made of nanowire array shows conductance variation in response to temperature changes and chemical changes.
    - Ge/Si core/shell nanowires have been used to form double quantum dots and control the coupled electron spins.
    - Pure buffer solution is used to purge the receptor from target molecules.
  - Photonic bandgap fibre ([7] - 62-63):
    - Photonic bandgap fibre is used as frequency selective waveguide and also as miniature gas cell.
    - A quantum cascade laser is focused into photonic bandgap hollow core waveguide and into MCT detector as the reference signal.
  - Photonic crystals ([7] - 63-64):
    - Microcavity resonator made from high index contrast two dimensional photonic crystals is used in quantum dot IR photodetector systems.
    - Electrochemical etching is used to form two photonic crystals from Si substrate.
    - Two photonic crystals are formed and then modified by chemical methods so that one becomes hydrophobic and the other becomes hydrophilic.
    - Sonication is used to break photonic crystals into many pieces.
  - Quantum point contact approach ([7] - 64-65):
    - Quantum point contact serves as an alternative to optical methods, which suffer from optical diffraction limits.
    - Laser is used to position the cantilever with respect to quantum point contact so that measurements can be tuned.
  - Spectroscopic approaches ([7] - 65):
    - THz Fourier transform transmission spectroscopy and Raman spectroscopy are utilized as detection mechanisms.
    - Controlled charge transfer of DNA is investigated using $TiO_2$ nanoparticles on the PMMA substrate surface.
    - Laser photoacoustic spectroscopy is employed to detect chemical warfare agents.
    - In general, the sensors are grouped into two: those that detect to treat and those that detect to protect.
    - One of the first bio-detection network is the so-called BASIS, which was developed to be used in the important organizations.
    - BioWatch sucks air inside and separates the aerosol particles, which are subsequently collected and tested in a laboratory.
    - Faster sensors can be used in buildings, i.e. they can stop/change the ventilation of the hall in order to prevent people from being influenced from attacks.

- *Nanotechnology impact on UAV scenarios* ([7] - 77-79):
  - Propulsion and Power / Fuel: Novel, compact power systems, Solar cells, Batteries, Super capacitors, Commercial market-driven, ...
  - Sensing Systems and Processing: Integrated vehicle health monitoring (sensors), Bio-chemical monitoring systems, Ultra-fast processing, ...

- Structural / Multifunctionality in Materials: Increased functionality per unit weight, Actuation: controlling position, shape or load, Electrical: either insulate or conduct, ...

### 4.3.4 Uninhabited Military Vehicles (UMVs): Human Factors Issues in Augmenting the Force

#### 4.3.4.1 Analysis of Operational Requirements

- *Military relevance* ([8] - 41-91):
  - Military relevance of human factors of UMV systems ([8] - 41-82):
    - Human Factors ([8] - 42-48):
      - User Requirements:
        - Context sensitivity is important for assessing the quality of military decision making.
        - To exercise good military judgement, humans need to feel the texture and "granularity of the battlespace."
        - As a minimum, the operator needs to be able to discriminate between what is a valid military target and what is not.
        - Technological limitations, legal and moral constraints, and most effective human involvement, suggest that some form of human-in-the-loop control always will be required.
        - Dependence on human supervisory control is risky for safety critical events and tasks.
        - Over-use of automation risks deskilling the user in the important cognitive domain, reducing the essential human capability for exercising critical judgement and decision making in the appropriate use of lethal force.
        - Over-use of automation implies the risk that the human supervisor is placed 'out-of-the loop' so that he lacks actual process state knowledge.
        - Supervisory control requires robust and reliable communications with the battlespace.
        - Communications technology limitations and communications breakdown can limit feedback on mission performance and prevent real-time mission intervention during remote control operations.
        - Human involvement is required in military operations to direct and plan the use of military capability, and to ensure lawfully correct use of lethal force.
        - With autonomous UMVs, some responsibility is delegated to increasingly competent computer controlled machines, but the authority and accountability for the delegation ultimately remains with humans.
        - UMV control requirements need to be integrated with C2 frameworks and architectures, chains of command and CONOPS.
        - Computer-based information processing systems are limited in that they cannot comprehend the meaning of information in human cognitive terms.
      - Integration of Human and Automation Requirements:
        - It is a priority UAV research programs to reduce the manpower burden by reducing the ratio of operators to vehicles for flight and mission control.
        - With human-in-the-loop control, advances in autonomous vehicle technologies are worthless without an effective and efficient operator remote control/display interface.
        - Separating operators from the context of use risks disconnection from the battle-space.

        - User involvement in systems requirement specification will become increasingly important to ensure that critical military judgement can be properly exercised in the context of use.
        - The paradigm for operator control will need to progress to one based on human-computer co-operation, as implemented in advanced pilot assistance systems.
        - Real-time HF engineering of variable levels of automation or adjustable levels of autonomy are important for controlling multiple autonomous UMVs.
        - For efficient and effective mission supervision and discrimination, the operator/ supervisor needs to be able to bring added value to the understanding of the situation.
        - To mitigate this, the C2 system and UCS need to provide a rich operating picture for mission assessment and appropriate mission performance critiquing tools.
- Legal and Moral Issues ([8] - 66-71):
    - All weapons systems must undergo a thorough legal review before entry into service.
    - In the case of UCAVs, the regulations and limitations concerning its use require legal review.
    - The pilot is required to discriminate between what is a valid military target and what is not.
    - In modern warfare, it is very difficult for an autonomous machine to discriminate between civilians and military targets.
- Military relevance for Uninhabited Aerial Vehicles (UAVs) ([8] - 82-91):
    - The Map of Relevance ([8] - 83):
        - To appropriately judge the relevance of anything, both strengths and weaknesses must be known and assessed according to a common ground of values.
    - The Human Axiom ([8] - 83-88):
        - Independent need not necessarily imply uncontrolled, which the technological hysteria tends to impose.
        - Artificial intelligence will never be able to handle something that it's not designed to handle.
        - The automation paradox, that regardless the capability of automation it will always require human guidance.
        - Although it's virtually impossible to completely eliminate situation uncertainty, it's definitely possible to constrain it and keep it under control by reducing the number of degrees of freedom.
        - It's a significant difference between to have control and to perform control.
        - System will do what it always does, if possible, which sometimes is welcome – but it will do that even if the situation happens to require something else.
        - The problem is to design the automation to avoid making it more difficult for the human to discover and add the new inputs to the matter and to tweak the performing of the task according to the new situation.
        - Question is how the human should be involved and hence, yet another principle is defined.
    - Relative Weaknesses ([8] - 90-91):
        - Weaknesses of uninhabited systems are consequences of loss of control depending on automation either forced by the separating design or by unsuccessful automation efforts.
        - There is a severe risk that automation assumes or disregards something that is uniquely important and perhaps important at exactly that situation only.

        - The weaknesses are mainly lack of robustness in the higher contexts.
        - Automation should help humans handling such by always being designed to support human control as opposed to being a replacement for the human.
- Uninhabited military vehicle operator training ([8] - 197-212):
    - Embedded Training for UMV Crews ([8] - 201-211):
        - The mission plan must be frequently adapted while the air vehicle is in-flight, again requiring coordination between the operators.
        - In live training physical entities are needed that act as targets, threats or friendly forces.
        - Intelligent methods are needed to keep track and analyze the crew's activities, to categorize crew error and to determine mission success.
        - An important part of the UAV system simulation is a realistic assessment of mission effectiveness.
        - The behavior of the virtual entities has to be in exact accordance with their individual role.

#### 4.3.4.2 Analysis on Technological Possibilities

- Military relevance ([8] - 41-91):
    - Military relevance of human factors of UMV systems ([8] - 41-82):
        - Automation technology and computer-based information processing are increasingly important for balancing affordability, capability and achievability with increasing pressures on scarce, skilled human resources.
        - Since UMV technologies are expected to actually reduce human involvement in some tasks.
        - Human Factors ([8] - 42-48):
            - User Requirements:
                - UMVs can make certain tasks safer by reducing human involvement and risk to life, allowing the possibility of human resources being re-deployed more efficiently and effectively.
                - Vehicle control and safety becomes a complex issue, especially when mixing UMVs with manned vehicles and "dismounted" forces.
                - Classes of control can be characterized as either manual, semi-automatic, and fully autonomous, with and without human supervisory control.
            - Integration of Human and Automation Requirements:
                - HF is traditionally concerned with the study of the man-machine interface.
                - Humans are involved throughout the UMV life cycle, from conceptualization, specification, design and development.
                - UMVs change the challenges of system safety, health hazards, survivability and habitability, reducing risks compared with manned vehicles, particularly for remote "reachback" operations.
                - Personnel and Training: integration and interaction with civilian airspace constraints is a key training issue.
                - The role of psychomotor abilities will become diminished.
                - It has been suggested that UMVs may shift the balance of responsibility and accountability for UMV behaviors and effects from users' decisions during systems operation towards engineers' decisions during system design.

- Military relevance for Uninhabited Aerial Vehicles (UAVs) ([8] - 82-91):
  - The Map of Relevance ([8] - 83):
    - The entrance of technology into the area of abstracts has introduced the possibility to develop automation, which in turn has made it possible to design uninhabited platforms.
    - The relative strengths of automation and UVs are quite direct results of platform, vehicle or system characteristics and thus are comparatively easy to spot.
    - The relative weaknesses are mostly more indirect consequences of loss of human control as consequence of conditions created by the characteristics of the systems.
  - The Human Axiom ([8] - 83-88):
    - Technology exists solely to extend, magnify or complement human abilities.
    - It was done to serve the humans and technology has no own free will.
    - The aim in designing systems should therefore be to allow for a natural interaction and cooperation between the human operator and the technology.
    - The highest form of automation is not necessary autonomy since that implicitly implies loss of control, which is a considerable price to pay.
    - Automation is always automation and it has no private desires or personal values that may constitute truly autonomous decisions.
    - Control and interaction are performed at all levels, or in all layers, simultaneously.
  - Relative Strengths ([8] - 90):
    - Is the class of strengths that comes from the perhaps most common aim of automation itself.
    - The direct strengths may be sorted into the three classes of time, task and environment.
    - The indirect ones are mutually dependent on each other, but could be described with cost, risk and importance.
    - Tasks may be unsuitable for humans in quite many ways.
    - The indirect strengths are for instance, while being without the risk of human loss, having the possibility to take risks.
- Theoretical frameworks ([8] - 93-141):
  - Framework descriptions ([8] - 99-107):
    - Literature Review ([8] - 99-103):
    - Searching fields were beyond suggested areas such as tele-robotics and human computer interaction, and included supervisory control, information management and decision support, automatic manufacturing, medical diagnosis and consultation, and other social behavior areas.
  - Frameworks from Survey Returns ([8] - 103-107):
    - Conventional automation is predominantly focused on subgoals and subtasks of the work process.
    - ACUs have the potential to achieve high-level goals compliant with those of the human operator, and therefore may act as an operator assistant system as well as act autonomously.
    - The Extended Control Model (ECOM) − the model provides a framework for describing how a joint cognitive system can maintain control of a situation or a process.

    - Cognitive system: "a system that can modify its behavior on the basis of past experience so as to achieve specific anti entropic ends."
    - Multiple Agent Interaction (MAI) Model:
        - At the lowest levels, control is subconscious and might be described by classical linear control theory.
        - At the highest levels, control is conscious and deliberate requiring rule-based thinking, logic, and reasoning.
    - Human-machine interaction is often analyzed by treating the machine as a simple input-output transfer function with some known disturbances, and the human is part of the machine's controller algorithm.
    - Principles were highlighted during the analysis of multiple agent interaction using control theory techniques:
        - Closed-loop feedback modelling techniques.
        - Designers should consider goals, sensing and decision-making strategies, and world states as part of their system design.
        - Agents should act on separate states.
- Military Relevance Philosophy (MRP):
    - The human axiom is to facilitate the development of technology and the use of it to actually serve the human in the best possible way.
    - The human axiom is to put the technologies of automation and uninhabited systems into a necessary context in order to reduce the risk of having these capabilities become counterproductive.
    - The technological system must not only trust the human, but also itself particularly when the system functions outside its design envelope.
    - Current technologies do not have the capability to trust.
- As Unmanned Military Vehicles become more intelligent and capable, and as there is an attempt to control more of them with fewer humans in the loop.
- The Mission Analysis Component (MAC) is an automated planning system that understands instructions and:
    - Evaluates them for feasibility; and/or
    - Expands them to produce fully executable plans.
- Policy provides a method for human operators to mathematically define what constitutes "goodness".
- If a system is considered dynamically it is with a task related perspective.
- If statically it is more at a function, constraint, architecture, capability, or generic process perspective of consideration.
- Survey results:
    - Table 3-2: Survey Results ([8] - 108).
- Summary ([8] - 111):
    - The common elements:
        - Control Theory.
        - Hierarchy.

        - Sensing the world, own state, other actors, and understanding the mission objectives.
        - Descriptive analyses.
        - Design philosophy and guidelines.
    - The unique elements were:
        - Playbook;
        - Mathematical analyses; and
        - Reduced ratio means increased uncertainty.
- Manpower and skills ([8] - 193-197):
    - UMVs are new technologies for most militaries around the world, and potentially require new jobs, positions, occupations, and units to command and control these assets.
    - UMV operators are positions with the expected high level of expertise.
    - Common crew selection methods – new method has four steps as follows:
        - Decompose a composite scenario involving new technologies into a hierarchy of goals – the technique used in this case is based on Perceptual Control Theory applied to function and task decomposition.
        - Propose and link the new job elements to the goals – the job elements are not limited to task and knowledge statements, but may include the other elements depending on the level of fidelity required.
        - Compare the new job elements to the CF job element inventory – the mathematical equation for the comparison has been referred to as a Job Similarity Index (JSI).
        - Select positions based on the best match.
    - There are indications that JSI can be used to predict job performance to some degree.
    - There are other factors that influence job performance including the simplicity of the job in combination with a good human-computer interface.
- Uninhabited military vehicle operator training ([8] - 197-212):
    - Training of Decision Making Skills Based on Critical Thinking ([8] - 197-201):
        - Theory − critical thinking is a series of questions and answers that serves to investigate alternative positions of what the available information may indicate. Three roles are involved:
            - The proponent who defend a position by introducing more reasons that are only consistent with the current position.
            - The opponent who asks for missing reasons or introduce rebuttals that cancels reasons or their effect on the conclusion.
            - The facilitator who regulates the process in terms of the relevance of reasons and whether the dialogue achieves the overall goals.
        - There are several dialogue types, such as persuasion, inquire, information seeking, negotiation, deliberation, and eristic that vary to which extent assumptions are questioned.
        - The ability to adapt the decision process depending on the context is often an important aspect of expertise.
        - A reliable decision making process, such as critical thinking, is essential for maintaining control of UMVs.

- Embedded Training for UMV Crews ([8] - 201-211):
  - While the C2 structure for the future battle space may not be different from current operations, the ability to fluidly push and pull information over long endurance missions is vastly improved.
  - The core team consists of those operators that are responsible for mission C2 tasks and planning, air vehicle control, payload operation and immediate data analysis.
  - The core team's primary purpose is guaranteeing mission effectiveness and safety.
  - The effectiveness of the core team as a whole depends to a large extent on the teamwork of the members, more than on individual SKAs.
  - For the current purposes we define Embedded Training (ET) as a form of training in which simulated 'entities' such as threats and targets are fed into the various avionics systems of an actual working UAV system.
  - Although the circumstances and tensions of a real mission will probably never be accurately simulated, ET can come closer than traditional forms of training by representing assets in the real environment.
  - Why ET in UAV? A number of arguments can be given, including:
    - Provides increased training effectiveness through added immersion, highly effective training scenarios and team involvement.
    - Potentially enables 'complete' team training.
    - Would also lead to efficient use of costly flight time.
  - An ET system, consists of three main simulation modules:
    - The simulation management module performs many functions.
    - The UAV simulation module stimulates the on-board sensors and simulates the own weapons and electronic warfare systems.
    - The virtual world simulation simulates the virtual entities in the exercise.
  - Systems and working procedures help the operators to guarantee a sufficient safety level.
  - Since displays can contain both real and virtual information at the same time, operators should always be aware which information is real and which is virtual.
  - Automatic monitoring of the air vehicle and its interaction with the real environment can prevent unsafe situations.
  - The simulation immediately stops when one of the rules is violated, that is, when it detects an unsafe situation.
  - Various architectures implementing a UAV embedded training system − two distinct groups:
    - An air vehicle is not required, only a GCS is needed for the exercises − ET is built into the GCS and directly communicates with the GCS systems.
    - Involves a flying air vehicle during the exercises − ET then communicates with the on-board systems and with the GCS.
  - Team characteristics that distinguish teams from small groups include the following:
    - Multiple sources of information.
    - Task interdependencies.
    - Coordination among members.
    - Common and valued goals.
    - Specialized member roles and responsibilities.

        - Task-relevant knowledge.
        - Intensive communication.
        - Adaptive strategies to help respond to change.
    - Team skills:
        - 'Team monitoring' − mutual performance monitoring by team members, but also mutual workload monitoring and predicting each other's behavior.
        - 'Exhibiting flexibility' − adapting to novel and unpredictable situations.
        - Exhibiting team leadership or followership − motivating team members, exhibiting team initiative, exhibiting assertiveness and providing supporting behaviors.
        - 'Team coordination' − the skill of giving suggestions or criticisms, but also accepting suggestions or criticism, including performing of self-correction.
        - Response coordination, coordination activities, resource distribution, timing, interpersonal coordination, team decision-making, shared situation awareness.
    - Team attitudes − team spirit, team morale, belief in the importance of teamwork, team cohesion, shared vision, mutual trust, collective orientation.
    - Use of ET would promote unity in operational procedures and doctrines, and be of use to train effective communication techniques, …

- Artificial cognition and co-operative automation ([8] - 213-292):
    - Scope ([8] - 214-216):
        - Modern electronic fly-by-wire systems enable an almost fully automatic performance of an entire mission, as daily demonstrated in thousands of civil airliner flights.
        - A car navigation system supporting on the supervisory control level is almost present in every upper middle-sized class car.
        - Typical Scenario from the Military Aviation Domain ([8] - 214-215):
            - Multiship air-to-ground attack mission: forces consist of the airborne component covering different rolls such as reconnaissance, suppression of enemy air defence and attack.
            - Hostile forces consist of two components: a military target, fixed or moving and a ground based air-defence system represented by surface-to-air missile sites.
        - Forces Structure ([8] - 215-216):
            - The own airborne forces will be a whatsoever mix of manned and unmanned platforms, to begin with.
            - The entities may differ from each other with respect to resources and capabilities, such as sensors, actuators, weapons, and information processing.
            - We certainly have to face the technological challenges of the solution of supplementation of forces, including the issues of manned-unmanned teaming, co-operation and supervision.

- The work process and conventional automation's solution ([8] - 216-223):
    - The Work System ([8] - 216-219):
        - Consists of three major elements:
            - Operator: the human operator is the high end decision element of the work system.
            - Work object: is not necessarily restricted to the physical nature of whatever machine, but also comprises dynamical processes.

  - Operation-assisting means: can be seen as a container for whatever tools or automation of the work place, being computerized pieces of technology in many cases.
- Environmental conditions and external resources, such as information, material, or energy will affect the ongoing work process.
- Exactly this technical or organizational structure might as well be easily modelled and analyzed by the framework given by the work system.
- In order to do so, a very common model of human control performance shall be mentioned here, where a distinction is drawn between manual and supervisory control.
- Many real-world applications in fact will require human-machine interaction as a mixture of manual and supervisory control as a function of the level of automation selected.
- On a supervisory control level gathered and filtered information will be fed into a functional block representing problem-solving, planning and decision-making.

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# Chapter 5 − LETHAL AUTONOMOUS WEAPON SYSTEMS

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Any military robotic system research sooner or later faces the question if implement a weapon or not. Another question is how independent (or autonomous) this system should be to fulfil desired tasks on the battlefield. This chapter was made to help to clarify certain aspects of Lethal Autonomous Weapon Systems (LAWS) development and usage as well as to clarify rambling terminology used among non-technician and technician community. This chapter is also based on the conclusions of the CCW Meeting of Experts on Lethal Autonomous Weapons Systems (LAWS) that took place from 13-16 May 2014 at the United Nations in Geneva.

## 5.1 TERMINOLOGY

Today, there is no exact and deeply understood terminology of what is autonomous or not (with relation to military operations). According to Ref. [1], autonomy is the capacity of a rational individual to make an informed, un-coerced decision. To apply this definition to artificial intelligence or robots we have to express the autonomy of robotic entity in relation to its environment or better to its human operator[1]. For military purposes, there already exist several definitions of the level of control or level of independency on the human operator. Scharre in Ref. [2] defines in fact five states of control – automatic, automated, human-in-the-loop (or semi-autonomous), human-on-the-loop (or supervised-autonomous) and human-out-of-the-loop (or fully-autonomous) systems. According to Ref. [2], "automatic systems have simple, mechanical responses to environmental inputs" and automated systems are "more complex, ruled-based systems". Automated type of control is in use for decades, automatic for centuries. However, this chapter is focused on the last three types or modes of control – human-in-the-loop, human-on-the-loop and human-out-of-the-loop.

Human-In-The-Loop (HIL) or Semi-autonomous Systems (Figure 5-1) – Systems that are under control or supervision of human operator and are not allowed implementing their critical algorithms outputs (decisions) without approval. The HIL systems level of autonomy is very low in accordance with the freedom of actions especially in conjunction with the use of weapons. Each human-in-the-loop system (armed or not armed) making a decision that could somehow affect the use of force (directly or indirectly) has to stop and wait for the final approval of the human operator. In case of indirect use of force there exist e.g., air force identification systems able to recommend or set the aircraft identity, however these systems are not allowed to set an identity that requires an engagement like hostile ID and have to wait for human approval. In case of direct use of force there are e.g., certain types of Unmanned Aerial Vehicles (UAVs) able to fly over defined area and to search targets on the ground. The final decision on weapon use remains on the human operator. Such systems are already in service for years within many armed forces around the globe.

Human-On-the-Loop (HOL) or Supervised-Autonomous Systems (Figure 5-2) – Systems that are allowed to implement their decisions, however the human operator has override rights to stop or change performed actions of the HOL system in case of error or failure. The reason why to build such systems lies in the necessity to have a system quickly reacting on certain inputs the human operator is not able to.

[1] The term "operator" here stands for the human being that is using, leading, guiding, commanding, remote-controlling or teleoperating the robotic entity.

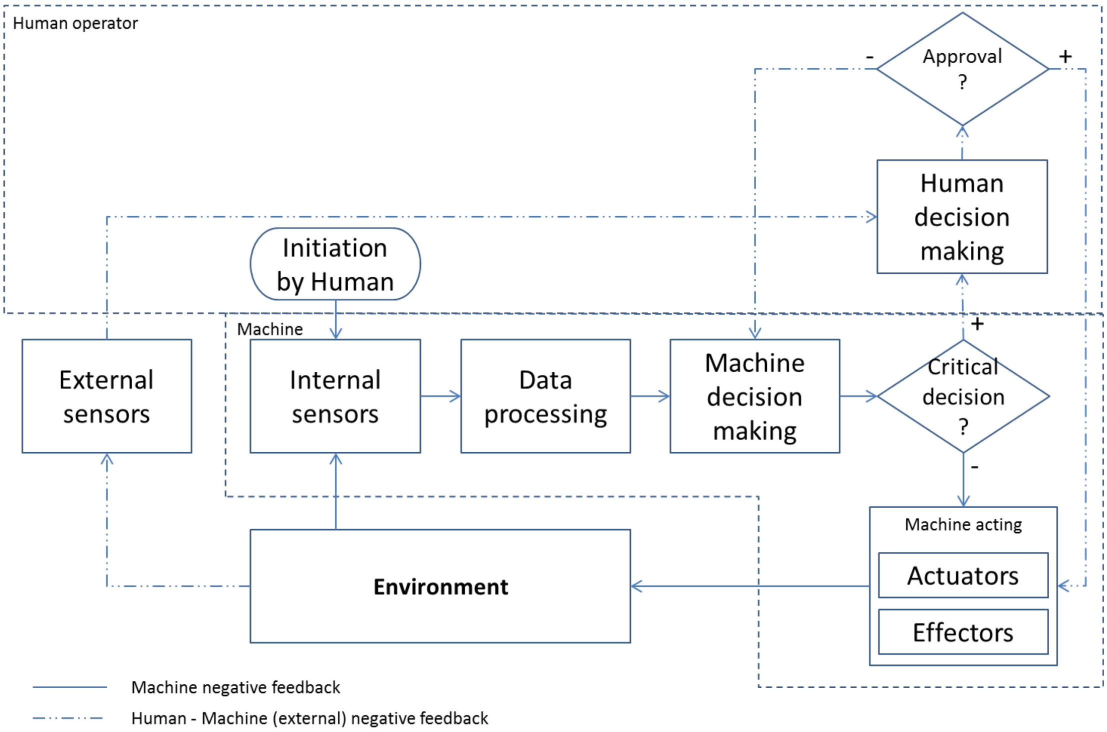


**Figure 5-1: Simplistic Diagram of Human-In-the-Loop System.**

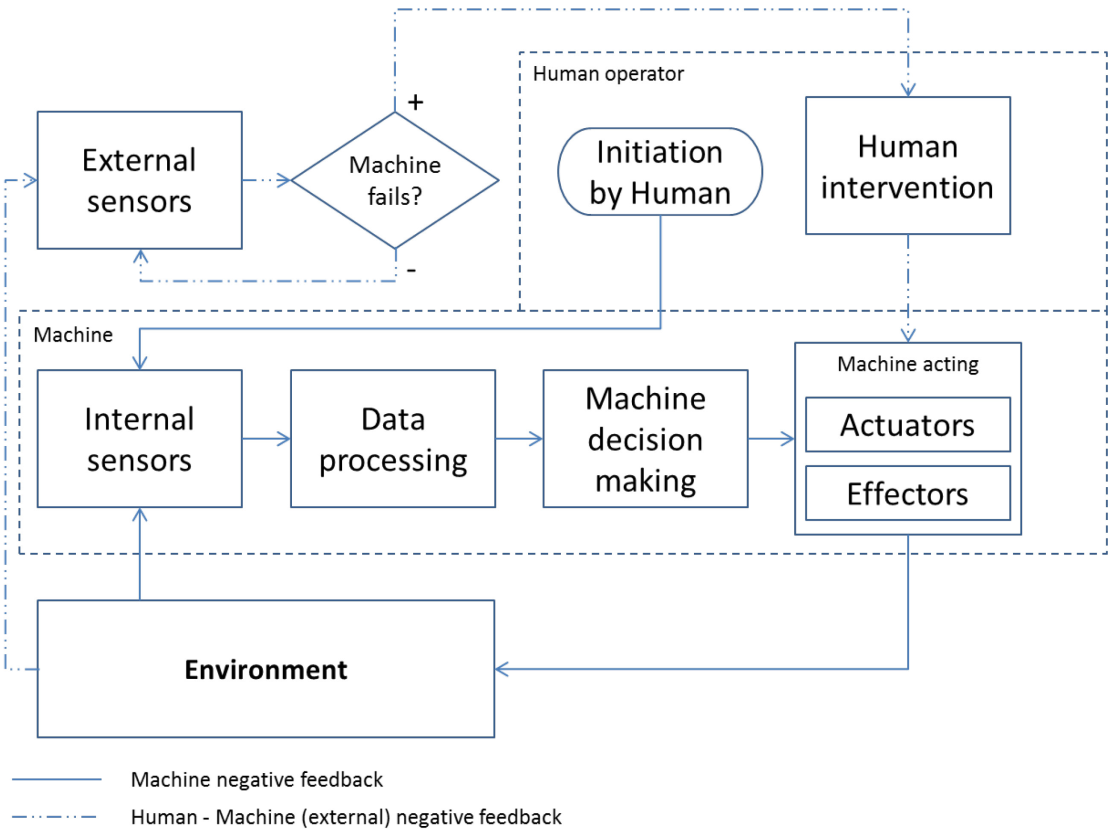


**Figure 5-2: Simplistic Diagram of Human-On-the-Loop System.**

Those systems usually perform thousands or millions of calculations and offer the advantage of quick reaction. Today, such systems are often mentioned in connection with tactical ballistic missile defence like Patriot or Aegis platforms. Another example is the space missile (e.g. satellite carrier) able to autonomously reach the predefined orbit in space. In case of failure, the ground command and control center has the right to override the board systems and destroy the missile.

Human-Out-Of-the-Loop (HOOL) or Fully Autonomous Systems (Figure 5-3) – Systems allowed to implement their decisions including those critical without human operator approval. These systems act according to their inner code (as well as HIL and HOL) but are not restricted by any external intervention that would change their decisions.

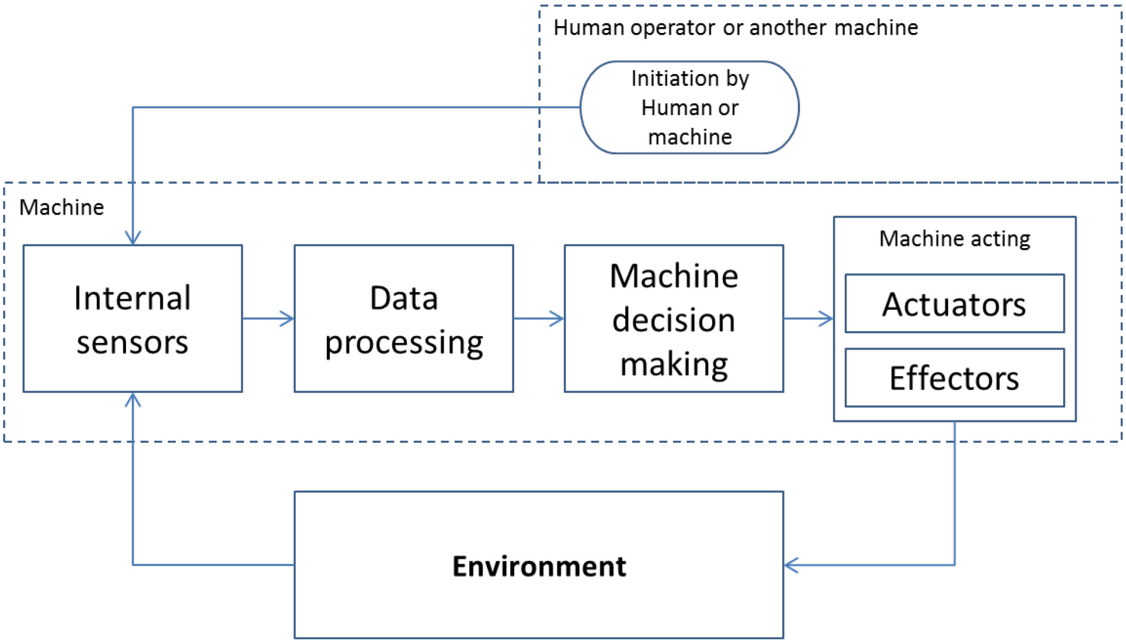


**Figure 5-3: Simplistic Diagram of Human-Out-of-the-Loop System.**

Contemporary operating military systems are usually automated (means with minimal adaptation ability and with strictly defined behavior usually based on reaction to certain inputs) or human-in-the-loop. There is also rise of human-on-the-loop systems because they manage to act more independently on human operators and are able to process more data and act more quickly than the platforms based on HIL configuration. Development and proliferation of HOOL systems is very sporadic now due to uncertain influence on human operations that is not satisfactorily described yet.

## 5.2 AUTONOMOUS WEAPON SYSTEMS VERSUS INTERNATIONAL COMMUNITY

Last decade was in token of massive technology development. Civilian as well as military technology has spread to almost each part of human culture. Robotics and cybernetics evolved new ways to substitute certain human activities and capabilities. Fragile human body was strengthened or compensated by robotic systems like motion skeletons, artificial hands and legs or just supported by robotic mules, dogs or other walking devices. World armed forces realized that robotics and mechatronics could help to find new ways of warfare including defensive and offensive operations. More and more military systems are evolving from purely automated to human-in-the-loop autonomous platforms and many of them aspire to human-on-the-loop platforms. There are certain areas where HIL or HOL systems can contribute to faster decision making and acting like command and control systems or surveillance and reconnaissance systems however at this stage, the machine does not decide to take or not to take a human life. The massive robotic technology proliferation raised a question (and fear) if there is serious possibility to develop, produce and use the fully autonomous or HOOL robotic systems that are somehow able to initiate or finish the kill chain. The International Committee for Robots Arms Control (ICRAC) that was founded in 2009 as a Non-Governmental Organization (NGO) was one of the first organization that calls attention to all aspects of military utilization of robotic systems and pointed out their potential dangers. Thanks to ICRAC, ICRC and other worldwide NGOs together with the “Campaign to stop killer robots”, the series of meetings was initiated to try to ban or limit the development, production and usage of lethal autonomous systems. Finally these NGOs managed to attract the interest of international community and from 2013, there is series of formal and informal meeting held on the United Nations ground. One of the biggest meetings took place in Geneva, 13-16 May 2014. The name of this meeting was CCW Meeting of Experts on Lethal Autonomous Weapons Systems.

The main issue of this meeting was to discuss the potential threats of LAWS from several aspects – technical, operational, military, legal and ethical. Each aspect was discussed within special session (held by the Chair of the meeting or Friends of Chair) and supported by side events (held by NGOs representatives). The meeting itself prove one. The international community is not uniform in the opinion of what the autonomous weapons systems are and could be and if there is urgency to strictly ban future development, production and usage of LAWS. That’s why international community needs more time to clarify advantages, disadvantages, threats or opportunities of such systems. On the other hand, the meeting provided the excellent opportunity to hear opinions of experts in the branches of robotics, military operations, law, ethics and other and proved that the topic is very challenging. Main message of the meeting pointed the necessity of meaningful human control over the development, production and especially use of LAWS (targeting and attack decisions of LAWS). To clarify and unify facts about the potential development, production and usage of lethal autonomous weapon systems, experts mentioned many interesting opinions as stated below.

**Technical Issues:**

- Mr. Raja Chatila outlined a general definition of a robotic system and stated four basic capacities (data acquisition, data interpretation, and decision-making and action execution) and two additional capacities (communication and learning) [3]. Also stated that these capacities could be developed up to different degrees of complexity. The main message was that the autonomy is a relative notion depending on implemented capacities and what type of tasks are performed. He also stated differences between operational and decisional autonomy.
- Mr. Paul Scharre explained the term autonomy itself according to three different concepts – level of human control (HIL, HOL, and HOOL), complexity (automatic, automated and autonomous) and task performed [4]. Mr. Scharre also explained how autonomy is used in weapons today. Next part of Mr. Scharre presentation outlined the U.S. policy on autonomy in weapons (DoD Directive 3000.09, “Autonomy in Weapon Systems”, Nov. 2012). Finally he calls for development of “rules of the road” for appropriate use of autonomy in weapons [4].
- Debate between professor Ronald Arkin and professor Noel Sharkey proved that opinions across top experts on world robotics are not unified and some are for absolute LAWS development, production and usage ban and others support the technological exploitation of some kinds of LAWS (even all participants clearly stated their disagreement with wars and arms proliferation).
- Mr. Jean-Paul Laumond presented today robotic platforms and pointed out some advantages and disadvantages of human-like robotic platforms [5]. He also drew attention to the current problems of humanoid robots with respect to their motion, stability, speed, etc.
- Mr. Hajime Wakuda presented contemporary and possible applications for robotics technologies and pointed out issues that should be considered when discussing the potential ban of LAWS,

because all robotic applications could be dual-in-use with respect to civilian and military angle of view [6].

- Mr. Yong Woon Park presented the trend of autonomous technology for military robot (with robotic views of autonomy).

**Ethical and Social Issues:**

- Dr. Dominique Lambert presented his views on the ethics of robotics and the human-machine interrelation [7]. He stressed that the use of autonomous robotic systems (civilian or military) raises some ethical and technological questions that have to be answered before proliferation.
- Professor Peter Asaro presented ethical questions raised by military applications of robotics [8]. Among others he also highlighted some aspects of autonomous killing with respect to International Humanitarian Law (IHL).

**Legal Aspects:**

- Dr. Nils Melzer presented principle of humanity and Martens Clause [9]. He further stated some LAWS usage aspects like LAWS may lower the attacker's risk, LAWS may increase the difficulty of assigning responsibility to individuals, or that LAWS may increase the risk of violations in case of insufficient control.
- Professor Matthew Waxman, presented implementation of Article 36 and jus in bello [10].
- Professor Marco Sassoli presented LAWS - advantages and problems compared with other weapon systems from the point of view of International humanitarian law [11].
- Professor Thilo Marauhn gave the opinion on Responsibility and accountability [12].
- Professor Christof Heyns presented Human rights law issues [13].
- Dr. Nils Melzer presented the topic Jus ad bellum [14].

**Operational and Military Aspects Issues:**

- Dr. Mark Hagerott presented his views on LAWS from a military officer's perspective [15]. He noted, inter alia, three realms of warfare – social-human realm, integrated human-machine realm and autonomous machine realm and tricky aspects of the third one.
- Dr. Heigo Sato presented Military implications of LAWS and possible ways to develop a risk management scheme [16].
- Lieutenant Colonel Olivier Madiot presented Views of the Joint Staff [17]. His presentation included the view that use of LAWS will not lead to significant reduction of the force, that LAWS will cause higher procurement and maintenance costs. He also questioned the argument of casualty reduction.
- Col (Ret.) Wolfgang Richter gave presentation on Utility and limitations of the use of LAWS in military operations [18]. He also noted some potential benefits of certain kinds of LAWS especially at the tactical and combat level. He stressed that there should be no need for autonomous targeting of individuals or groups of persons.

**Among others, there were a lot of interventions from state representatives as well as from experts and NGOs members. Some interesting opinions or conclusions were:**

- Leaders and commanders consider twice the human soldiers employment. Ones the LAWS are available, they would not be so hesitant to use force and warfare will be more intensive.

- Responsibility for what LAWS have done may not be clear if used in armed conflict and should be covered by international law.
- There is no exact definition of the term autonomous. Above stated three categories (HIL, HOL and HOOL) could be understood differently if used in different circumstances. Autonomy of one system part doesn't mean autonomy of the whole system.
- There are serious concerns whether LAWS would be able to comply with international humanitarian law.

## 5.3 CONCLUSION

Autonomy in weapon systems is quite new phenomenon and many aspects of the development, production and usage are not clear. There is no overarching consensus of what LAWS are or will be. Thanks to certain campaigns, most of the civilian community is convinced that LAW means humanoid killing Hollywood-like Terminator and do not consider other aspects of the problem. On the other hand, there is no country today (countries participating at CCW informal meeting of experts in Geneva 13-16 May, 2014) that is hundred percent for the LAWS without any constraints.

The meeting in Geneva showed one – use of weapons, especially Lethal Autonomous Weapons, without any sort of control is very dangerous and against a common technical sense because nobody can proof the existence (event in the future) of hundred percent reliable, hack-proof, jamming-proof and malfunction-free device or system.

Another conclusion from Geneva meeting is that the term "Meaningful human control" is not clear yet. What does the word "meaningful" stands for in accordance with military operations, command and control, technical or other angles of view? Meaningful human control is differently understood by civilian population, humanitarian organizations, governments' representatives, military personnel or technicians. This definition has to be discussed more deeply in the future to reach the consensus.

The use of LAWS is not inherently bad. The only problem is humanity itself, because people will implement the software leading the LAW behaviour and people will employ LAWS on the battlefield (or somewhere else). One of partial solution might be strictly defined procedural control according to rules based on international law (similar to e.g., ICAO flight rules).

The research of autonomous systems including those lethal should continue not to lose pace with the other states or organizations. However, parallel to research itself, the tactics, techniques and procedures for LAWS employment should be developed too, not to have lethal devices without any sort of self-defence (or remote "switch-off button") in case of malfunction. This statement includes the necessity to have HILs and HOLs. The fully autonomous weapons (HOOLs) are from the military perspective very dangerous (excluding the case of certain static fully autonomous LAWS platforms like air defence systems guarding closed part of air space) and commanders will probably never have full trust in these systems and will not be willing to employ them together with their own human forces.

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# Chapter 6 − ASPECTS OF DEPLOYING AUTONOMOUS ROBOTS

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## 6.1 ADVANTAGES AND CONSTRAINTS FOR THE USE OF ROBOTS

### 6.1.1 Expectations and Advantages of Unmanned Systems

Robots are new components that are changing the nature of war [1]. On the one hand, they undeniably bring new capabilities and performances to armed forces, but on the other hand, implementation constraints could raise obstacles to their acceptance or use. In all cases, robots should never be used as an excuse for stopping or cancelling a mission.

Robots are used for protection; i.e. reduce the exposure of a soldier to risks. Robots can also increase the effectiveness of a fighting soldier, bringing tactical advantages in executing his/her mission. They are used most notably to extend areas of control and coverage of a tactical unit (see Figure 6-1 below). This is done by using remote effectors, sensors, and weapons placed on-board of each robot. In a sense, they are the "remote organs" of a soldier's eyes, ears, arms, touch and even mouth.

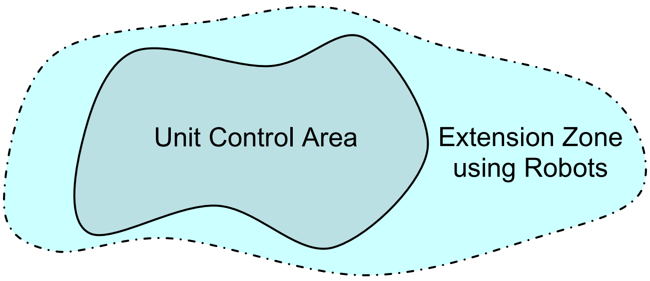


**Figure 6-1: Robots Extend the Unit Control Area.**

Robots can have much higher deployment speeds than Man. This can help in anticipating enemy actions or reacting immediately to a threat with greater efficiency.

Finally, robots give help in reducing human energy: they can replace soldiers in repetitive, tedious tasks, making room for operational forces to act when needed. Robots can also on a more strategic level, reduce attrition as combat operations continue, enabling fighting units to stay on the battlefield much longer than before.

### 6.1.2 Limitations and Constraints in the Use of Robots

Engineers should ensure human constraints in combat – and the consequence of conducting battles with robots – have been clearly defined prior to any development. In the heart of a battle, an operator must be able to master his/her robot and not just rely on it.

#### 6.1.2.1 Operational Constraints

In a classic daytime mission, ideal power autonomy should be 12 to 24 hours 12 and 24 hours. The ideal robot is one posing no constraints in its use. It should move at the same pace as the platoon and not be the cause of delays, nor hasten the advance of the platoon. It should move discreetly and avoid identifying friendly devices. During night operations, additional discretion is required and the robot must not be noisy so that it endangers the mission.

The traditional organization of combat units should not be burdened by the use of military robotics, but can be adapted.

#### 6.1.2.2 Environmental Constraints

Robots should be operational at any time and in all weather conditions (heat, cold, rain, snow, mud). At night, operators should also be capable of grasping a robot's exact position. Robots mobility must be the same that the one of the supported unit. Practically, physical obstacles humans are able to cross (e.g. fences) can be impassable for UGVs: the ability to perform jumps or leaps, or even occasionally fly, would solve some of these problems.

#### 6.1.2.3 Communication Transmissions Constraints

Outside recurrent transmission problems (e.g., speed, range, penetration), spectrum sharing should be checked before commencing a mission to ensure communications frequencies are available and unscrambled. As frequencies are shared within Coalition Forces, each unit should ensure the availability of the frequencies used on the battlefield before any movement.

When a unit moves into unknown terrain, military infrastructure has not yet been deployed. The officer should consequently ensure the radio coverage of robots. A mesh network topology could be a solution where each robot acts as a node that can receive, send, and relay data. Naturally, all forms of latency in executing commands should be avoided for a proper control of robots.

#### 6.1.2.4 Human Constraints

During combat, a soldier's hands should not be hindered by control devices which should be simple to use, not disturbing his/her attention. Data should be kept simple because "too much information kills information" and can distract an operator.

### 6.1.3 Requirements for the Use of Military Robots

#### 6.1.3.1 Adaptation Phase

An operator should acquire a natural exchange with robots. Prior to combat operations, soldiers will require training to understand how to manoeuvre with robots in the field.

Before each mission, robots have to be configured. This is only one aspect in mission preparation which can be secured with a back-up system and a copy of the initial configuration. It will enable a rapid reconfiguration of a blank robot in case of failure or destruction.

#### 6.1.3.2 Modular Design

Robots should be configured appropriately for each mission where adaptable modules could be mounted for a more versatile use. Modularity would help in adapting to the terrain and reacting immediately to a given threat.

#### 6.1.3.3 Controlling Robots

In overseas operations, "friendly fire" unfortunately causes collateral damage. Accordingly, it is of utmost importance to control robots when placed in autonomous mode to avoid the risk of casualties. Similarly, if a robot performs some discrimination in target recognition, it must be controlled by an operator to confirm a target and obviate blunders.

A soldier should not be technologically dependent on robots. As high information exchanges could occur with high stress levels, therefore, it is important to have the possibility of switching to a downgraded mode whenever necessary.

#### 6.1.3.4 Cooperating with Others

An increasing volume of data transiting via networks will need to be structured in such a way that an adequate amount of information is delivered at command level. Specific rules will be established to deliver the right level of information to the correct echelon of command for decisions to be made.

It is recommended that robot operators interact with one another on the battlefield and get to know each other for improved coordination.

We should prevent friendly military equipment from falling into enemy hands. We should therefore prevent an enemy from recovering data from a captured robot.

Given the non-human nature of robots, contacts with the population should be avoided in certain missions. It depends on the tension and danger of a mission and also how soldiers are perceived.

## 6.2 THE SENSITIVE ISSUE OF LETHAL AUTONOMOUS ROBOTS USAGES

### 6.2.1 A Necessary Characterization

In this Chapter, we should at first characterize what is a LAR (Lethal Autonomous Robot): it is an air, land or sea reusable mobile system (which differentiates it from missiles), which has the ability to fire autonomously, also known in the English-speaking world under the term “fully autonomous weapons”.

It can theoretically handle any type of target, humans or equipment, with or without warning. Nevertheless, as NATO countries respect the law of armed conflicts, it is imperative for a LAR to comply with them, which requires it to embed programs strictly respecting these laws and specific rules of engagement.

It is important to note that the distinction on the battlefield as to the status “inhabited” or “unmanned” of a threat does not always appear easily. On the contrary, the uncertainty of the characterization of a threat, that is to say whether or not a human component is hosted in the target, will go increasing with the development of military robotics.

### 6.2.2 “LAR” is a *Programming* Mode

For robotic systems, it is generally accepted the following classification in three operating modes: man can be in the loop, on the loop, or out of the loop.

The “LAR mode” for its part is a mode where the operator is not in the loop (out of the loop), but with a delegation of opening fire autonomously.

This mode must be activated by an officer, who is aware of the operational context and implications of such a decision. And therefore, if a lethal system can enter the LAR mode, it can also come out and regain the control of the operator, if for example the conditions for the execution of its mission are no more assured (if the security constraints of its weapons are not proven anymore). A LAR mode can therefore not be activated by its own, but can be disabled independently, or be disabled by a human operator.

### 6.2.3 Justification of the LAR Mode at the Operational Level

We will now try to determine what a military robot in a LAR mode can change at operational level, by considering at first the 3D rules (Dull, Dangerous and Dirty) that summarize the benefits of using military robotics to preserve the human capital and allow to keep operational forces to act when needed:

- **Dangerous**: In the case of threats proved to be highly dangerous, it is imperative to automate certain actions to deal effectively with multiple targets, or to treat a target before it will treat you or a friend. The speed to respond is premium in this case.
- **Dull**: For highly repetitive tasks, man relies on machines whose technology can detect threats or alarms with more rigor and consistency that men can do. In the case of highly secure area surveillance missions (nuclear missile warehouses, no man's land etc.), requiring absolute prohibition on access, responsiveness is critical.
- **Dirty**: It is very stringent for military units to operate in polluted or contaminated CBRN environment. Fighting in such environments requires substantial equipment for a very high risk, in areas where only a fully equipped enemy or enemy robots might be deployed.

This does not cover the entire spectrum of reasons to justify a possible use of Lethal Autonomous Robot at operational level. Other factors can advocate for their use:

- In our context of strong budget reduction, and paradoxically expansion of military overseas operations due to the international situation, the scarcity of combatant or its overexploitation makes it very valuable. The lack of human resources to cover large areas becomes obvious, requiring the use of weapons systems deployed in high risk areas to protect our array of troops.
- Facing saturating threats, responsiveness in time is essential to carry out the treatment of these threats, within a timeframe unattainable by a human operator. Any millisecond can be crucial.
- If the weapon system is unable to maintain a data link with the operator, the question arises as to trust the machine to find and treat threats. This is a question that may arise, particularly with combat drones (UCAV) that we will send to the other end of the world to destroy enemy military equipment, or to intercept aircrafts violating duly demarcated areas of exclusions.

### 6.2.4 Constraints of Use

Enable a lethal robotics system to be in a LAR mode requires having defined during the design of the machine, the safeguards for its use: here are below some prerequisites, guidelines and rules that are considered as necessary for an autonomous decision of fire.

#### 6.2.4.1 Programming Instructions and Rules of Engagement

- Outline a physical space in which the move of the robot is strictly limited, and define precisely firing areas allowed within this space.
- Set a time frame for the lethal function activation: to be run from H to H + t.
- It operates in an area corresponding to the detection capabilities of its sensors (which detect and characterize the threat) and not to its weapons (which allow the processing of the threat), meaning that outside the sensors limits, threats are not processed.
- The list of potential targets is duly confirmed by a military authority, based for example on a database including image heat signatures, etc.

#### 6.2.4.2 Operating Mode

- In LAR mode, it is essential before firing, to carry out the following iterative process: detect the target (through its sensors), locate it, identify it (based on the list of targets validated by the military authority), discriminate it (combatant or not according the rules of law of armed conflicts) and characterize it (hostile behavior or not).
- Based on this analysis, and depending on the rules of engagement, the target can be described as valid or not. This firing decision algorithm takes into account the operational constraints of the moment, and whether or not this target is a firing priority.
- Any firing decision must be registered, in order to ensure the traceability of the decision (e.g., a black box must be embedded).
- Finally, after firing, the recorded data has to be sent to the operator, or in case of transmission failure, once the contact and communication are restored.

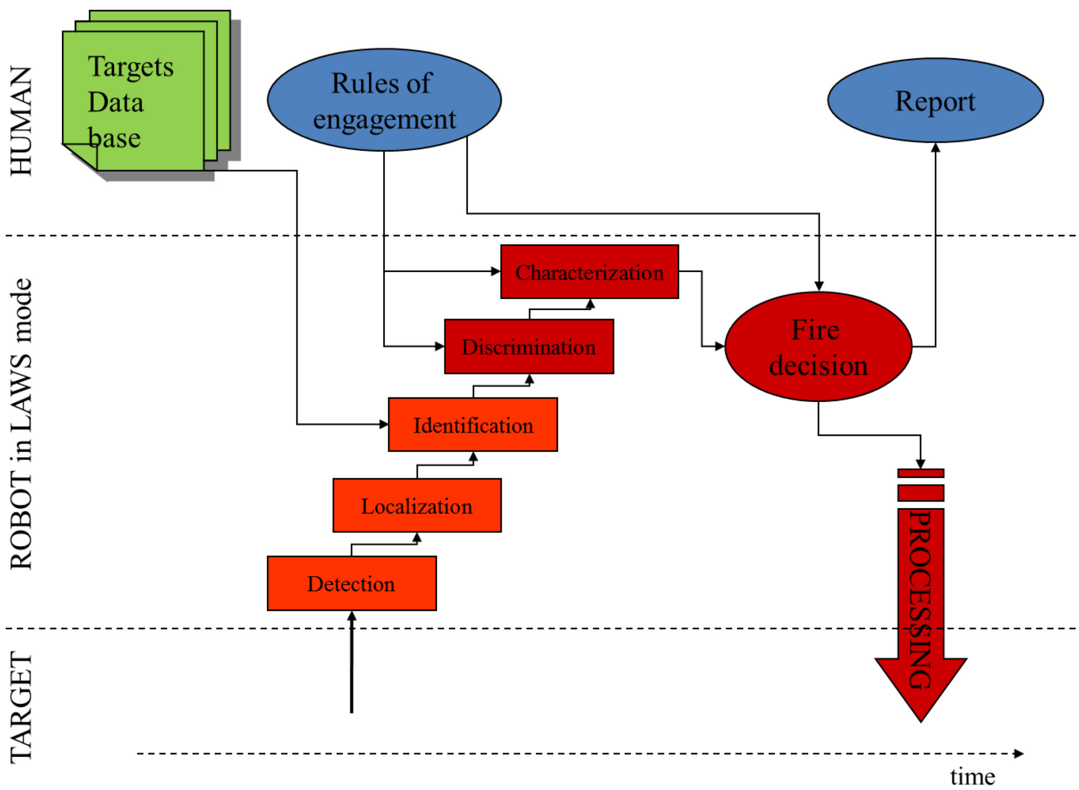


**Figure 6-2: Fire Decision Process for a LAR.**

### 6.2.5 Conditions of Safety

- Ensure the operator has the possibility to activate the autonomous firing function, but especially to remotely disable it, that is to say to ensure the activation of the “veto power”.
- Need for an emergency communication function (HF, Satellite or radio relay) so that an operator can take control of the LAR if the main communication module is inoperative.
- If any technical failure is detected that restricts the discrimination capabilities of the target, the LAR mode is deactivated.

## 6.3 CONCLUSIONS

Without considering the existing technological constraints, it is clearly apparent that an autonomous lethal decision should be subject to very severe constraints and strict supervision. People should be in the very early specifications process of these systems to specify and develop the necessary safeguards (algorithms, security mechanisms, etc.). They also need to configure them ahead of their operational use on the battlefield (rules of engagement, spatial and temporal constraints, etc.).

To conclude, it is always a person who will ultimately activate the LAR mode, a decision that can only be taken by military personnel with the responsibility of an officer, and according to the threats he perceives on the battlefield and by the means he has at his disposal.

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# Chapter 7 − FAN-OUT

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Earlier work proposed simple models, which omit mission objective, characteristics and task/environment complexity. None of the earlier models consistently predicts the fan-out, and account for the limitations of human cognition and task saturation, thus additional aspects; e.g., mission achievement, environment, and utilization have to be considered in human-robot interactions.

In this chapter, we briefly review related literature and provide important definitions related to the fan-out. [1] discuss six interrelated metrics that can guide the design of human-robot interaction. The most related ones for an H/M-R system are Task Effectiveness (TE), Task Complexity (TC), neglect tolerance, Fan Out (FO) and Interaction Effort (IE). TE is a measure (e.g., speed, time, error based) of how an H/M-R team achieves the task given. Depending on the measure, TE can be categorized into overall and current task effectiveness. Neglect tolerance measures the decline of a robot's current task effectiveness over time when the user neglects a robot, which is usually represented by a neglect curve. The neglect curve illustrates how expected robot performance deteriorates with time-off ($t_{off}$) task, e.g., time elapsed since the last human interaction. Neglect Time (NT) is a measure of neglect tolerance that is defined as the expected amount of time that a robot can be ignored before its performance drops below a task effectiveness threshold. Task complexity is a composite measure of the task difficulty and complexity of the world, e.g., obstacle density in routing and location applications for HR systems. Neglect tolerance can be determined by averaging neglect time through random task and system conditions. While this average measure measures robot's capability and task complexity, it excludes the effect of user interface and global system space (e.g., other robots).

A simple measure of the IE is the expected amount of time that a human must interact with a robot to bring it to peak performance, namely IT. We note that IT time is more than the time spend on manipulating input control devices, as there are other elements of interaction such as sub-task selection, context acquisition, planning and expression [1]. A portion of the IT is spent on deciding which robot the operator should service following interaction with another or at the start of the system. This is referred as the Switch Time (ST) during which the operator gains awareness of the robot's state [2], [3]. Olsen and Goodrich proposed an equation relating fan-out to a robot's activity time and its interaction time which serves as an upper bound on the number of how many independent homogeneous robots can be managed by a single human [1]. Their equation assumes homogenous robots and can be expressed as:

$$\text{Fan} - \text{out}_1 \ = \ NT/IT + 1$$

In the above equation, the ratio represents the number of other robots that the human can manage during the neglect time interval and the +1 term represents the original robot. An alternative measure of the fan-out is proposed by Olsen and Wood [4] where the authors introduce the definition of Activity Time (AT) which is the time the robot makes progress until the next operator input and stops before or after completing the operator's command. Neglect time and activity time are not the same as the latter one could include passive interaction of the operator, e.g., monitoring the progress of the robot without actively controlling. The AT, NT, and IT are related through:

$$AT = O \cdot IT + NT,$$

where $O$ is the overlap between robot activity and interaction time. The proposed fan-out is:

$$\text{Fan} - \text{out}_2 \ = \ AT/IT.$$

Another method to estimate the fan-out is proposed considers the Wait Times (WT). The robot's waiting occurs when a robot waits to be serviced after completing operator's last command or reaching its goal. It is the expected amount of time during interactions that the robot is in a degraded performance state and waiting for the operator:

$$\text{Fan} - \text{out}_3 = NT/(IT + WT)$$

The above fan-out effect equations do not consider the performance of the individual robots. Crandall *et al.* [5] proposed an alternative proposed method where they determine the number of robots by maximizing robot's expected instantaneous performance calculated by averaging over all possible interaction and neglect times subject to a feasibility condition. This feasibility condition determines whether a human can manage a team of robots, e.g. $NT_i \geq \sum_{j \neq i}^{N} IT_j$ for every robot $i$ with neglect and interaction times ($NT_i$, $IT_i$).

## 7.1 REFERENCES


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# Annex A – MISSION TO TASK DECOMPOSITION ASSOCIATED WITH ROBOTICS

This annex derives the Mission to Task Decomposition used within the NATO Defence Planning Process and shows those tasks with particular missions wherein robotic systems would be of best potential.

**Table A-1: Mission-to-Task Decomposition and Related Robotic Tasks.**

| **Mission Type – Collective Defence** | | |
|---|---|---|
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Establish rail facilities | Set up facilities to support rail transport operations to and from, and within the JOA. | Laying rail, preparing rail beds, moving cargo |
| Establish sea port facilities | Set up facilities to support sea transport operations to and from, and within the JOA. | Moving containers, constructing piers |
| Improve theatre reception / transit centers | Improve existing theatre reception / transit centers to assist the reception, staging and onward movement of forces, equipment and material and to assist the sustainment of the force once deployed. | Moving cargo, loading and unloading aircraft/ships, AI-driven stockpiling |
| Conduct MCM in very shallow water | Conduct operations in very shallow waters, including beaches and harbor areas, to permit military and civilian vessels to use the seas and enter or leave ports for the furtherance of military efforts or for the support of the population without unacceptable damage or losses from mines. | Mine detection, mine removal, UUV |
| Provide harbour protection | Provide protection for units, facilities and infrastructure used in support of a NATO operation and located in port areas. | UUV, UAS, UGV, sentry function- air, land and sea |
| Provide perimeter security | Provide security around designated sites, preventing unauthorized access and warning of attack. | Sentry function – land |
| Conduct protective naval minelaying | Conduct naval mining in NATO territorial waters intended to deny the opponent freedom of movement, and to protect allied forces from opposing force offensive action. | Mine laying, UUV, UMV |
| Conduct defensive land minelaying | Conduct mining laying of land areas to shape the battlefield, to protect designated areas, and to deny the opponent freedom of movement. | Mine laying, UGV |
| Conduct electromagnetic spectrum denial operations to counter remote controlled IED | Conduct electromagnetic spectrum denial operations to counter remote controlled IED. | UAS, UGV |
| Conduct explosive ordnance disposal operations | Conduct conventional munitions disposal, improvised explosive device disposal and battle area clearance operations. | UGV, EOD |
| Remove or overcome obstacles and improve routes | Provide combat engineering support, including bridging, to remove or overcome obstacles and to ensure that designated routes are traversable by combat forces. | AI-driven construction, moving material |

| Mission Type – Collective Defence (cont'd) | | |
|---|---|---|
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Conduct airborne armed reconnaissance | Obtain, by visual or other detection methods, information about the activities of an enemy (or potential enemy) or a tactical area of operations from the air and engage targets of opportunity. | UAS, Automatic Target Recognition, AI-driven response |
| Conduct ground patrols | Conduct ground patrols in support of efforts to control designated land areas. | Sentry function – land, AI-driven response |
| Provide direct convoy protection along land transportation routes | Provide protection to a designated convoy moving along a land transportation route within the JOA. | Moving sentry function – land, ATR, AI-driven response |
| Conduct route assessment | Ensure that designated routes for the movement of land forces and civilian transport are clear of threats. | EOD, Surveillance |
| Provide fighter escort of strategic air transport | Provide air escort to civilian or military air transport to ensure safe passage through to destination. | UCAV, engagement |
| Protect movement of forces along shipping lanes | Conduct ASUW or ASW to secure sea lines of communication. | UUV, AI-driven response, engagement, ATR |
| Conduct barrier operations | Conduct maritime operations which prevent opponent maritime forces from crossing a designated geographic line. | USV, UUV, UAS, surveillance, engagement |
| Provide protection to sealift | Provide an escort to civilian or military shipping providing sealift to prevent them from being scattered, captured or destroyed. | USV, UUV, UAS, surveillance, engagement |
| Provide naval anti-air warfare | Provide water-borne defence against aircraft and airborne weapons launched from aircraft, ships, submarines, and land-based sites. | USV, UUV, UAS, surveillance, engagement |
| Provide protection against sub-surface threats | Provide protection to commercial or military shipping against sub-surface threats operating in the area. | USV, UUV, UAS, surveillance, engagement |
| Provide protection against surface threats | Provide protection to commercial or military shipping against surface threats operating in the area. | USV, UUV, UAS, surveillance, engagement |
| Conduct MCM operations | Conduct measures intended to reduce the effect of naval mines upon NATO forces or friendly shipping. | ATR, UUV, mark or destroy |
| Conduct MCM in littorals / open water | Conduct operations in littorals or open water to permit military and civilian vessels to use the seas and enter or leave ports for the furtherance of military efforts or for the support of the population without unacceptable damage or losses from mines. | ATR, UUV, mark or destroy |
| Conduct MCM in very shallow water | Conduct operations in very shallow waters, including beaches and harbor areas, to permit military and civilian vessels to use the seas and enter or leave ports for the furtherance of military efforts or for the support of the population without unacceptable damage or losses from mines. | ATR, UUV, mark or destroy |

| Mission Type – Collective Defence (cont'd) | | |
|---|---|---|
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Provide protection to MCM forces | Provide naval anti-air defence, anti-surface defence, and anti-submarine defence to forces conducting MCM operations. | ATR, UUV, mark or destroy |
| Conduct defensive space operations | Preserve space capabilities, withstand enemy attack, restore or recover space capabilities after an attack, and reconstitute space forces. | Unmanned space vehicles, rendezvous, surveillance, engagement |
| Conduct active defensive space control operations | Protecting, preserving, recovering and reconstituting friendly space-related capabilities before, during and after an adversary attack. | Unmanned space vehicles, rendezvous, surveillance, engagement |
| Conduct offensive counter air operations against opponent strategic offensive air capabilities | Conduct air operations to destroy, disrupt, neutralize or limit adversary aircraft, missiles and supporting structures or systems. | UCAV, engagement |
| Destroy / Degrade / Neutralize opponent offensive air bases | Destroy, degrade or neutralize the ability of the opponent to effectively use offensive air basing. | UCAV, engagement |
| Destroy / Degrade / Neutralize opponent air C2 | Destroy, degrade or neutralize the ability of the opponent to effectively command and control air forces. | UCAV, engagement, cyber |
| Opponent space capabilities eliminated | The opponent has been denied the effective use of space for military operations. | Unmanned space vehicles, rendezvous, surveillance, engagement |
| Conduct offensive space operations | Deny, degrade, disrupt, destroy or deceive an adversary's space capability or the service provided by a third party's space asset(s). | Unmanned space vehicles, rendezvous, surveillance, engagement, UCAV, ATR |
| Destroy / Degrade / Neutralize opponent space C2 | Destroy, degrade or neutralize the ability of the opponent to effectively command and control its space assets. | Unmanned space vehicles, rendezvous, surveillance, engagement, UCAV, ATR |
| Destroy / Degrade / Neutralize opponent space assets | Destroy, degrade or neutralize opponent space assets to ensure they cannot be used against friendly forces. | Unmanned space vehicles, rendezvous, surveillance, engagement, UCAV, ATR |
| Destroy / Degrade / Neutralize opponent space support capabilities | Destroy, degrade or neutralize opponent ability to provide space lift, satellite operations and reconstitution of space forces. | Unmanned space vehicles, rendezvous, surveillance, engagement, UCAV, ATR |
| Compile and disseminate a common operational picture | Collect real-time or near-real-time data pertaining to all services in the JOA, process that data into a coherent picture, and disseminate that picture to relevant parties. | UGV, UAS, UUV, surveillance, ATR |
| Compile and disseminate a recognized maritime picture | Collect real-time or near-real-time data pertaining to maritime contacts or contacts directly threatening maritime contacts, in the JOA, process that data into a coherent picture, and disseminate that picture to relevant parties. | UGV, UAS, UUV, surveillance, ATR |

| Mission Type − Collective Defence (cont'd) | | |
|---|---|---|
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Compile and disseminate a recognized ground picture | Collect real-time or near-real-time data pertaining to land contacts in the JOA, process that data into a coherent picture, and disseminate that picture to relevant parties. | UGV, UAS, UUV, surveillance, ATR |
| Compile and disseminate a recognized air picture | Collect real-time or near-real-time data pertaining to airborne contacts or contacts directly threatening air contacts, in the JOA, process that data into a coherent picture, and disseminate that picture to relevant parties. | UGV, UAS, UUV, surveillance, ATR |
| Compile and disseminate a recognized space picture | Collect real-time or near-real-time data pertaining to friendly and adversary space capability, process that data into a coherent picture and disseminate that picture to relevant parties. | UGV, UAS, UUV, surveillance, ATR |
| Compile and disseminate a recognized logistic picture | Collect real-time or near-real-time data pertaining to logistic infrastructure, capability and demand and disseminate that picture to relevant parties. | UGV, UAS, UUV, surveillance, ATR |
| Conduct combat search and rescue operations | Conduct operations to detect, locate, identify and rescue downed aircrew and isolated military personnel in distress. | UAS |
| Conduct detention functions | Provide specialist planning and advice, oversight and surety for the correct handling and processing of prisoners of war, internees and detainees. | Sentry |
| Provide CBRN collective protection | Provide a toxic free environment for personnel, allowing relief from the wearing of IPE for prolonged periods, in a nuclear, biological or chemical environment. | Detection, decontamination, movement of material |
| Provide CBRN decontamination | Provide CBRN decontamination capability for deployed personnel, vehicles, equipment and terrain. | Detection, decontamination, movement of material |
| Provide CBRN detection, identification, sampling, monitoring, surveillance and reconnaissance | Provide a mobile and static detection, identification and monitoring capability to protect forces against CBRN threats within the JOA. Collect and analyze samples to substantiate or renounce the presence of CBRN hazards in a specific area. | Detection, decontamination, movement of material |
| Provide CBRN warning, reporting, data management, and hazard prediction | Provide a timely response to CBRN attacks and releases other than attack through the reporting, analysis and dissemination of detection, identification, location, and warning information; this includes the prediction and warning of hazard areas. | Detection, decontamination, movement of material |
| Provide operational and tactical JISR | Provide timely information and intelligence to support joint forces in defining and achieving operational and tactical objectives. | UGV, UAS, UUV, surveillance, ATR |
| Provide environmental assessment | Provide an assessment of geospatial, oceanographic and meteorological conditions in support of the planning and conduct of the joint operation. | UGV, UAS, UUV, surveillance, ATR |

| Mission Type – Collective Defence (cont'd) | | |
|---|---|---|
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Provide medical treatment support for deployed forces | Provision of medical support (Role 1, 2 and 3) to deployed forces, including those based on land and at sea. This includes: the maintenance of health and prevention of disease; the holding, treatment and evacuation of patients; and the resupply of blood and medical materiel. | Movement of personnel, surgery |
| Provide in-theatre medical evacuation | Provide medical evacuation and movement of casualties from point of wounding to the relevant medical treatment facilities within agreed medical timelines. | UGV, UAS |
| Support own forces mobility | Conduct military engineering activities, e.g. bridging and road improvements, to support the mobility of own forces. | Moving material, construction |
| Support counter-mobility | Conduct military engineering activities, e.g. bridging and road improvements, to support counter mobility operations. | Moving material, construction |
| Conduct joint recovery, maintenance and repair operations | Maintain and restore relevant elements to a serviceable condition. This includes the recovery of inoperable elements such that they can be repaired and prepared for further operation. Where appropriate, this function also includes the need to dispose of materiel in a manner that does not result in unwanted effects. | Moving material |
| **Mission Type – Consequence Management** | | |
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Support provision of mortuary services | Assist, with relevant and available NATO/national expertise, personnel and equipment, the host government and appropriate non-NATO actors develop and deliver mortuary services to the affected population. | Grave preparation, moving material |
| **Mission Type – Conflict Prevention** | | |
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Gain / Maintain control of designated borders | Gain and maintain control of designated border areas of a country to prevent unauthorized activity while retaining NATO freedom of action. | Sentry, surveillance, ATR |
| Conduct surveillance and control of border areas | Conduct ground patrols to establish or maintain control of designated border areas. | Sentry, surveillance, ATR |
| Prevent unauthorized movements | Monitor and control the movement of personnel and materials within an area through the establishment of check-points. | Sentry, surveillance, ATR |
| **Mission Type – Counter Terrorism (Failed State)** | | |
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Terrorist infrastructure eradicated | The basing and training infrastructure within the country used by the international militant extremist group to plan and prepare for international terrorist operations has been eradicated. | UCAV, UGV, UUV, autonomous operations, surveillance |
| Destroy terrorist infrastructure (e.g., training camps) | Destroy terrorist infrastructure such as training camps to disrupt their ability to continue hostilities. | UCAV, UGV, UUV, autonomous operations, surveillance |

| Mission Type – Counter Terrorism (Failed State) (cont'd) | | |
|---|---|---|
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Destroy terrorist training camps | Destroy terrorist training camps within the JOA. | UCAV, UGV, UUV, autonomous operations, surveillance |
| Destroy terrorist operating bases | Destroy terrorist operating bases within the JOA. | UCAV, UGV, UUV, autonomous operations, surveillance |
| Destroy terrorist support facilities | Destroy terrorist support sites within the JOA. | UCAV, UGV, UUV, autonomous operations, surveillance |
| **Mission Type – Extraction Operations** | | |
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Conduct personnel legitimacy control | Ensure, through the use of biometrics and other methods, that personnel to be evacuated are members of the population at risk and neither members of opposing forces wishing to infiltrate and sabotage the operation nor other individuals, not legitimately requiring evacuation. | Surveillance, ATR |
| Conduct evacuation | Relocation of designated non-combatants in a foreign country to a place of safety. | Movement of personnel |
| Rescue hostages | Conduct specialized operations to rescue personnel detained by hostile parties. | ATR, movement of personnel |
| Support and sustain evacuees | Provide necessary supplies and life support services to evacuees. | Movement of material |
| **Mission Type – Enforcement of Sanctions and Embargoes** | | |
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Monitor ports of interest in support of embargo operations | Monitor, covertly or overtly, ports of interests in support of embargo operations, to directly observe the ingress and egress of commercial shipping. | Surveillance, UAS, UUV |
| Monitor commercial shipping movements in support of embargo operations | Monitor commercial shipping movements (for example through such systems as Automatic Identification System or Long Range Identification and Tracking) in support of embargo operations. | ATR, sentry, surveillance |
| **Mission Type – Peace Enforcement** | | |
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Destroy or secure CBRN weapons, material and infrastructure | Destroy or secure WMD in the JOA. The requirements for this task may vary considerably depending upon the nature of the WMD involved. | Strike, CBRN detection, decontamination, movement of materiel |
| Secure significant toxic industrial sites | Secure significant industrial sites to prevent the intentional or accidental release/dissemination of toxic industrial material in the JOA. | Strike, CBRN detection, decontamination, movement of materiel, sentry duties |

| Mission Type – Peace Enforcement (cont'd) | | |
|---|---|---|
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Support environmental remediation | Assist, with relevant and available NATO/national expertise, personnel and resources the host government and appropriate non-NATO actors, in identifying environmental industry/ waste management issues and in devising strategies to remedy decontamination and in assisting contamination management efforts. | CBRN detection, decontamination, movement of materiel, sentry duties |
| Support humanitarian de-mining operations | Assist as appropriate in searching, finding and marking, and safe detonation or disposal as appropriate of land mines and other unexploded ordinance in the JOA. | Mine detection/removal, movement of materiel, sentry duties |
| **Mission Type – Peace Keeping** | | |
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Monitor lines of demarcation, zones of separation, and demilitarized zones | Monitor geographic lines and zones as established through a ceasefire agreement to ensure opposing factions have deployed according to the ceasefire agreement. | Sentry, surveillance, ATR |
| Establish presence of forces in designated areas | Conduct operations in designated areas of the JOA to show military resolve and Allied capabilities, and to reassure friendly parties as appropriate. | Sentry, surveillance, ATR |
| Prevent unauthorized movements | Monitor and control the movement of personnel and materials within an area through the establishment of check-points. | Sentry, surveillance, ATR, detention, engagement |
| Facilitate and monitor demobilization and decommissioning of weapons | Support as appropriate the monitoring of demobilization and decommissioning of weapons required for the implementation of ceasefire agreements. | Sentry, surveillance, ATR, detention, engagement, destruction of materiel |
| **Mission Type – Support of Humanitarian Assistance and Disaster Response** | | |
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Support environmental remediation | Assist, with relevant and available NATO/national expertise, personnel and resources the host government and appropriate non-NATO actors, in identifying environmental industry/waste management issues and in devising strategies to remedy decontamination and in assisting contamination management efforts. | CBRN detection, decontamination, movement of materiel, sentry duties |
| Support hazardous material abatement | Assist, with relevant and available NATO/national expertise, personnel and resources the host government and appropriate non-NATO actors, in efforts to identify, collect and abate hazardous chemical, biological or radiological material. | CBRN detection, decontamination, movement of materiel, sentry duties |
| Support remediation of ammo and fuel storage facilities | Assist, with relevant and available NATO/national expertise, personnel and resources the host government and appropriate non-NATO actors, in identifying shortfalls, priorities and sequence in the remediation of ammo and fuel storage facilities. | CBRN detection, decontamination, movement of materiel, sentry duties |
| Support humanitarian de-mining | Assist, with relevant and available NATO/national expertise, personnel and resources, the host government and appropriate non-NATO actors to detect and remove mines and assist survivors. | Sentry, surveillance, ATR, detention, engagement, destruction of materiel |

| Mission Type − Support of Humanitarian Assistance and Disaster Response (cont'd) | | |
|---|---|---|
| **Task** | **Sub-Task** | **Robotic Applications for Task** |
| Support mine detection mine clearance | Assist, with relevant and available NATO/national expertise, personnel and resources the host government and appropriate non-NATO actors to detect and clear mines. | Mine detection/removal, movement of materiel, sentry duties |
| Assess mine clearance operations through quality assurance processes | Conduct an assessment, using relevant and available NATO/national expertise, to evaluate mine clearance operations and make suitable recommendations. | Mine detection/removal, movement of materiel, sentry duties |

# Annex B – STANDING NATO AGREEMENTS RELATED TO ROBOTICS

The following Standing NATO Agreements (STANAGs) are related to robotic applications within NATO.

**Table B-1: Standing NATO Agreements (STANAGs) Related to Robotics.**

| | | |
|---|---|---|
| AEP-77 | 4660 | INTEROPERABLE COMMAND AND CONTROL DATA LINK (IC2DL) FOR UAV |
| AEP-78 | 4732 | EMPLOYMENTS OF UAS DATA LINKS |
| AEP-80 | 4702 | UNMANNED SYSTEMS AIRWORTHINESS REQUIREMENTS - ROTARY WING |
| AEP-82 | 4737 | GUIDELINES FOR THE INTEGRATION OF WEAPONS ON UNMANNED PLATFORMS |
| AEP-83 | 4703 | LIGHT UAV SYSTEMS AIRWORTHINESS REQUIREMENTS |
| AEP-84 | 4586 | STANDARD INTERFACES OF UAV CONTROL SYSTEM (UCS) FOR NATO UAV INTEROPERABILITY |
| AEP-57 | 4586 | STANAG 4586 IMPLEMENTATION GUIDE |
| AEP-89 | 4746 | LIGHT ROTARY WING UAS SYSTEMS AIRWORTHINESS REQUIREMENTS (USAR-RW-LIGHT) |
| ANEP-81 | 4671 | UAV SYSTEM AIRWORTHINESS REQUIREMENT |
| ANEP-81 | 4671 | STANAG 4671 CONFIGURATION MANAGEMENT PLAN |
| ANEP-81 | 4671 | STANAG 4671 IMPLEMENTATION GUIDE |
| ATP-3.3.7 | 4670 | GUIDANCE FOR THE TRAINING OF UNMANNED AIRCRAFT SYSTEMS (UAS) OPERATORS |
| Search Terms = unmanned, uninhabited, autonomous, robot, robotics, UAV, UAS, UGV, UUV<br>AEP = Engineering ANEP = Naval Engineering ATP = Tactical | | |

# Annex C − SCIENCE AND TECHNOLOGY PRIORITIES RELATED TO ROBOTICS

*Reference: AC/323-D(2014)0003 2014 STB Science & Technology Priorities 4 April 2014.*

This list was derived from the reference and includes capability areas wherein the development of robotic capabilities could have a significant impact and implications on future Alliance operations. The list includes the Long Term Aspects (LTA) of requirements found within the Minimum Capability Requirements derived from the last cycle of the NATO Defence Planning Process, the Emerged/Emerging Disruptive Technologies (E2DT) and Science and Technology Hard Problems (STHP).

## C.1 LONG TERM ASPECTS OF REQUIREMENTS

The Long Term Aspects (LTAs) of the Minimum Capability Requirements are used as the principle reference for NATO long term military capability requirements:

- Area Access Control − Capable of controlling access to designated unattended areas and borders, denying or allowing access to appropriate personnel and equipment:
  - Rationale: Current unattended area denial methods are indiscriminate, affecting animal, human, friend, foe, civilian, or military alike. Most are effective for an indefinite period and remain a hazard long after their original purpose has become invalid. After time, locations and sizes of areas are forgotten or were poorly documented originally during periods of intense conflict. Even if locations are precisely known, removal is difficult even for the originator (Driver 1). Likely future operations will require the control of large areas without the use of large pools of manpower to preventing individuals from entering controlled areas (Driver 2). Possible adversaries will continue to use remote areas for training and resupply while using difficult terrain to infiltrate controlled areas (Driver 3). Advances in technology, especially in wide area detection and surveillance systems, will provide supporting components to the systems required to provide this capability (Driver 4).
  - Effectiveness: The capability provides a means of denying access to an area or border yet still allow for the safe passage of those desired. It can be employed in remote areas where manpower is scarce. This capability must deny area access yet discriminate among intruders whether animal, human, friend or foe to prevent unintended injury to friendly/neutral forces and allow safe passage when required. Capability may use lethal or non-lethal means, but should be controllable and not produce long lasting environmental contamination. It must be capable of monitoring across all environments: air, land, sea and subterranean.
  - Potential Areas of Research, Technologies and Systems: Non-lethal mine fields, electronic fence, radiation, directed acoustic, remotely controlled mine fields, pattern recognition, biometrics, and image analysis, seismic sensor nets, fusion of intelligence capabilities.

- Assured Precision Strike − Capable of employing precision strikes with assurance and minimum risk of collateral damage:
  - Rationale: Threat systems in the future battlespace will be increasingly mobile, hard to find, and lethal. Failure to rapidly detect, identify, assess, track, and accurately attack time critical targets, including weapons of mass destruction, will heighten the risk to NATO's military forces (Driver 1 and 2). Unintended effects, such as collateral damage, civilian casualties and fratricide, reduce the ability of the Alliance to achieve its objectives and also could seriously damage its image and cohesion. The increasing complexity of the battlespace foreseen in the

future will heighten this concern (Driver 2). Possible adversaries are aware of Alliance restraint and will use numerous tactics to disguise targets and draw forces into committing targeting and strike errors in order to make use of these actions in the media to condemn the Alliance and strengthen popular support (Driver 3). Advances in supporting technologies within the overall 'kill chain' will allow significant improvements in assurance and accuracy (Driver 4).

- Effectiveness: The Alliance will require the capability to mount selective lethal or nonlethal precision strikes from the full range of delivery platforms (land, sea and air) with assurance of target discrimination to limit unintended effects. The capability must be persistent and responsive, minimizing the time between decision to strike and effects on target. It should have an ability to abort as near as possible to impact and be capable of being rendered inert. Once correctly identified, mobile and static targets must be quickly and accurately attacked either from land, sea, air, and space. Sensors and engagement systems will have significantly improved resolution, portability and accuracy driven by improvements in underlying technologies. Foreign Disclosure regulations will likely hinder full cooperation across nations.
- Potential Areas of Research, Technologies and Systems: Command and information system design, image/pattern processing and data fusion techniques, advanced sensors, precision guided weapons, warhead design, scalable weapons, alternative precision navigation system, EMP, non-lethal systems.

- Battlefield Medical Attention − Capable of providing remote / immediate medical assessment and treatment to ensure that battlefield casualties receive appropriate medical attention within appropriate medical timelines:
  - Rationale: The early and accurate diagnosis of the need for medical attention and the fastest possible treatment is the most effective way to deal with casualties; this can currently only be achieved by placing qualified practitioners in close proximity to all forces (Driver 1). If large numbers of casualties are taken, either during a high intensity battle, from weapons of mass destruction or due to natural disasters, there is currently little or no capacity – due to limited numbers of qualified medical staffs – to ensure that medical timelines or levels of clinical excellence can be guaranteed (Driver 1). Failure to treat casualties in a timely manner would have a negative effect on forces' morale, popular support and Alliance cohesion (Driver 2). Advanced technologies, especially in the area of autonomous and robotic systems, will improve critical components of the systems supporting this requirement and significantly improve the overall capability (Driver 4).
  - Effectiveness: The capability needs to be able to quickly identify the requirement for medical attention and deliver an accurate diagnosis. The capability should provide prompt remedial treatment to either cure or stabilize the patient and prepare them for evacuation (if necessary). Focus should be on immediate care to the second level of care at the medical aid station (the first location capable of performing emergency surgery). The capability will enable the effective management, movement and treatment of patients resulting from events with large scale casualties to maximize the chance of successful remedial treatment. System must allow the Alliance and its participating nations to increase effectiveness and efficiency in the medical care allowing for tracking of patients, learning cycles within treatment and Command and Control. Capabilities, systems and processes will need to include integrated assessment of the health situation, support to effective human performance, the delivery of accurate diagnosis, the provision for remedial treatment, tracking the availability of supply and medical evacuation assets, and the sharing of information with all medical stakeholders in the field. Physical, mental health and environmental considerations need to be considered within the capability.
  - Potential Areas of Research, Technologies and Systems: Artificial intelligence, robotics, medical unmanned systems, optics, secure and dependable communications, biometric data

collection and transmission, nanotechnologies, medical decision support tools (telemedicine), autonomous ambulances, autonomous diagnostics of patients, autonomous administration care and treatment, development of "stasis" techniques to enable stabilization to improve medical timelines without decrease in medical effectiveness, improved medical command and information systems, remote triage.

- Counter Chemical, Biological, Radiological and Nuclear (CBRN) − Capable of detecting, warning and neutralizing the full spectrum of CBRN agents or contaminants and identifying the type of agent or contaminant and the area affected:
  - Rationale: Most current CBRN detection is done at close range through collecting samples. This is undesirable as it is potentially harmful to human collectors and it contaminates remotely operated vehicles. A long-range detection capability is required. This would be particularly useful in cases where border crossing authority has not been granted, but there is a suspicion of the release/escape of CRBN agents (Driver 1). Advanced detection of CBRN agents will enable planning for an appropriate response (warfighting or humanitarian). Currently, there is limited standoff capability for containerized biological/chemical agents, enhancing this ability will avoid the potential risks of sending personnel to affected areas (Drivers 1 and 4). CBRN capabilities are being sought by several potential adversaries and will continue to be highly prized by asymmetric actors (Driver 3). Advances in technology, especially in the area of nanotechnology, will allow improvements in several components of this system (Driver 4).
  - Effectiveness: The capability must detect, classify and quantify the full spectrum of CBRN agents, preferably at appropriate stand-off distances or prior to release. The position of the release/escape and the size of the affected area(s) need to be accurately determined and relayed to end users in a timely manner. The capability must be reliable and durable, able to withstand the effects of the agents or contamination should it come into contact with them. The sensing capability needs to be fully integrated into the wider Joint Intelligence, Surveillance and Reconnaissance (JISR) system. The capability must operate regardless of the delivery mechanism. The capability must be able to effectively conduct mass decontamination and undertake forensic analysis of CBRN events. The capability should allow for the development of pre-crisis CBRN situational awareness on related technology and proliferation.
  - Potential Areas of Research, Technologies and Systems: Biotechnology, chemical agents, materials, AI, laser sensors, multi-hyper-spectral sensors, meteorological estimation, nanotechnology.

- Counter Improvised Explosive Device (C-IED) − Capable of countering the threat from improvised explosive devices (IED) at any point in the life cycle:
  - Rationale: IEDs pose a lethal hazard to all personnel - uniformed military, contractor personnel and civilians. The devices are inexpensive to produce and can explode from direct contact or remote activation by a distant observer. IEDs can be placed in a variety of locations including pedestrian traffic areas and along roadways. The use of IEDs to attack forces will remain a serious component of future operations (Drivers 1 and 2). Possible adversaries will continue to use asymmetric means to attack superior forces. IEDs provide a cost effective means to inflict damage on enemy forces and will progress with the continued proliferation of both the technology to construct these devices and emerging tactics, techniques and procedures through the internet (Driver 3). The threat is evolving in parallel with progress in new available technologies. The ability to counter IEDs in a timely manner would prevent death or injury to individuals and reduce damage to vehicles, equipment, and materiel (Driver 4). Detection of IEDs components before they are constructed or placed reduces the risk to personnel and impact on operations more than simple detection of placed devices (Driver 4).

  - Effectiveness: The capability must allow the interception of constituent IED parts before reaching the point of construction. If this is not possible, it must prevent IED construction when base materials are co-located. The capability must permit the interception of constructed IEDs before they are positioned and detect IEDs that have been positioned. It must make safe/dispose detected IEDs and, where necessary, reduce the impact of detonated IEDs. The capability must also encompass a learning function for IED operations and develop Tactics, Techniques, and Procedures accordingly. The capability must include forensic analysis of C-IED events and the exploitation of information to trace events back through to their initiators. Counter IED must work in all weather conditions and across all relevant military domains (Air, Land and Sea). The monitoring must cover the whole of the theatre of operations and possible neighboring/nearby countries possibly involved in the production process. Foreign Disclosure regulations will continue to hinder full cooperation across nations.
  - Potential Areas of Research, Technologies and Systems: Advanced sensors (hyperspectral, UWB, smell, etc.), biological sensors (sensor system), smart dust, data fusion, advanced pattern recognition, directed energy (EMP/HPM) and acoustic weapons, advanced materials for self-protection (nanotechnology, meta-materials, etc.), detection of power sources, IM/IX (Information Management and Sharing).

- Counter Naval Mines − Capable of countering static underwater threats, including detecting and disposing of all types of naval mines in all water bodies and at all water depths:
  - Rationale: Naval mines represent relatively inexpensive and simple means of damaging and destroying ships, resulting in personnel casualties, and hampering military and commercial maritime operations. They can be used for access denial purposes as damaged vessels can block harbors and waterways preventing the movement of commercial and military traffic. At times, even the threat of mines will seriously hamper the ability of Alliance forces to freely operate (Driver 1). Modern naval mines are more sophisticated and can discriminate between targets and sweeps, thus, reducing the efficacy of current mine countermeasures. Naval mines can be difficult to detect (e.g. buried mines) and if unmoored, their location may be unknown even to the emplacing party. Disposal of naval mines, particularly in very shallow water, ports and harbors can result in collateral damage (Driver 1). Assured access to littoral areas, and in some cases inland waterways / rivers will continue to be vital to the successful transport of equipment and personnel to operational areas, and to the projection of power from the sea in support of joint operations. The capability to counter emerging naval mine threats will continue to be essential to ensure the successful conduct of future NATO joint operations (Driver 2). The use of these types of systems against Alliance forces will continue to be attractive to possible adversaries – state and non-state – due to their ease of use, relative cost and effectiveness (Driver 3).
  - Effectiveness: The capabilities must allow for rapid deployment, faster detection and identification of naval mines, with higher probability of detection and lower false alarm rate, against all types of naval mines, including (but not limited to) contact or influence mines whether floating, moored or bottom mines, and self-burying pressure-sensitive mines. It must allow for the conduct of covert and in-stride counter mine activities. The capability must also accurately locate and dispose of naval mines in a timely fashion whilst minimizing collateral damage and enabling timely access to affected areas. The detection, localization and disposal capabilities must be effective against naval mines in all water bodies, particularly seas and rivers, and at all water depths (including ports and harbors), and be carried out at greater range from operational units to minimize the risk to personnel and infrastructure.
  - Potential Areas of Research, Technologies and Systems: Advanced sensors for local and wide-area threat detection and location (e.g., lasers, radar, imaging acoustics), sensor fusion, water space management systems, improved automation, advanced signal processing (e.g., target

assessment and change detection), advanced decoys, mine-homing munitions, Autonomous Underwater/surface Vehicles (AUV), new weapon types (e.g., high-power acoustics), capable gun systems with Advanced Hit Efficiency And Destruction (AHEAD) ammunition.

- Counter Threat to Low Altitude Air Vehicles − Capable of countering threats to low speed/low altitude air vehicles:
  - Rationale: Low speed and low altitude aircraft such as helicopters and small fixed wing aircraft will continue to be particularly vulnerable to low technology weapons such as shoulder-fired Rocket Propelled Grenades (RPGs) and Man-Portable Air Defence Systems (MANPADS). High performance aircraft are also vulnerable during takeoff and landing (Driver 1). These low technology weapons are relatively inexpensive and will continue to proliferate throughout the world, putting NATO assets at risk (Driver 2). The ability to safely operate NATO low altitude vehicles is crucial to mission success, making it imperative to counter threats to those vehicles (Driver 2). Possible adversaries will make use of the continued proliferation of these systems and supporting technologies to interrupt lines of communication and inflict losses on Alliance forces (Driver 3).
  - Effectiveness: The capability must reduce the losses of and damage to low speed / low altitude air vehicles. It must encompass the ability to search for and detect, identify and track potential and active threats at sufficient range to allow threat engagement or avoidance before detrimental effects occur. It must locally and remotely inform as to the position, speed, heading and overall behavior of threats and provide an accurate threat assessment. It will cover protection of all air platforms (Transport, Jet, Helicopter, UAV). It must consider IR, RF and EO threats' sensors. It could include passive measures to reduce the effectiveness of the threat.
  - Potential Areas of Research, Technologies and Systems: Sound damping, jamming (IR, EO), armors, materials (alloys, nanotechnology), sensors to detect threat, signature reduction (acoustics, IR). Advanced expendable (chaff, flares, optical decoys), Directed Energy (IR, Laser, HPM).

- Counter Underwater Threats − Capable of countering mobile underwater threats:
  - Rationale: Assured access to open sea and littoral areas will continue to be vital to the successful sea transport of equipment and personnel to NATO operational areas, and to the projection of power from the sea in support of joint operations. The protection of NATO forces is an essential component of successful NATO expeditionary operations. Therefore, it is crucial that NATO forces have the ability to counter emerging underwater threats (Driver 1). Many countries will continue to acquire diesel-electric submarines and there is a trend toward the development of more sophisticated and lethal underwater vehicles (manned and unmanned). The threat from these vehicles is becoming more complex as they become quieter and air independent. A small group of underwater vehicles is capable of conducting coastal defence or sea denial missions, including attacks against merchant, logistics and amphibious ships, covert offensive mining and support to special operations forces (Driver 2). The threat from combat swimmers, including marine animals trained to deliver ordnances against shipping, is particularly relevant for ships (military and commercial) in ports and harbors. The detection and classification of such threats with sufficient warning to allow the employment of appropriate measures represents a significant challenge, particularly in the noisy and cluttered environment typically found in ports and harbors, and coastal waters in general (Driver 3). Torpedo technology continues to evolve and improve. Torpedoes represent a serious threat to maritime operations in a range of water depths. Current capabilities for countering torpedoes, are mainly focused on soft-kill and must therefore improve to remain effective against emerging torpedo threats (Drivers 3 and 4).
  - Effectiveness: The capability must be improved to develop the ability to rapidly and reliably detect, identify, localize, track, and neutralize or destroy all types of underwater threats, in all

environmental conditions. There is also a supporting requirement to improve the ability to analyze and characterize the underwater operating environment through enhanced detailed modelling and simulation. A hard-kill capability, employable when appropriate by both surface and sub-surface units, to rapidly and reliably intercept and neutralize inbound torpedo threats will, when combined with passive measures, increase the likelihood of defeating threat torpedoes. Detection of threats must provide sufficient warning to allow the employment of appropriate measures.

- Potential Areas of Research, Technologies and Systems: Advanced decoys, advanced sensors for local and wide area high-precision underwater threat detection and tracking (e.g., lasers, radar, new sonar waveforms etc.), advanced signal processing (such as AI, image exploitation and data fusion), enhanced electro-magnetic and acoustic spectrum denial capabilities, non-lethal weapons (e.g., acoustics), advanced seekers and warheads, lasers, multi-static, low frequency sonar, animals, high-speed hydrodynamics, chemical/acoustic countermeasures, deployable barriers in harbors, mobile barriers.

- Deployment and Mobility of Forces − Capable of rapidly deploying military and civilian capabilities at strategic distances into a theatre of operations, and then moving them in theatre to enable swift crisis resolution:
  - Rationale: The ability to project and move capabilities from a strategic distance are fundamental to creating a deployable force. While current capabilities exist to perform both strategic and tactical movements, they are expensive and not available in quantities required. Currently, the majority of capabilities for operations are deployed by sea; for strategic distances this requires significant time. Lightweight combat forces can be delivered into theatre quickly by air, but the force is not fully effective until their equipment arrives later by conventional sealift. The limited amount of strategic lift currently within the Alliance restricts the size of combat force and associated support that can be rapidly deployed (Driver 1). Faster delivery of an effective force into theatre may enable a swifter resolution of conflicts or prevent civilian casualties in some missions such as peacekeeping (Driver 4). Quicker and safer tactical redeployment within a theatre may mitigate some of the future IED threat as well as take the fight to the enemy, thus preventing escalation of a crisis or alleviating it earlier. Any savings from a more efficient delivery method can be reinvested in modern engagement capabilities and improving the quality of the lift to reduce material damaged in transit (Driver 4).
  - Effectiveness: The capability must reduce the time required to deploy an effective force at strategic distances from Alliance territory. Forces include but are not limited to heavy, light, special operations and specialized forces in support of coalition operations (e.g. communications squadron, helicopter squadron etc.) Once in theatre, rapid tactical and operational redeployment and forward movement must be achieved to ensure NATO forces retain the initiative within a crisis. Focus should be maintained on the multinational aspects of deployment and movement of forces especially in the areas of improvements to doctrine and pre-identifying movement ‘hubs and spokes’ around the world. Alternate approaches must be faster, cheaper or provide higher quality movements capabilities than currently exist. Alternate approaches should seek to reduce the amount of capability that needs to be physically forward deployed. A reduction in the logistics footprint will improve both the cost and speed of deployment and tactical movement. Standing Memorandums of Understanding for transit rights may support this requirement.
  - Potential Areas of Research, Technologies and Systems: High Speed Ships, Wing In Ground (WIG) effect technology, larger cheaper air transport methods (airships), Decision Support Tools / modelling, Deployable Port Of Debarkation (POD) / Improvement of POD, Asset / Force Tracking, Multi – Role Assets, Air-to-Air Refueling, standardization / common fit of equipment to lift assets. Short(er) haul aircraft, convertible rotary-to-fixed wing aircraft, austere environment aircraft, total asset visibility and global positioning systems.

- Dismounted Soldier Situational Awareness − Capable of enhancing the Situational Awareness (SA) of individual soldiers and increasing shared knowledge:
  - Rationale: Situational awareness is a key factor in the effective conduct of operations. Increased situational awareness provides a better perception of elements in the local environment and increases team cohesion leading to an increased battle tempo and a reduced risk of fratricide within the team as well as reducing the risk of collateral damage. This is accomplished through seamless transfer of tactical information at the lowest tactical level and between soldiers of different nationalities operating at the platoon, squad or section level. Through data interoperability, soldiers in a coalition environment will have improved Command Execution, Target Acquisition and Situational Awareness, leading to an increased comprehension of the situation, a more accurate understanding of possible future events and more informed decisions by the soldier. However, many required technologies are not currently available, requiring R&D efforts (Driver 1). The evolution of the strategic environment, with the increased focus on asymmetric warfare, increasingly requires soldiers to operate in small teams. In this environment this capability is even more important, as soldiers are required to make life-of death decisions amidst very confusing situations (Driver 2). Likely advances in nanotechnologies, component miniaturization and power requirements and sources will bring about a significant increase in the potential equipment that could be carried by individual soldiers. This capability could reduce the manpower required to fulfil some missions, as the increased situational awareness of the soldier will increase his ability to execute (Driver 4).
  - Effectiveness: These capabilities will be operated in dynamic and austere environments. The capability needs to be lightweight, compact, robust for extreme conditions and optimized to consume a minimum of battery power. The system's display must also be clear and easy to understand. The system needs to provide information on opposition forces, friendly forces and neutral/non-combatant elements with a high enough level of accuracy and timeliness to enable targeting. The system needs enough available bandwidth to transmit and receive various formats of information (maps, schematics, imagery, data, messages, positional updates etc.) and sufficient power to transmit in all terrains over various distances. The system must be interoperable with other situational awareness tools available to NATO using NATO standard interfaces. The system should possess tools that can automatically filter appropriate information based upon learning accomplished within the environment. The system must not limit the ability of the soldier to experience and interact with the physical environment around him/her.
  - Potential Areas of Research, Technologies and Systems: Smart/functional materials, electric power cells, integrated microsystems, human/technology interface, pattern/image processing and data fusion techniques, communications services, augmented/mixed reality, improved batteries.

- Electro-Magnetic (EM) Spectrum Denial − Capable of selectively denying the use of the EM spectrum to opponents without impacting its use by the Alliance:
  - Rationale: Future opponents will seek to exploit the EM spectrum to counter NATO forces and capabilities. EM applications such as radar surveillance, radio communications, target designation and directed energy weapons continue to evolve, and will directly or indirectly place NATO forces and missions at risk. The continued scarcity of current electronic warfare assets severely constrains the Alliance's ability to control, degrade and deny opponent's use of the EM spectrum (Driver 1). This, in turn, will continue to limit the effectiveness of NATO forces to shape the increasingly complex battlespace foresee for the coming decades and places at risk the Alliance's ability to rapidly and efficiently achieve mission success with the minimum of casualties (Driver 2). Possible adversaries continue to close the technology advantage that the Alliance has thus far enjoyed and will continue to make use of the global technology proliferation and dual-use technology to threaten Alliance operations (Driver 3).

- Effectiveness: The capability must selectively, flexibly and ubiquitously deny the use of the full EM spectrum to opponents, independent of the environment (EM pollution). It must cover all areas of EM spectrum potentially useful to adversary/NATO forces.
- Potential Areas of Research, Technologies and Systems: Low-signature materials (including nano-technology and intelligent materials), own use of advanced and jam resistant signal waveforms (LPI/LPD), advanced high-precision EM countermeasures (including EMP and HPM), pattern recognition, advanced signal processing (e.g., AI or neural networks), cellular telephone technology. Power generation and packaging, Directed Energy Technologies, Palletized jammer system, stand-off jamming and jamming techniques.

- Enhanced Human Performance − Capable of increasing the performance and endurance of personnel during operations:
  - Rationale: A wide range of conditions may adversely affect human performance on deployed operations including sleep deprivation/mental fatigue, disease, injuries, shortages of food and water, heat and cold stress, muscle fatigue, and data overload. Personnel with increased physical performance and endurance will lead to a more effective force which can sustain a higher operational tempo (Drivers 1 and 2). Stress and disease can significantly reduce the effectiveness of personnel deployed on operations. An increasing understanding of the mechanisms that support these conditions will allow the development of methodologies to reduce these underlying conditions (Driver 4). Increased human performance in terms of resistance to disease and stress (and the contributing factors to stress such as fatigue and low calorie intake, etc.) will reduce the impact of battlefield stress and endemic diseases. This will increase the effectiveness of deployed personnel and also reduce the workload of medical staff (Driver 4).
  - Effectiveness: The capability needs to significantly improve the performance and endurance of deployed personnel on operations in terms of increased disease resistance, enhanced human performance (the ability to lift more, move more for longer periods, etc.) and increased stress resistance/reduction. Lines of development could include Medical Prevention, Protection and Treatment, and Health Promotion; Physical Status Optimization and Psychological Readiness and Resilience.
  - Potential Areas of Research, Technologies and Systems: Exo-skeletons (and measures to reduce threatening appearance of such systems), improved vision systems (contact/sun lens), biotechnology to prevent disease and fatigue, concentrated nutritional time release additives, preventative medicine, psychological research and training, performance enhancing drugs, ergonomics, immunization and prophylaxis biology/microbiology/molecular biology, advanced trauma care, advanced diagnostic and treatment techniques, biomedical computer modelling, macro content optimization for performance enhancement, neuro-protective nutrients, physiological interactions of nutrition and dietary supplements.

- Increased Self-Sustainment − Capable of increasing the self-sustainment of units deployed in theatre by an efficient exploitation of available resources within the Area of Responsibility:
  - Rationale: The quantity of equipment and materiel required to support a deployed combat force is extremely large and places a large burden on strategic lift. Reduction in the requirement to deploy the ‘logistics tail’ will place less strain on already overburdened strategic lift assets in the initial deployment and reduce the amount of re-supply required in theatre (Driver 1). If the ‘logistics tail’ is reduced through the exploitation of emerging and novel technologies, it enables a more effective combat force to be deployed more quickly (Driver 4).
  - Effectiveness: The capability must significantly enhance the self-sustainment of units in theatre through the better use of available resources, thus reducing the equipment deployed, the combat service support requirements and the sustainment requirements in theatre. The capability must

encompass enhanced production of consumables and reduction/exploitation/conversion of waste. This capability is coupled to the development of more efficient personnel and equipment. Focus should be on reducing the deployed footprint and improving the acquisition and equipment life-cycle support processes.

- Potential Areas of Research, Technologies and Systems: Novel renewable energy sources, water from the air, water from exhaust, Health and Usability Monitoring System (HUMS), In Transit Visibility (ITV), Asset Tracking (AT), Logs C4I, efficient weapon systems, platform efficiency, fuel/energy efficiency, reliability and maintainability, novel expedient surfacing, food and water from waste, lightweight portable UV water filtration, energy from waste, greater personnel efficiency through improving skills, reduced equipment maintenance and improved reliability, asset visibility including sense and respond Logistics, on-site manufacturing and power generation, in-theatre production and fabrication of equipment, reach back support for conducting in-theatre repairs (i.e. to manufacturer/supplier).

- Influencing the Physical Environment – Capable of influencing the physical environment to produce conditions that are advantageous to Alliance operations:
  - Rationale: The physical environment is a critical factor in all military operations. The ability to influence factors such as the weather may arise in the time horizons of this study. There is open source material that indicates that possible adversaries are conducting research and experiments in this area. This capability could seek to improve conditions for Alliance forces or degrade conditions for enemy forces. It could also be used to support humanitarian and disaster relief (Driver 4).
  - Effectiveness: This Long Term Aspect is concerned with generating short term effects on the local environment not long term global climate. This capability will have to be supported by exact measurements of environmental factors and the development of accurate forecasting models. Capabilities in this area should not result in long term damage to the environment. Trans-border effects must be considered.
  - Potential Areas of Research, Technologies and Systems: Cloud seeding, polymer gels, lasers, ionized particles, solar radiation management and carbon dioxide removal.

- Intelligence Surveillance & Reconnaissance (ISR) Collection Capability – Capable of collecting in a timely manner the imagery, data and information on opponents/neutrals and the environment required to meet Alliance end-user requirements:
  - Rationale: Despite significant advances, timely collection of the imagery, data and information needed to generate the products that end users require continues to pose a challenge that cannot be solved with current technologies (Driver 1). Furthermore, the increasingly complex security environment, future asymmetric threats and the need for the Alliance to take a Comprehensive Approach will pose added challenges for Alliance ISR and its associated collection capabilities. Failure to meet such challenges undermines the Alliance's ability to achieve Information Superiority and consequently Decision Superiority (Driver 2). The enemy is constantly improving its ability to protect itself against our collection efforts; unless new technologies are developed, we could reach a point where we would be unable to extract useful information from our targets (Driver 3). New technologies, especially in the area of improved sensors, also offer the prospect of enhancing the efficiency of currently available capabilities, reducing manpower requirements and the costs associated with the collection of ISR data (Driver 4).
  - Effectiveness: Future Alliance ISR must support an Alliance Comprehensive Approach which involves the combined use of Alliance military, political, economic and civil powers. It also needs to support operations to control and exploit the air, land, sea, space, electromagnetic and cyberspace domains of the battlefield. It must support the full range of NATO missions and

provide strategic, operational and tactical end users (decision makers, planners, operators...) with relevant, accurate and timely products in a form that can be readily assimilated. Such products need to cover the appropriate Political, Military, Economic, Social, Infrastructural, Informational aspects of opponents and neutrals (which may be state or non-state) and other relevant parties. The military component may feature irregular as well as regular forces and the threat they pose may be asymmetric. It must be able to obtain information on factors such as objectives, capabilities, intentions and plans from strategic, operational and tactical perspectives, as well as environmental information. The capability must be able to schedule assets to support operations as required. Alliance ISR and its associated collection capabilities must support the creation of the various tactical and recognized pictures, and ultimately the Common Operational Picture as required by end users. Collection capabilities must be persistent, pervasive and commensurate with the Alliance's global outlook, allowing timely warning of crises. It must be capable of identifying and tracking individuals and moving targets regardless of terrain and clutter.

- Potential Areas of Research, Technologies and Systems: Active and passive sensors, hyper-spectral sensing, unmanned air, ground and underwater vehicles, robotics, meteorological assessment, bio-technology, automated pattern, object and change recognition, Information processing and management, artificial intelligence, cognitive and behavioral sciences, visualization and human/technology interface and modelling and simulation, see through walls/underground, energy systems for deployed sensor networks, very small sensors, renewable/rechargeable power sources.

- Land Engagement Capability − Capable of engaging in land high mobility, high tempo maneuver dominance operations with increased effectiveness and survivability:
  - Rationale: The Alliance will likely continue to conduct expeditionary operations either at the periphery of the Area Of Operations (AOR) or Beyond AOR (BAOR). NATO operations often require rapid tactical deployment over long distances to be successful. Size, weight and range of current armored systems are limiting factors to rapid deployment. Once deployed, future high-tempo NATO operations require long range and agile assets against mobile, asymmetric threats. Legacy systems lack the speed, agility and range required for rapid force projection and battlespace maneuverability (Driver 1). Future land engagement systems must have the survivability, lethality and range to successfully perform future NATO missions. Land engagement capability needs to evolve and advance to remain viable with flexible fighting systems against future NATO threats (Driver 2). Possible adversaries continue to progress counter measures against land systems that have the potential to negate the Alliance ability to conduct operations in some areas (Driver 3).
  - Effectiveness: The focus should be on "effectors" and their integration in vehicles to be used for "land engagement". These systems must be capable of integration into the CIS network. The future land engagement capability needs to be lighter, faster, have higher availability / lower maintenance, have greater operational range and greater engagement effectiveness than legacy systems, and yet be no less survivable. It must allow operation in all terrains including littoral zones to support amphibious operations.
  - Potential Areas of Research, Technologies and Systems: Advanced armors, directed energy weapons, active protection, intelligent munitions technology, smart materials, renewable energy sources, helicopters, hovercrafts, land surface effects, robotics, automation and unmanned systems, electrical drives, energy storage, IR and "electro-optical sight, sensor fusion.

- Space Capability Preservation − Capable of maintaining access to space. [old Capable of preserving space as a sanctuary for NATO assets. No real change to Rationale and Effectiveness]:

- Rationale: Future Alliance operations could occur anywhere around the world. This places more reliance on space based capabilities for communication, geo-positioning, and intelligence collection. Thus, ensuring access and functionality of these capabilities is paramount to successful NATO operations (Driver 1). Evolutions in the strategic environment will see the Alliance undertaking deployments at strategic distance that will require space assets to provide weather observation, intelligence support and communications (Driver 2). Recognizing the reliance of the Alliance on space-based assets, possible adversaries can be expected to improve their capabilities to disrupt these systems (Driver 3). Advances in technologies to protect NATO assets from electromagnetic, laser and physical threats must be developed (Driver 4).
- Effectiveness: The Alliance requires the capability to counter opponent's space denial operations, and hence preserve a space capability/situational awareness for NATO assets, through a combination of defensive measures of space- and ground-based assets and rapid, affordable replacement of space assets. Space Situational Awareness (SSA) will be critical component of this capability. Three principal pillars must be considered: (1) critical understanding and shared awareness of NATO's equities and dependence; (2) identification and monitoring (via SSA) of current and future risks/threats to NATO's utilization of space; and (3) effective accommodation (of risks) and reconstitution of lost space capability.
- Potential Areas of Research, Technologies and Systems: Smart/functional materials, space propulsion, radar absorbing materials/signature reduction technology, advanced armors, electronic counter measures, unmanned space platforms, robotics, rapid launch capability, CubeSats, power systems.

- Support to Insertion and Extraction of Special Operations − Capable of minimizing the detection of deployment and extraction of Special Forces into areas of the operations theatre, whether on land or sea:
  - Rationale: Forces deployed into theatre are susceptible to detection from multiple means. To maintain the element of surprise and minimize the force ratio to ensure a successful operation, it is important to minimize the announcement of the arrival of forces into theatre (also the ability to extract force without the enemy knowing can be beneficial e.g., in reconnaissance missions). Forces covertly inserted into theatre may be more effective (i.e. force multiplier) if complete surprise can be achieved (Driver 1). Increasing use of small teams of Special Forces to conduct operations or provide training and support to indigenous forces will be seen in the coming decades. The ability to covertly bring these forces to bear will be a higher priority (Driver 2). Incorporation of advanced technologies to this capability would significantly reduce the risk of deployment and extraction (Driver 4).
  - Effectiveness: The capability to safely insert and extract forces (company size and larger, i.e. not only Special Forces) into the theatre of operations with a very low probability of detection from visual, aural, or any other electro-magnetic spectrum detection means (e.g. Infrared, Thermal Imaging, Radar, etc.). Delivery of supplies should be self-verified and, if required, should be able of being neutralized (i.e. self-destruct or made not usable).
  - Potential Areas of Research, Technologies and Systems: Electro-magnetic spectrum absorption/diffraction material, active stealth, signature reduction, low noise engines, precision air drop, chameleon camouflage, cloaking systems, sound damping systems, Artificial Intelligence (AI), novel guidance and power systems, lightweight materials, UAVs, autonomous delivery systems, holography, nanotechnology for PAD (controllable porosity, controllable line links).
- Vehicle Mobility, Safety and Survivability − Capable of improving the mobility, safety and survivability of vehicles:

- Rationale: In future operations, the asymmetric threat to vehicles will continue to increase. Therefore, enhanced vehicle survivability, either by reduced signature (i.e. not being detected / targeted) or by protection from direct or indirect threat attack, is required (Driver 1). Continuing advances in vehicle technology and lower costs for systems, such as proximity and collision avoidance for example will make movement more effective in all conditions, providing major improvements in darkness and brown/white out conditions (Driver 4). Vehicles with increased mobility in a range of terrain and climates will enable operations in all threat environments. Vehicles that can self-deploy, carry more, move quicker and are more robust and more easily maintained will reduce the logistics tail. These technologies could be extended to air vehicles (Driver 4).
- Effectiveness: The capability will need to significantly improve the mobility and survivability of vehicles (including combat service support vehicles) used on deployed operations in all environmental conditions. Vehicles will need to be easily deployed by a range of strategic lift capabilities, have increased self-deplorability in-theatre and provide improved survivability against a range of current and future threats without significantly impacting the weight or dimensions of the vehicle. In general, vehicles will be lighter, faster, have longer range and increased payloads. It should enhance the general safety of the vehicles. They must be capable of operating in all terrains, all weather, and may need to be amphibious. Their endurance must be greater and must be more sustainable and more easily maintainable i.e. less breakdowns, interoperable components/parts.
- Potential Areas of Research, Technologies and Systems: Advanced armor technology, multi-spectral stealth technology, active stealth, signature reduction, advanced detection systems (e.g. Smell), Modular / multi-functional assets, autonomous vehicles, multi-fuel capable, hybrid vehicles, alternative propulsion, fuel cells, Smart/Functional Materials, image processing, Health and Usage Monitoring (HUMS), High temperature superconducting cables, active suspension, rubber tracks, proximity detection.

## C.2 EMERGED/EMERGING DISRUPTIVE TECHNOLOGIES

The Emerged/Emerging Disruptive Technologies (E2DTs) are technologies which are either disruptive or deemed to be potentially disruptive, either from the opportunity it presents to the Alliance or from the threat it poses in the hands of potential adversaries. The nature of the disruptive effect may not yet be fully identified:

- Autonomous Intelligent Technologies – Autonomous sensors, systems, and platforms including reducing manning requirements in large systems such as marine platforms (includes self-organizing, adaptive and collaborative behaviors). Integrated ground/air systems of micro-robots and sensors: development of micro-robots and sensors into a full autonomous and cognitive system deployable in extreme conditions during special operations or irregular circumstances. Autonomous Effectors: Link ISR and weapon systems on unmanned platforms to dramatically reduce response times. Would require Commanders intent and Rules of engagement on board.
- Ubiquitous Wireless Networking Technologies – Rapidly evolving commercial/industrial community with dual use potential including internet exploitation. Ad hoc Mobile element is the important part.
- Sensing Technologies for RF and Electro-Optical Applications – Rapid development of conventional and novel sensors including Hyper spectral imaging (a result of over-laying of sensor information at various frequencies) and Tera-Hertz technology.
- Low Cost Night Vision – Including solid state silicon technology at room temperature, primarily threat if obtained by adversaries.

- Smart Materials − Micro / Nano-Engineered / MEMS/ MEOMS. Including 'meta-materials' that have been engineered on a sub-wavelength scale to have highly controllable electromagnetic/ acoustic properties. Materials adaptive to external influence.
- Nano-Robotics − Development of molecular-based nano-elements will enhance ISR capabilities.
- Power Sources and Storage − Bio-generation, fuel cells, fusion, wireless power transmission. Development of 'super-capacitors' and nano-engineered devices will enable increased performance owing to their high ratio of surface area to volume. Novel batteries for unmanned platforms. Novel approach to energy storage. Micro fuel cells. Energy for the Future Soldier Concept.
- Stealth/Counter Stealth Technologies − Modern technologies of large scale integration exhibit the need for new concepts for heat deception. Platform related. Thermal signature management.

## C.3 SCIENCE AND TECHNOLOGY HARD PROBLEMS

The Science and Technology Hard Problems (STHPs) represent problematic gaps in the collective knowledge and technology base of NATO where progress is deemed to be particularly critical to the future of the Alliance:

- Reduce the Burden on the Dismounted Soldier − In current operations the dismounted soldier has to be protected from many types of threats, and as well carry effective weapon and communications systems, that increasingly will need to interact with NEC. This all adds to the weight a soldier has to carry on missions. Substantial reduction is needed not only to undertake missions effectively and in a timely manner, but also to address the morale and recruitment impact of carrying such heavy loads. One could also consider taking a systems approach within the NEC approach to reduce the load on soldiers.
- Improve Air Assets Survivability − Combat operations, search and rescue, and medevac efforts rely on air vehicles which are exceptionally vulnerable to enemy fire. How can we better protect these crucial assets and their crews while retaining the valuable capability they provide?
- Defeat the CBRNE Terrorist Threat − Position dual-use knowledge and technology to prepare, prevent, protect and respond to the CBRNE threat to military forces and civilian societies.
- Deliver Persistent ISR in a Counter Insurgency / Counter Terrorism Context − Improve understanding of the factors shaping effective, integrated ISR for maintaining Situational and Domain Awareness in complex COIN/CT operations (including Maritime Domain Awareness, counter-Piracy operations and underground tunneling) and contribute solutions, so as to contribute to comprehensive objectives.
- Integrate Autonomous Intelligent Systems into the Battle Space − Integration in the battlefield of systems with increased intelligent autonomy including unmanned systems.

# Annex D – LITERATURE RELATED TO SAS-097

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# Annex E − VIRTUAL REALITY AS A SUPPORT FOR AN OPERATOR OF A MOBILE ROBOT

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This annex primarily focuses on description of tools designed to assist operators of remotely controlled mobile robotic systems.

The first part mentions some selected existing mobile robots operator stations with their user interfaces. The main point of this analysis is to show arrangement of control elements and ways how important information about the state of the robot is presented to the operator.

In the second part, some robotic simulation systems are listed, together with their main properties and possible applications. Most of the currently available simulation systems are focused on testing of algorithms of autonomous mobile robot. However, in the field of operator-controlled robotic systems, a simulator can be used already in the design stage to verify for example driving abilities or image perception of the robot surrounding environment according to the proposed placement of cameras. Subsequently, it can also serve as a way how to verify arrangement of controls and the overall usability of the user interface during simulated missions. Another important area is application of simulation systems in operator training without risk of damaging the real robot. After a brief theory of rigid body dynamic simulation, a summary of existing physical engines capable of mobile robot dynamic simulation is given in this chapter of the document. Then more detailed description of the engine Havok follows, with relation to mobile robot dynamics.

The following part of the document deals with application of stereovision for improvement of spatial perception of the mobile robot surroundings by a human operator, using commonly available components; in more detail is described the new head-mounted device Oculus Rift. Proposed is also a possible way how to utilize stereovision with a head-mounted device to create a virtual operator station.

The next chapter presents the simulation system RoboSim developed on the Department of Robotics. The system covers all the aforementioned application fields of simulators of operator-controlled mobile robots. Described is its structure, properties and implementation of kinematics and dynamics simulation. Special attention is given to simulation of images acquired by robot cameras, including advanced rendering quality of the virtual scene. Accurate interpretation of virtual camera images makes it possible to use the simulation system to verify placement and types of cameras during the robot designing stage by examining the resulting view from the robot. The simulation system can easily be used for mobile robots with almost any kinematic structure and also new testing environments can be added.

The final chapter deals with an anti-collision system developed on our department for our mobile robot manipulator arms. It is based on a relatively simple principle of bounding volumes, which makes it very fast, computational power undemanding, reliable and also easy to modify for any kinematic structure of manipulators. This system is being used on all of our existing manipulator arms.

***Keywords:*** *Mobile robot, simulation, dynamical simulation, physical engine, stereoscopic vision, user interface, manipulator, anti-collision system.*

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## E.1 USER INTERFACES

### E.1.1 Examples of Real UI

Operator-controlled mobile robotic systems typically contain an operator's station in the shape of a durable suitcase equipped with all necessary controllers and a monitor displaying pictures from the robot cameras. In some cases the camera images are supplemented with various information about the current state of the robot, in the form of a simple 2D display or even plain text.

As an example we can mention the mobile robot tEODor by German producer Telerob [1]. Its operator's station contains a bottom part with mechanical controllers and a simple LCD display showing the state of the robot; and an upper part with a monitor designated purely for pictures from one or more cameras using PIP (Picture In Picture).

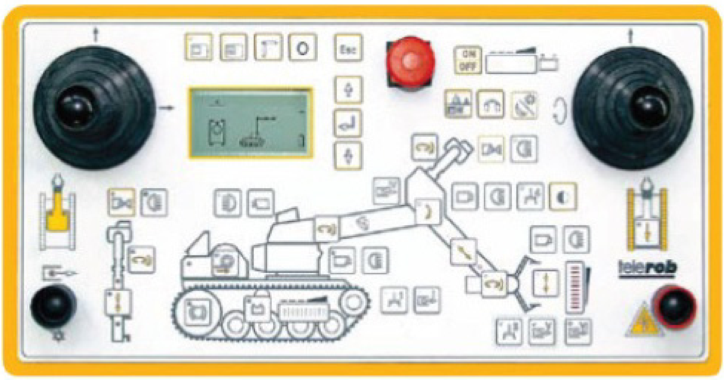


**Figure E-1: Operator Control Unit of the Mobile Robot tEODor and Detail of the Control Panel [1].**

Portable control panel OCU (Operator Control Unit) made by Cybernet and designed primarily for NetMAX robots is capable of displaying various icons and menus for robot functions controlling [2]. The bottom part contains a passive 2D view of the robot; positions of individual joints are represented by diagrams.

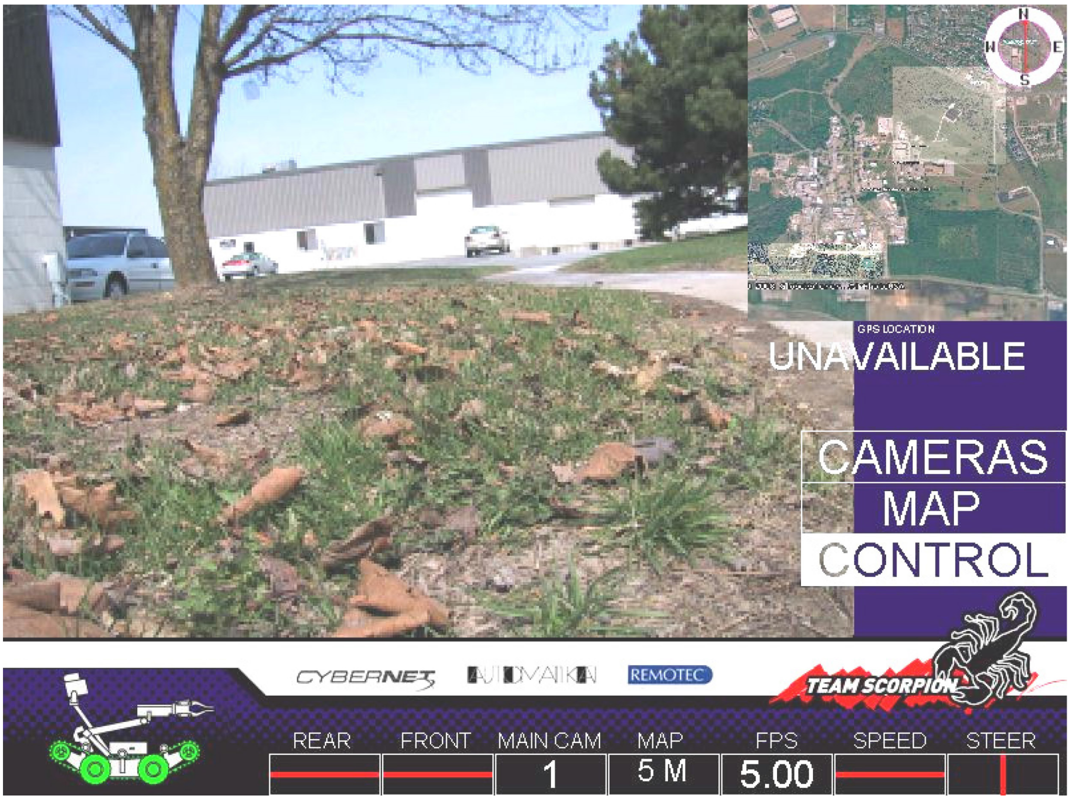


**Figure E-2: Screen of the Cybernet OCU Control Panel.**

The operator's station developed by iRobot [3], intended for their ground mobile robots, shows on the screen besides camera images and simple 2D information about the robot also automatically built map of the surrounding environment. This 2D map is created using a laser scanner during movement of the robot.

**Figure E-3: Operator Control Unit for Mobile Robot iRobot.**

Robot Orpheus [4] developed by the Laboratory of Telepresentation and Robotics at VUT Brno uses a notebook or a PC to interact with the operator and provides him with camera images supplemented with additional data. The operator can also use virtual reality glasses. Images are drawn using Direct3D, but only in 2D.

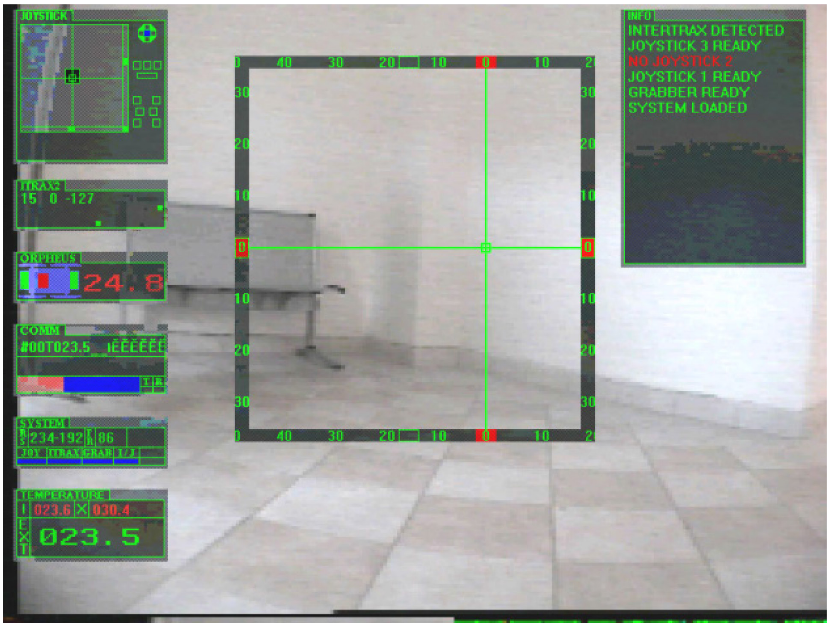


**Figure E-4: Screen of Operator Control Unit of Mobile Robot Orpheus.**

Similar control panels utilize for their mobile robots also for example Mesa Robotics [5] and others [6].

### E.1.2 Research Projects

Application of virtual reality in mobile robotics is being addressed by various research teams. These solutions however are not currently in practical use.

Few teams deal with creation of virtual models of real environment using data acquired by a mobile robot (laser scanners and cameras) – for example Peter Biber and Sven Fleck from Eberhard Karls Universität Tübingen [7]. The resulting 3D model is not built in real time and is not used for robot navigation in any way.

**Figure E-5: 3D Reconstruction of a Real-World Scene Captured by a Mobile Robot [7].**

Curtis W. Nielsen in his dissertation thesis [8] focuses on mobile robot navigation in unknown terrain and suggests application of augmented reality – virtual image mixed with pictures from real cameras. Specifically it is a simplified 3D representation of the mobile robot and map of the real environment created using laser scanner, and a rectangle with pictures from the real camera displayed at the correct place and orientation according to the view of the camera (Figure E-6).

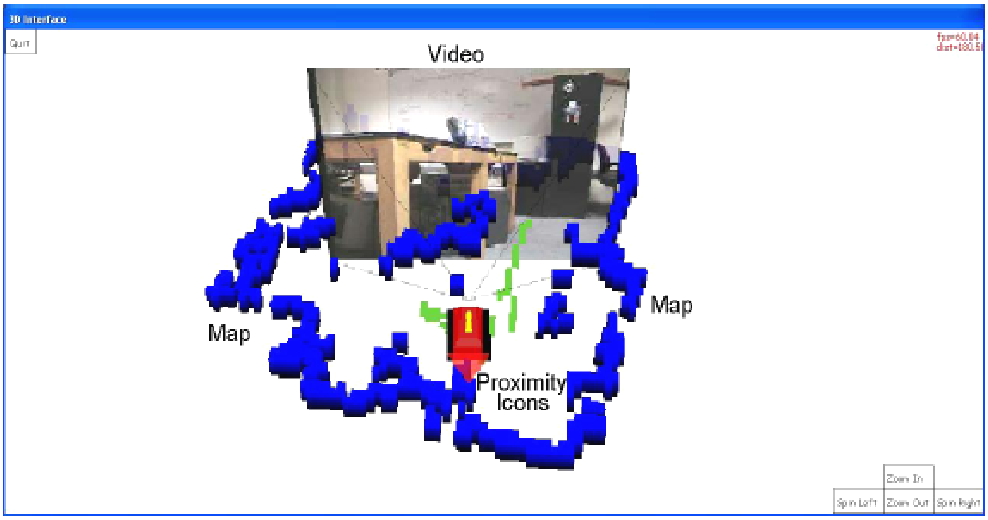


**Figure E-6: Application of Augmented Reality for Mobile Robot Control [8].**

Nielsen tested his solution not only using a real robot, but also in a fully simulated version, where the testing environment was made in gaming graphical engine Unreal Tornament. In this case the map was not acquired by a laser scanner, but prepared in advance according to the testing environment. The tests confirmed benefits of 3D display for easiness of navigation in complicated environment.

In article [9] the Nielsen's technique is further evolved by Space and Naval Warfare Systems Center (research center of the US navy), especially from the point of view of practical application. The 3D display is improved by images of the Earth surface from Google Earth and is implemented into operator control unit MOCU [6].


**Figure E-7: Using Satellite Images for Improved Augmented Reality [9].**

## E.2 PHYSICS ENGINE FOR 3D VIRTUAL SIMULATION

A physics engine is necessary for proper simulation of kinematics and dynamics of objects in a virtual world, including collisions between objects, reactions to external forces, friction, etc.

There already exist multiple mobile robot simulation systems that include some sort of a physics engine. In the next chapter a brief overview of some of them will be presented.

### E.2.1 Overview of Existing Mobile Robot Simulation Systems

#### E.2.1.1 Microsoft Robotics Developer Studio

This probably the most powerful currently available simulation system is developed by Microsoft and exists in both a commercial and non-commercial version [10].


**Figure E-8: Microsoft Robotics Developer Studio.**

The software is especially suited for creation and thorough testing of control algorithms for autonomous systems, but it is possible to also simulate operator-controlled mobile robots. *Robotics Developer Studio* (RDS) works together with *Microsoft Visual Studio*, robot programming is done by programming languages *Visual Basic or Visual C#.* It is also possible to use a special fully visual programming language *Visual Programming Language*, where the whole behavior of a mobile robot is defined by a set of interconnected blocks.

The 3D simulation and visualization module is called *Visual Simulation Environment*. NVIDIA PhysX is used for calculations dynamics of rigid bodies, graphical output is rendered by Direct3D.

### E.2.1.2 Gazebo

System *Gazebo* is a part of the project *Player* [11], which is a relatively large open source project focused on virtual simulation of robots, developed primarily on the University of Southern California. *Player* is responsible for calculations of dynamics simulation and especially for simulation of mobile robot subsystems including sensors and control logic, while *Gazebo* is an extension responsible for 3D vizualization using a 3D graphical engine *OGRE*. The system can be used for simulation of large numbers of robots with mutual interactions.

*Gazebo* is a powerful system with huge flexibility thanks to the possibility to create user modifications, which unfortunately goes against the easiness of usage and installation (the system uses separate modules *Player*, *Gazebo* and uses some external libraries like *OGRE*).

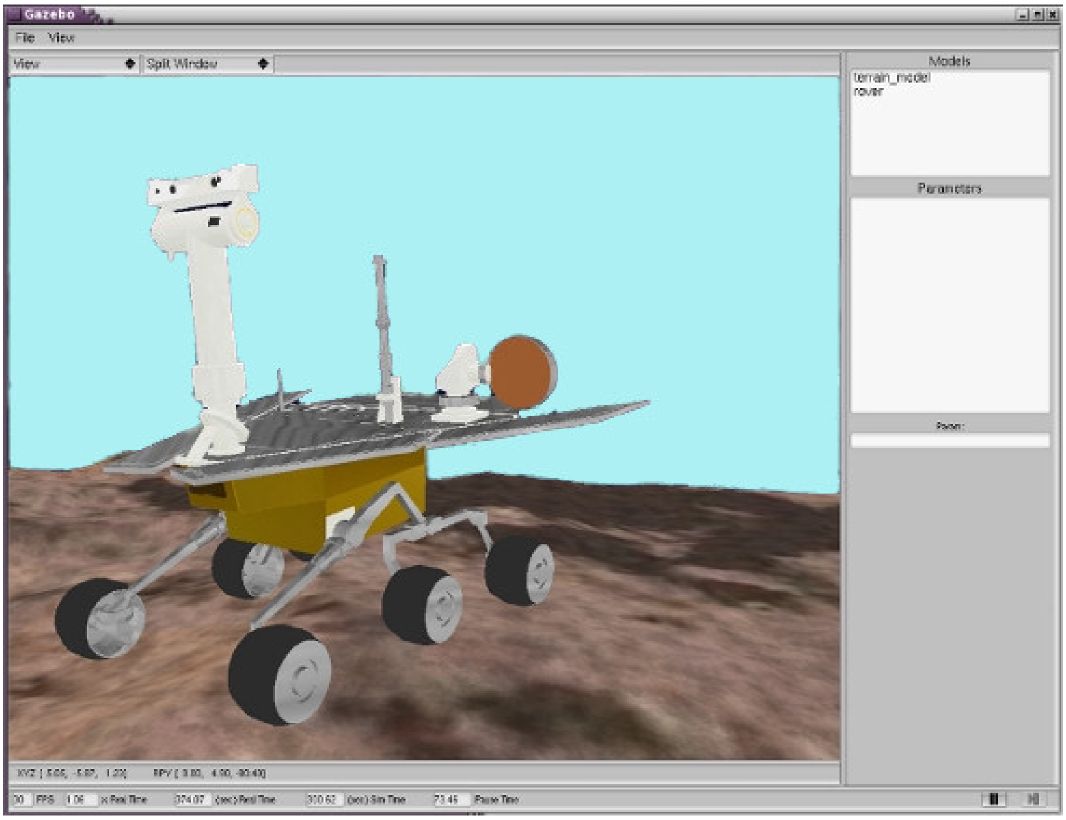


**Figure E-9: Simulation System Gazebo.**

### E.2.1.3 Other Simulation Systems

#### *E.2.1.3.1 Webots*

*Webots* is a system for modelling, control and simulations of mobile robots, used by more than 750 universities and research teams over the world [12]. It is a commercial project; a free version has limited features.

Because of the commercial focus, the system is very complex with great flexibility; the 3D visualisation is on a high level thanks to advanced features like lighting, shadowing, fog, transparency, etc. Control algorithms are programmed using an integrated editor, but it is also possible to use *MATLAB*. *Image Processing Toolbox* of *MATLAB* can also be used to process images from the virtual cameras of *Webots*.

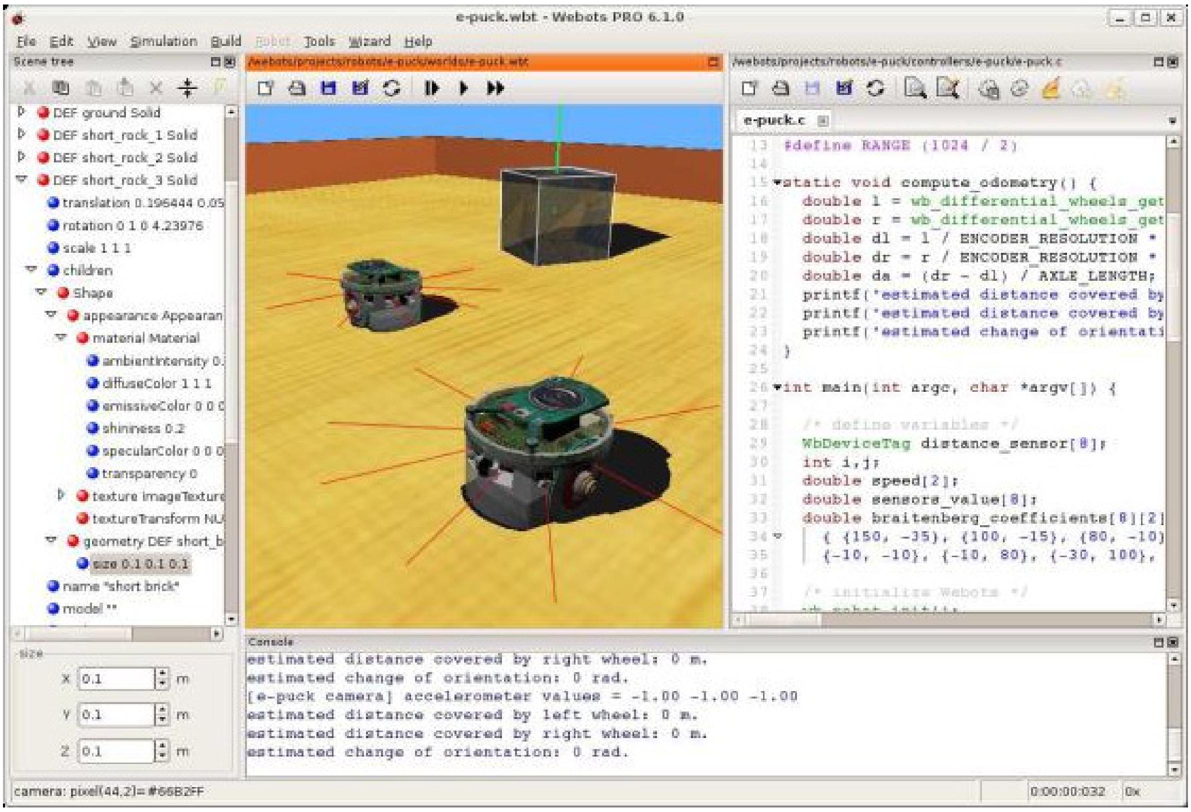


**Figure E-10: User Interface of Webots.**

### *E.2.1.3.2 Ipzrobots*

Project *lpzrobots* of the Leipzig University is in fact a collection of algorithms and tools developed by university researchers engaged in robotics [13]. One of the modules is *ode_robots* – a 3D simulator of robots using the physics engine *ODE (Open Dynamics Engine)* and graphics engine *OSG (OpenSceneGraph)*. This system by its own functions only as a software library and to create a whole simulation it is necessary to code a user application which links this library.

### *E.2.1.3.3 V-REP*

*V-REP* (*Virtual Robot Experimentation Platform*) is a commercial 3D simulator or industrial and service robots with very user-friendly user interface [14], available for a fee or in a free student version.

Simulation is driven by user scripts, which can run simultaneously. Dynamics calculations and done by the library *Bullet* or *ODE*, including inverse kinematics for any mechanism.

### *E.2.1.3.4 Other*

Some of the less important simulation projects include:

- *OpenSim* [15] – a 3D simulation system utilising *OpenGL* together with *OSG* (*OpenSceneGraph*) for 3D graphics rendering and *ODE* (*Open Dynamics Engine*) for dynamics simulation. The project was suspended in 2006.
- *Simbad* [16] – a simple simulation system in Java, designed especially for scientific and educational purposes and as an auxiliary tool for verification of artificial intelligence algorithms and autonomous behavior of mobile robots.

- *SimRobot* [17] – simulation software developed on the Universität Bremen, used by this university for robotics research. The source code is freely available.
- *Vecna Simulator* [18] – a commercial simulation SW for the robot *BEAR* (*Battlefield Extraction-Assist Robot*) from Vecna Robotics.
- *EyeSim* [19] – system for simulation of robots based on the control system *EyeBot*.
- *UchilSim* [20] – simulator of 4-legged robots for the *RoboCup* competition.

### E.2.2 Dynamical Simulation

Almost any kind of simulation requires the following:

- Physical process that will be simulated (this can be a weather system, mechanical system, communication system, etc.).
- Model of the process – the process must be modelled with equations.
- Simulation algorithm – a method to solve the equations, to find out how the system changes over time.
- Computer program – a software written to implement the algorithm.

Dynamical simulation, in computational physics, is the simulation of systems of objects that are free to move, usually in three dimensions according to Newton's laws of dynamics, or approximations thereto [21]. Here is physical process mentioned above is a mechanical system with its mechanical behavior.

#### E.2.2.1 Rigid Bodies

When a force is applied to an object (body) in reality, the object reacts by both deformation and change of velocity (if possible). The deformation however is mostly negligibly small compared to the motion and it is also very difficult to model, so typically deformation is ignored and physic engines works with idealized rigid bodies. A rigid body is defined as a body in which the distance of any two points remains constant in time regardless of any external forces.

Moreover, the mass of a rigid body in most physics engines is considered constant over time and also evenly distributed over the whole body.

#### E.2.2.2 Commonly Used Models

The simplest model that can describe behavior of mechanical system is *Particle model* [21]. It governs the motion of infinitely small objects with finite mass, called particles. Newton's Second law can be applied to these particles, because each of them has its mass and acceleration and force acting on it. This model is very simple and fast, but not sufficient for most rigid body simulations because it does not account for the rotational motion of bodies.

To account for rotational energy and momentum, the second model called *Inertial model* can be used [21]. It must be described how force is applied to the object using a moment, and the mass distribution of the object must be described using an inertia tensor. Compared to the previous model (Particle model) this model is dealing not only with force, acceleration and mass (and the translational movement in general), but also with moment (torque), angular acceleration and inertia moments (rotational movement). This allows a complex simulation of the rigid body behavior and requires the engine to solve a set of 6 ordinary differential equations at every simulation step.

The Inertial model is typically more complex than really needed for a simulation. It can be made faster for calculations when modified into so called *Euler model* [21]. In this model the inertia tensor is simplified into a set of Euler's equations. This model can be further optimised by applying some symmetry on the inertia tensor, which works for most typical bodies, and makes a very big difference in the simulation speed, which is very good for real-time simulations.

#### E.2.2.3 Components of a Physics Simulation

Physics engines typically define the following types of elements for the simulation:

- Rigid bodies – solid objects defined by shape and mass properties that react to external forces and collisions by appropriate change of movement.
- Low-level constraints – ways how to limit movement of a particular body, for example by constraining one of its axes to stay in one orientation, by allowing a particular point of a body by moving only on a line, etc.
- Higher-level constraints or joints – usually created between two bodies to limit their mutual movement, used to simulate real world mechanical devices like hinges, spherical joints, cylindrical joints, prismatic joints, but also springs, dampers, etc.
- Contacts and collisions – interaction between bodies driven by their shape, made to prevent two bodies from penetrating and also to achieve proper reaction to contact of bodies (bouncing, etc.).
- Friction – very important feature for a believable contact simulation where a body slides on a surface of another body.
- Actions or controllers – a way how to apply external forces to bodies in the simulation to simulate for example drives, wind, etc.

#### E.2.2.4 Simulation Flow

A typical physics engine simulation flow is shown on the next diagram (Figure E-11). The simulation must be set up with description of the mechanical system and then each simulation step the engine calculates the new state of the system based on the previous state. For this calculation, the engine also needs additional input (external forces acting on the system) and also the time step value (how much time passed from the previous step) [22].

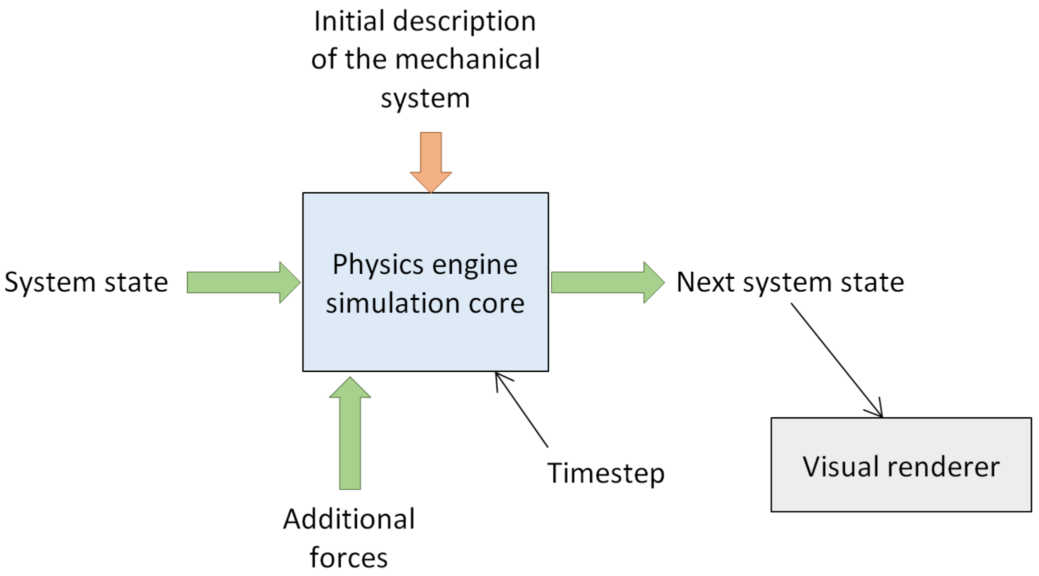


**Figure E-11: Physical Simulation Flow Diagram.**

The resulting new system state contains also positions and orientations of all simulated bodies and can be used to show them visually by rendering on the screen (or making graphs, etc.). The whole new system state including also accelerations and velocities of bodies is then again passed to the engine as the previous state and another simulation step can be executed.

The engine has three basic tasks to perform. Having set up the initial conditions for a given scene, begin the main simulation loop which steps through some task, updates the graphics and then repeats [23].

1) Determine which objects are overlapping or about to. This stage is usually divided into two or three sections.
2) Solve all forces acting on the objects. Some of these forces might occur as a result of collision detection or as a result of input from outside the simulation (the gravitational pull of the environment, the driving force of some engines, etc.).
3) Having gathered up all the forces, the simulation is advanced by the time step size and the new state of the objects (position, orientation, velocity, acceleration, etc.) is calculated for this time in the future. This information is then used to update the corresponding display representations of the objects.

### E.2.2.5 Iterations

With a physical simulation each result depends completely on the previous simulation step [23]. If in one step a very inaccurate result is produced, then the next step is likely to be even more inaccurate, resulting in a spiral of decreasing accuracy until the simulation becomes unstable or simply “explodes”. Unfortunately it is not possible to simply stop mid step, reduce the number of objects or ignore collisions to compensate for a reduction in the available CPU resources – each scene must be simulated stably even with the lowest expected CPU bandwidth.

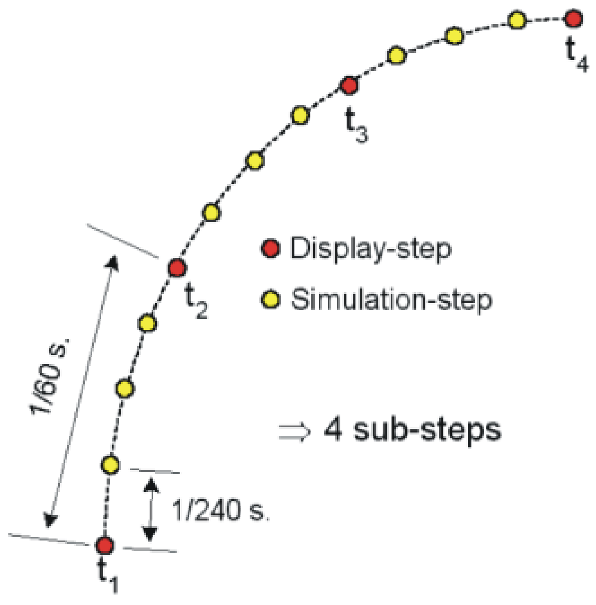


**Figure E-12: Substeps (Iterations) in Physical Simulation.**

Assume we need to update the geometry in the game so it can be displayed once every $1/60^{th}$ of a second. For simulation accuracy and stability, we might still need to do more simulation steps every second. To achieve this, some physics engines allow specifying the number of “mini-steps” (iterations) to perform.

Iteration is an internal physics simulation step that does not interact with the 3D display. The iteration parameter specifies the number of steps the physics engine takes before updating the 3D display. This gives control over the granularity of the physics simulation independent of the display update frequency.

In Figure E-12, the display is updated at 1/60$^{th}$ of a second, but the physics simulation will be stepped at intervals of 1/240$^{th}$ of a second. For every 4 iterations, the display is updated only once. By setting the number of iterations the accuracy of the physical simulation is controlled independent of the display.

#### E.2.2.6 Collision Detection

Collision detection is the process of detecting intersection of two objects. The information whether two objects have collided is not sufficient by its own for a physical simulation, so it is also necessary to properly react to a collision by calculating time of impact, the point of impact (which parts of the bodies collided) and to deal with a response to the collision. The whole process is extremely complicated, so physics engines running in real time implement a lot of optimizations, involving also some simplifications.

There are multiple ways how a physical engine can react to a collision. Commonly, engines use the softness of the material to calculate a force which is then applied to the objects in the following time steps and will resolve the collision.

The time of collision can be found by linear interpolation, which in fact splits the simulation timestep to much lower intervals for better precision. Some engines use the time of impact to roll back the simulation and thread the collision before it occurs. Other engines simply apply forces to the object and the collision will be solved afterwards.

A simple way of collision detection would be to check every object against every other object to see if the pair intersects. This would be extremely inefficient for larger number of objects, especially for objects with complex geometry (shape).

The most common optimization is a quick preliminary test using some bounding volume of the objects, usually *Axis-Aligned Bounding Boxes* (*AABB*) [24]. Intersection between a pair of AABBs is mathematically very easy and fast and if two AABBs are not intersecting, it is not necessary to perform more detailed collision tests on the actual shapes of the objects.

Some physics engines (for example Havok) split collision tests into even more steps – broadphase, midphase and narrowphase. The first phase is very coarse and uses only *AABB*, the second phase is performed only on objects with intersecting *AABB* and is done on *Oriented Bounding Boxes* (*OBB*) [24] and the last phase is executed only on objects with intersecting *OBB* and uses the actual collision shapes of the objects.

#### E.2.2.7 Deactivation of Bodies

One of the major factors determining the CPU load in a physical simulation is the number of objects that are active or moving i.e. being physically simulated [23]. In a typical scene a large number of objects do not actually move at all and (in theory) can be ignored until interacted with. Temporarily removing stationary objects from the simulation remains the best single way to reduce the CPU load. Energy management is concerned with identifying objects in a scene that are not doing very much and removing these from the physical simulation (known as deactivating or turning off the object) until such time as they begin to move again.

The engine must decide, when should an object be deactivated and when should it be activated again. Usually objects are deactivated when they have not moved much recently and are reactivated when hit by other moving objects.

#### E.2.2.8 Friction

A friction force is one that resists the relative motion or tendency to such motion of two bodies in contact, that quantity which attempts to prevent surfaces sliding off each other [23]. Friction is the key factor in allowing stable stacking (i.e. stacks or piles of objects that come to rest, held in place by the friction at the points of contact). During all collisions a certain amount of energy is lost due to friction (and mostly converted to heat in the real world).

Friction manifests itself in two forms, *static* and *dynamic*. Static friction operates when objects are at rest; it attempts to prevent objects moving or sliding. If a force is applied to an object large enough to overcome static friction, the object begins to move/slide. At this point dynamic friction kicks in and, so long as the object is in contact with another object or surface, dynamic friction attempts to slow the object down.

Sometimes a simulation must be set with non-realistically high friction coefficients to emulate higher friction of surfaces with rugged surfaces. For example, a mobile robot wheel with tyres shown on Figure E-13 would be extremely inefficient is the real complicated shape of the wheel was set as the collision shape for simulation. But if a cylinder is used instead, then it is necessary to set a very high friction to get a believable behavior.

**Figure E-13: Tire Pattern Problematic for Collision Detection.**

### E.2.3 Overview of Existing Physics Engines

For a believable and accurate behavior and mutual interaction of movable bodies in a virtual scene it is necessary to make calculations of their accelerations, velocities and positions according to basic Newton laws of dynamics and also to properly detect their collisions and react to them. With the exception of simple basic shapes this task is rather complex in 3D space and thus it is advantageous to use some existing robust physics engine.

The most important requirement on the physics engine is the ability to compute dynamics and collisions of rigid bodies in real time. This disqualifies a lot of systems performing very accurate calculations, but in a very low speed. A compromise is inevitable here of course, so a physics engine capable of complex calculations in real time cannot give absolutely accurate results, because it must do a lot of simplifications [25]. The following chapters will list some of the most important physics engines.

#### E.2.3.1 ODE (Open Dynamics Engine)

*ODE* is an open source, high performance library for simulating rigid body dynamics. It is fully featured, stable, mature and platform independent with an easy to use C/C++ API. It has advanced joint types and integrated collision detection with friction. *ODE* is useful for simulating vehicles, objects in virtual reality environments and virtual creatures. It is currently used in many computer games, 3D authoring tools and simulation tools [26].

*ODE* is a popular choice for robotics simulation applications, with scenarios such as mobile robot locomotion and simple grasping. *ODE* has some drawbacks in this field, for example the method of approximating friction and poor support for joint-damping.

#### E.2.3.2 Bullet

*Bullet* is a physics engine which simulates collision detection, rigid body dynamics and also soft bodies dynamics (for example cloth). *Bullet* has been used in video games as well as for visual effects in movies [27].

#### E.2.3.3 PhysX

This system was originally developed by *Ageia* for a special HW coprocessor designed exclusively for physics calculations. Later the company was acquired by *Nvidia* and the system was modified to be able to utilise the *GPU* of *GeForce* graphics cards made by *Nvidia* to accelerate also physics computations.

*PhysX* can simulate rigid and flexible bodies (including clothes), character behavior, vehicles, liquids, etc. It is free for all users [28].

#### E.2.3.4 Havok

*Havok* is probably the most well-known physics engine. It was commercial for many years, but after acquisition by *Intel*, *Havok* was offered for free, except for commercial non-gaming applications and gaming projects with a very high budget. Thanks to the long commercial development, Havok is a very mature and highly optimised engine with exceptional performance even without HW acceleration. Havok also offers modules for animation, artificial intelligence, destroyable bodies or inverse kinematics [29].

*Havok* is very good also for mobile robot simulations, mainly because of its capability of advanced wheel joint simulations, but also for the good documentation and high speed and accuracy of calculations.

### E.2.4 Practical Use of the Havok Physic Engine

The typical sequence of operations necessary for rigid bodies' dynamics using *Havok* is:

1) System initialization.
2) Creation and setup of the physical world (or multiple worlds).
3) Definition of the desired number of rigid bodies and their assignment to a physical world.
4) Definition of the desired joints, constraints, actions and their assignment to a physical world.
5) In each frame (step) of the application:
   a) Advancement of the simulation by the corresponding delta time.
   b) Update of the graphical display to represent the new positions of bodies in the world.

#### E.2.4.1 System Initialization

The necessary preliminary initialization performs especially allocations of some memory buffers for calculations and creation of calculation threads according to available CPUs. The process is described in the *Havok* documentation.

#### E.2.4.2 Physical World Setup

To make a physical world it is necessary to create an instance of the *Havok* world object (hkpWorld) and set some of its parameters, for example:

- Gravity vector;
- Size of the world bounding cube;
- Integrator configuration (number of iterations, softness, stability);
- Collision tolerance; and
- Way of deactivation of bodies with very low kinetic energy.

#### E.2.4.3 Calculation Steps

All calculations are made in discrete steps when the corresponding stepDeltaTime() method is called, with a parameter representing the delta time (time that passed since the previous step). *Havok* can internally divide the steps to sub-intervals, for example if some movement is too fast. The delta time should be rather stable; ideal is the value from 0.02 to 0.01 seconds (or 50 to 100 Hz).

#### E.2.4.4 Rigid Bodies

A rigid body in *Havok* is represented by an instance of hkpRigidBody class, which includes a complex definition of physical properties of the body, especially:

- Weight, center of mass position, moments of inertia;
- Body type;
- Shape for collision detection;
- Restitution (loss of energy during a bounce);
- Friction; and
- Linear and angular damping (loss of energy during movement without external forces).

##### *E.2.4.4.1 Weight Parameters*

Weight, center of mass and moments of inertia can be specified directly by numbers, or it is possible to use a complex auxiliary class `hkpInertiaTensorComputer`. This class computes weight parameters of a box, sphere, cylinder or even a general shape, by a given weight and dimensions.

##### *E.2.4.4.2 Body Type*

All bodies in the physical world are subject of collision detection (unless a body has collisions disabled explicitly). From the simulation point of view there are different types of bodies – a dynamic body (full kinematics and dynamics simulation), a static body (no movement, weight parameters are not used for anything) and an animated body (similar to static, but the body can be moved by directly specifying its position of velocity, with no real kinematics or dynamics simulation). Static bodies are especially useful to create background motionless environment (ground, etc.).

*E.2.4.4.3 Shape for Collision Detection*

Shape of a body is used for collision detection and proper reaction to collisions. It is not directly linked to mass properties, although for a believable simulation it is of course most of the time better to keep the shape and mass properties consistent. The shape is stored in an instance of the class `hkpShape`, which is a member variable of `hkpRigidBody`.

*E.2.4.4.4 Shape Optimization*

Collision calculation is an operation with extremely increasing complexity for complicated shapes. It is thus advantageous to define collision shapes as simple as possible, while preserving the required accuracy. Usually a different shape is used for visual representation (rendered triangular mesh with a lot of detail) and for collisions.

*E.2.4.4.5 Basic Shapes*

*Havok* offers some basic shapes with very fast calculations. These shapes include especially (ordered from the fastest): sphere (`hkpSphereShape`), capsule (`hkpCapsuleShape`), box (`hkpBoxShape`) and cylinder (`hkpCylinderShape`).

For better calculations of boxes and cylinders, Havok uses so called *shell*, which is a numeric value used to increase the dimensions of the shape. As a result, the sharp edges of box and cylinder are rounded. Adding a collision radius to a shape can improve performance. Convex-convex collision detection algorithms are fast when shapes are not interpenetrating, but slower when they are. Adding a radius makes it less likely that the shapes themselves will interpenetrate, thus reducing the likelihood of the "slow" algorithm being used. The shell is thus faster in situations where there is a risk of shapes interpenetrating – for instance, when an object is settling or sliding on a surface, when there is a stack of objects, or when many objects are jostling together.

*E.2.4.4.6 Compound Shapes*

Basic shapes can be combined to create more complex ones, while keeping good calculation efficiency. The first simplified representation of a chair on Figure E-14 consists of two boxes and 4 capsules; the second one uses only two boxes.

**Figure E-14: Detailed Visual Model and Two Possible Versions of Simplified Collision Shapes.**

*Havok* provides compound shapes using the `hkpListShape` class, which groups arbitrary number of shape instances. A basic shape is always defined in the coordinate system origin, so to position it properly inside the compound shape, it can be wrapped in a `hkpConvexTransformShape` (any transformation) or `hkpConvexTranslateShape` (translation only, much faster) object.

##### *E.2.4.4.7 Complex Shapes*

Sometimes it is not possible to properly represent a body using only basic shapes and it is necessary to specify a general complex shape. For this cases *Havok* provides a variety of solutions, from the simple `hkpConvexVerticesShape` (an array of verticles used by *Havok* to generate a convex envelope) to a very complicated `hkpMoppBvTreeShape`.

The later mentioned shape uses the *MOPP* technology (*Memory Optimized Partial Polytope*) developed by *Havok* and it allows efficient collision detection even for very complex shapes specified by a general triangular mesh. *Havok* internally generates a tree hierarchy of axis-aligned bounding boxes for subparts of the triangular mesh and uses them for preliminary quick elimination of most of the triangles for subsequent collision calculation.

**Figure E-15: Difference Between a Visual Representation of a Scene and Simplified Collision Models.**

##### *E.2.4.4.8 Collision Tolerance*

*Havok* has a global collision tolerance for the entire physical world, specified in world units. By default, the world has a collision tolerance of 0.1. A collision tolerance is an artificial buffer layer which tells the system that at some small distance two objects are “nearly” colliding.

Having a non-zero collision tolerance helps with two performance-related issues. Firstly, it is useful for the system to pick up potential collisions before they actually happen - when the distance between the objects is still greater than zero. For fast-moving objects, this allows the collision solver to prevent interpenetration as early as possible.

It is also useful for the system to maintain collision information even while the objects are slightly separated. For instance, when an object is sliding across or settling on another object, this allows the system to maintain a manifold (a kind of 2D map of the collision) rather than having to create new contact points in every simulation step.

#### E.2.4.5 Constraints and Actions

*Constraints* can be used to restrict movement between two bodies. Constraints can be defined in world or local coordinate systems. To use the world coordinate system, both bodies must be in their proper positions already when creating the constraint. When using the local coordinate system, a pivot point and constraint axis is defined separately for each body (in its local system) and when the simulation starts, Havok tries to “assemble” the constraint.

*Havok* provide a quite simple but also very powerful system for definition of new arbitrary complex constraints; but there are also of course some pre-made basic constraints: *point-to-point*, *stiff spring*, *hinge* (one rotation), *limited hinge* (one rotation with limited range), *wheel*, *pulley*, *prismatic* (translation), *point-to-path* and others.

*Actions* are an additional way how to control body behavior. Similarly to constraints, also actions can be defined from scratch directly for a specific situation, or pre-defined actions can be used (for example a spring or a motor).

There is also another way how to control body movement – by direct call of the corresponding methods of the `hkpRigidBody` object it is possible to for example:

- Change the actual position – can cause instability of the simulation if two bodies are interpenetrating after this forced position change.
- Change the actual velocity – a forced immediate change of velocity without any relation to acceleration or inertia.
- Apply a linear or rotational impulse – act of force concentrated into one simulation step, resulting in an immediate change of velocity (less unnatural than the previous change).
- Apply a force or torque – resulting in a natural change of acceleration.

### E.2.5 Using *Havok* to Simulate Mobile Robots

A complex simulation of Newton physics of a mobile robot is provided by proper use of the *Havok* engine. The mobile robot must be divided into separate bodies (at least a chassis and individual wheels, leg segments, arm segments etc.) and each of these bodies must be fully described as a *Havok* rigid body with mass properties, collision shapes etc. These entities (bodies) must also be connected using constrains and also some actions must be added (drives).

For interaction with environment, also a model of a ground and all obstacles in the scene must be added. When this complex simulation world is defined, the simulation can be executed.

#### E.2.5.1 Constraints and Actions

Wheeled mobile robots are very common and are also the easiest to simulate. The best shape for wheel collision detection is in most cases cylinder. To create a joint between the chassis and the wheel, one can use the *hinge constraint* (rotational joint with a fixed axis of rotation) or the special *wheel constraint* [23].

As the name of the later constraint suggest, it is designed especially for simulation of wheels. The constraint allows three degrees of freedom – two rotations and one translation. The first degree of freedom is the rotation around the wheel axle (usually horizontally oriented); the second rotation is around an arbitrary axis (usually vertical or almost vertical) and is used for steering. The translational degree of freedom involves another axis (again usually vertical or almost vertical) and acts as suspension (springing).

Simulation of springing is also part of the wheel constraint and is defined by the spring stiffness, damping coefficient and mechanical limits of movement along the translational axis. For robots with rigid suspension this function can be disabled.

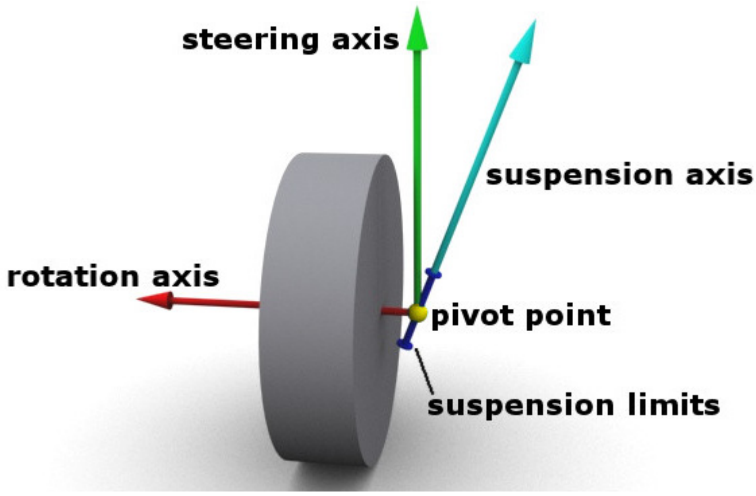


**Figure E-16: Complex Constraint for Wheel Simulation.**

### E.2.5.2 Actions

Mobile robots typically use DC motors. To apply it in a simulation, a torque should be applied to a wheel according to the DC motor characteristics, multiplied by the overall ratio between the wheel and drive. A typical DC motor graph [14] is displayed on Figure E-17: and can be described as:

$$\tau = \tau_s \left(1 - \frac{\omega}{\omega_n}\right) \tag{1}$$

where $\tau$ is the DC motor torque, , $\omega$ is angular velocity and $\tau_s$, $\omega_n$ are motor parameters (stall torque and no-load speed). In every simulation step the real wheel rotational velocity is determined and the corresponding torque is calculated and applied on the wheel.

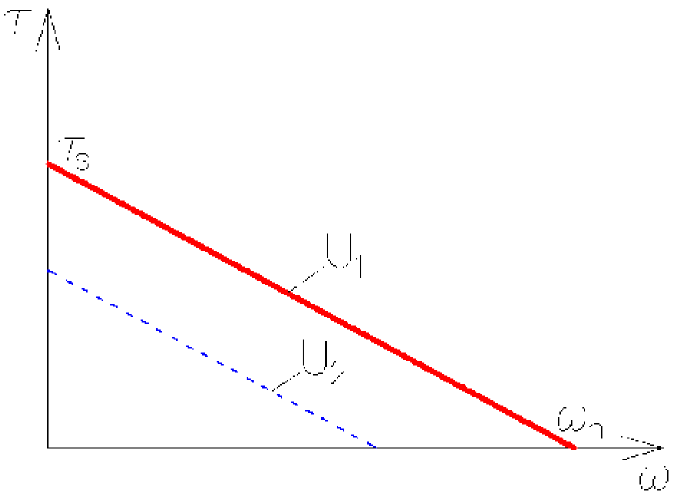

**Figure E-17: DC Motor Characteristic Curve.**

The rotation velocity is controlled similarly to reality – by voltage change (usually using PWM). Change of voltage modifies the motor curve (see Figure E-17).

# E.3 STEREOSCOPIC VISION

Stereoscopy (3D imaging) is a technique for creating the illusion of depth in an image by using two slightly shifter views of the same scene, each of them presented separately to the left and right eye of the view. Brain combines these images and gives the perception of 3D depth.

For real-time stereoscopic view from a mobile robot, two cameras are needed on the robot. Similarly in a simulated scene, two virtual cameras must be used.

## E.3.1 Arrangement of a Stereoscopic View

There are many ways how to show a stereoscopic view to a human user – usually by the means of various types of 3D glasses and head-mounted devices, or in combination with a special monitor.

### E.3.1.1 Anaglyph

Anaglyph is the stereoscopic 3D effect achieved by means of encoding each eye's image using filters of different (usually chromatically opposite) colors, for example red and cyan. Anaglyph 3D images contain two differently filtered colored images, one for each eye. When viewed through the color-coded glasses, each of the two images reaches the eye it is intended for, revealing an integrated stereoscopic image. The visual cortex of the brain fuses this into perception of a three-dimensional scene or composition [30].

A huge advantage of this method is that it does not require any additional hardware except for anaglyph glasses, which in their simplest paper form are extremely cheap (around 1 €).

There are multiple possible color combinations for anaglyph glasses, while the most widespread are: *red-blue*, *green-magenta* and *red-cyan*. The latter two provides better colors in the final image; using the red-blue version it is very had to watch images containing red colors.

**Figure E-18: Most Common Types of Anaglyph Glasses.**

Drawing anaglyph 3D image in real-time (for a mobile robot operator, for example) consists of mixing images from two cameras with a corresponding software color filter applied to each of them. For example, the image for an eye wearing red filter contains only the red channel; image for an eye wearing cyan filter contains only the green and blue channels etc. These two images are then added together and displayed on the same position.

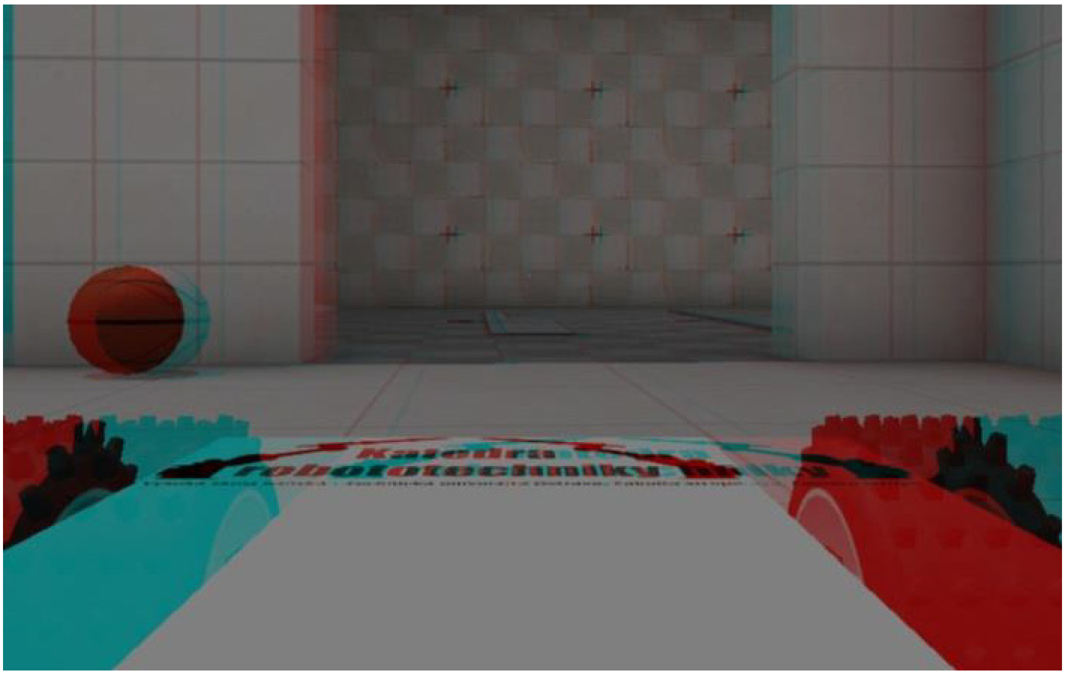

**Figure E-19: Stereoscopic View from a Mobile Robot Display Using Anaglyph "Red-Cyan".**

### E.3.1.2 Head-Mounted Displays

Other methods of displaying stereoscopic image require a special electronic device – *Head-Mounted Display* (*HMD*) [31]. The user typically wears a helmet or glasses with two small LCD or OLED displays with magnifying lenses, one for each eye. Head-mounted displays may also be coupled with head-tracking devices, allowing the user to "look around" the virtual world by moving their head, eliminating the need for a separate controller. Performing this update quickly enough to avoid inducing nausea in the user requires a great amount of computer image processing. If six axis position sensing (direction and position) is used, then wearer may move about within the limitations of the equipment used.

The various HMD devices differ in the way how two separate images (one for each eye) are sent to them. The most common methods are:

- Line interlacing – both images are displayed on top of each other; odd lines for the left eye and even lines for the right eye. The HMD chip then properly splits the images and displays them in front of the corresponding eyes. The HMD can be connected to a computer only via a single video cable (HDMI, DVI, VGA, etc., but the resolution of the final image is halved vertically.
- Two separate inputs – some HMD have two separate inputs for both screens. Such HMD must be connected to a PC using two cables, requires a video card with two outputs and also the application must render to two "monitors".
- Image alternation – rendered is the image for left eye, then for the right eye, then left again and so on. Images must be rendered in a fixed frequency using vertical synchronization. The resulting combined image has only half the frequency. This method is used also in many active shutter glasses: the user wears glasses that allow seeing only with one eye at a time and watches a monitor screen that shows always just the image for that particular eye.
- Widened image – images for both eyes are displayed next to each other on one "screen" with twice the width. For images with 4:3 aspect ratio, the combined picture has 8:3 ratio.

### E.3.2 Depth Position and Parallax

Human eyes, when watching a particular point in 3D space, rotate using muscles towards the point to look at it directly. This may be useful to emulate also when creating a stereovision perception by cameras and a HMD device, depending on the actual situation. The term "camera" here can mean either a physical camera (when creating stereovision view of a real world scene, in real-time or as a pre-recorded movie), or a virtual mathematical camera (when creating stereovision view of a virtual world scene in a virtual or augmented reality).

Most stereoscopic methods create an illusion of a screen that displays 3D world. In some cases, this screen is really an existing physical screen (3D cinema screen or computer screen watched through glasses); sometimes this screen is just perceived by the user and appears somewhere in front of him (the effect of some HMD devices). Objects that appear to be directly on this screen have zero parallax, objects in front of the screen have a negative parallax (and exist in "cinema space") and objects behind the screen have positive parallax (and exist in screen space). The distance of zero parallax can be altered my simulating of emulating the mentioned behavior of human eyes in two ways [32], as described in the following chapters.

#### E.3.2.1 Toeing-In Cameras

Toeing in is essentially angling (rotating) the cameras inward the way the human eyes converge. When human eyes converge on something, the brain fuses the two image fields at that point and sees a single image (based on overlapping left and right images). The rotation of the cameras toward each other produces an axial intersection point as well, and the plane of intersection determines the zero parallax distance. Objects closer to the camera than where the lenses axes intersect will be in "cinema space" while objects behind that intersection point will lie in screen space [32].

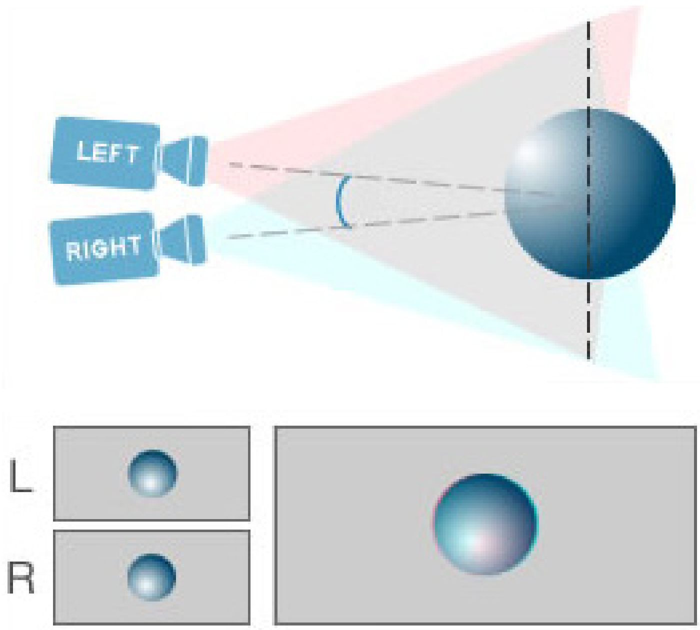


**Figure E-20: Principle of Camera Toe-In – Camera Configuration and Corresponding Images.**

For dynamic toeing-in on a given point of interest, the angle of rotation can be found by for example measuring the distance to this point of interest. This is very easy in virtual worlds, but harder in real world (some distance sensor may be needed). The angle depends on the inter-camera distance $d_c$ and the measured distance from the point of interest $d_i$:

$$\varphi_c = \operatorname{atan}\frac{d_e}{2d_t} \qquad (2)$$

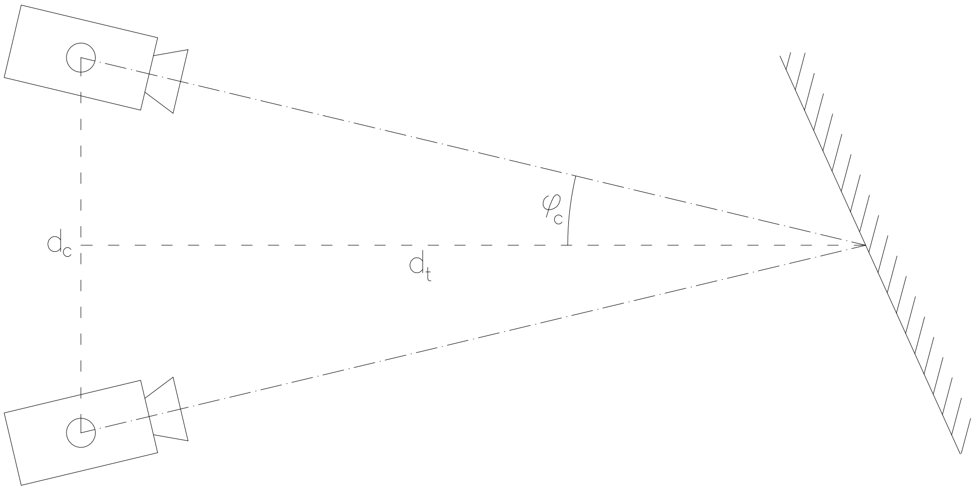


Figure E-21: Angle of Camera Toe-In.

### E.3.2.2 Horizontal Image Translation (HIT)

Rotating the cameras (toeing in) can be problematic with physical cameras, especially if the angle is supposed to be dynamically changing. The HIT method does not require any rotation, the cameras are set parallel to one another rather than rotated inwards. In this case, the camera lenses axes never intersect, so if we just stacked these images on top of each other, we end up with everything in “cinema space” (except for object at stereo infinity which would be on the screen plane). This is usually not acceptable, so it is necessary to horizontally shift the left and right images – a process called *Horizontal Image Translation* (*HIT*). The point where the two images overlap becomes the zero parallax. The problem with this method is that parts of the frames are useless, because they contain images only for one eye. These parts must be removed by either zooming in or matting off the edges, but some image resolution is lost [32].

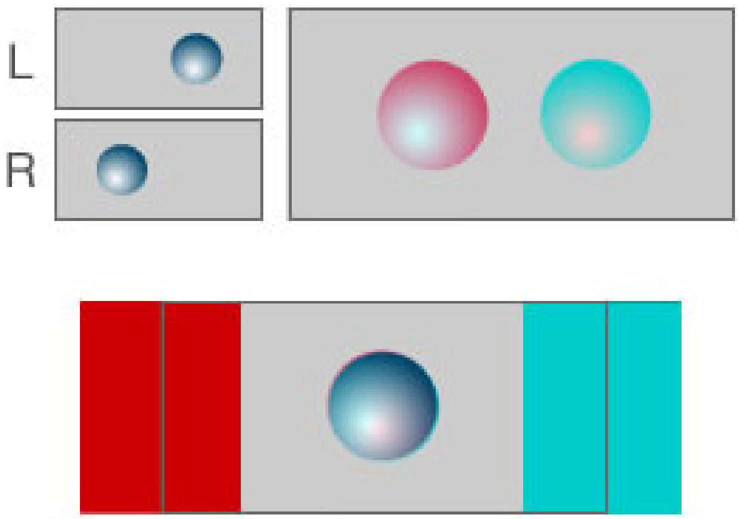


Figure E-22: Principle of HIT – Images Seen by Both Cameras.

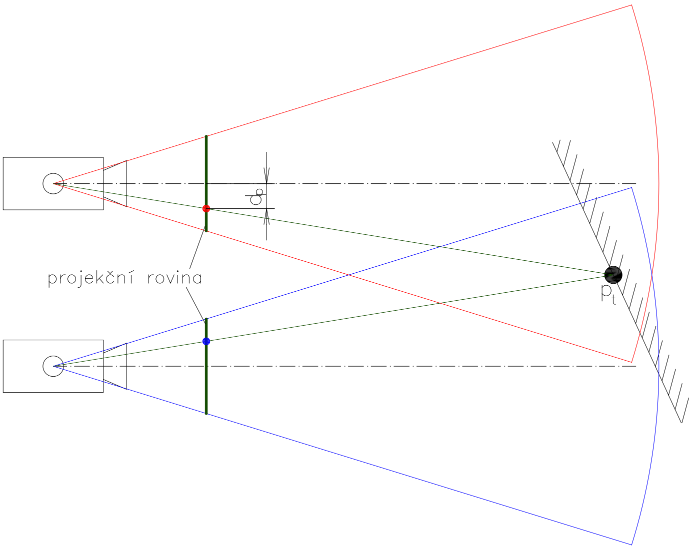


**Figure E-23: Principle of HIT – Shifting Distance.**

### E.3.3 Oculus Rift HMD

Various HMD devices have been available for few decades already and used not only in military or governmental applications, but also commercially, especially to create Virtual Reality (VR). However, big prices of the HMD devices (reaching even tens of thousands USD) and mediocre parameters, especially of the cheaper ones [33], were the reasons why VR was a marginal, albeit popular and often mentioned concern.

The upcoming HMD device Oculus Rift offers outstanding parameters together with extremely low price and already caused a big wave of new interest in VR, primarily in the gaming industry.

#### E.3.3.1 Description

Oculus Rift is still in development, but a special preliminary *Software Development Kit* (*SDK*) version is available for purchase. The device offers some major advantages over other similar devices [34]:

- Low price (300 USD for the SDK version);
- Large Field Of View (FOV);
- Low weight, good comfort while wearing the device; and
- Ultra-low latency 360° head tracking in 3 axes.

Especially *FOV* is very important for a good sense of virtual reality. Typical commercial HMD devices use two small LCD displays placed in front of each eye and have a very limited FOV between 30 and 45 degrees. There are few professional devices with larger FOV, but they are very expensive, for example the Sensics xSight with 123° FOV and price around 40,000 USD [35].

Oculus Rift has both the vertical and horizontal FOV larger than 110 degrees while keeping the device hardware very simple and thus cheap. The device consists of a single 7-inch LCD screen situated approximately 4 centimeters in front of the user's eyes and two plastic lenses projecting each half of the screen to the corresponding eye. A notable disadvantage of Oculus Rift is low resolution of the screen of the SDK version – only 1280 x 800 pixels, or 640 x 800 per eye, so individual pixels are clearly visible. The final version is however going to have a better resolution.

**Figure E-24: Oculus Rift Head-Mounted Display (SDK Version).**

### E.3.3.2 Principle of the 3D Display

Oculus Rift requires a specific method of rendering, different than most other HMD devices, especially because it contains only one LCD screen. The device can be used to display pictures from real-world cameras or from virtual cameras drawing the content of a virtual 3D world (VR). Two cameras are needed – one for each eye – with the distance between them corresponding to the *Inter-Pupillary Distance* (*IPD*) of the user. The cameras must be parallel, with the point of convergence in infinity. Image for the left eye is displayed on the left half of the screen and image for the right eye on the right half.

Besides having the correct resolution (640 x 800) and aspect ratio (4:5), each camera also must have the correct vertical FOV, which is given as:

$$\phi_y = 2\arctan\frac{h_{lcd}}{2d_{lcd}} \tag{3}$$

where $h_{lcd}$ is physical height of the LCD screen and $d_{lcd}$ is distance of the Oculus LCD screen from user's eyes (Figure E-25).

In VR it is quite simple to meet all the requirements, because optical parameters of a virtual camera (aspect ratio and FOV) are given by perspective projection transformation done by a projection matrix:

$$\mathbf{P} = \begin{pmatrix} \frac{1}{s\tan(0.5\phi_y)} & 0 & 0 & 0 \\ 0 & \frac{1}{\tan(0.5\phi_y)} & 0 & 0 \\ 0 & 0 & \frac{z_f}{z_n - z_f} & \frac{z_f z_n}{z_n - z_f} \\ 0 & 0 & -1 & 0 \end{pmatrix} \tag{4}$$

where $s$ is the aspect ratio and $z_n$, $z_f$ are depth distances of the near and far clipping planes.

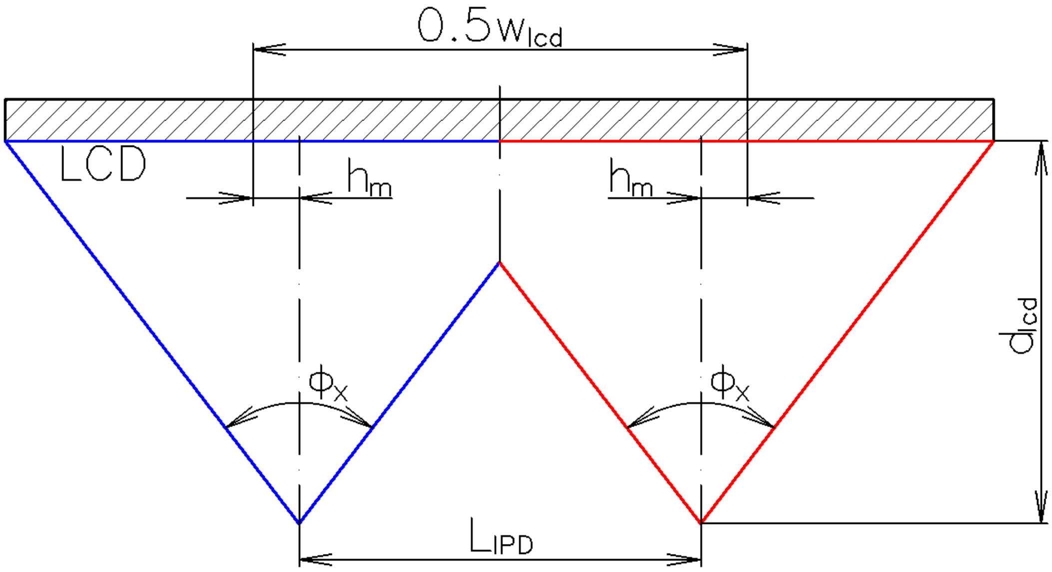


**Figure E-25: Physical Relation between the Eye View Cones and the LCD Display.**

The lenses are placed in a fixed distance $L_{IPD}$ = 0.0635 m (according to the average IPD of human), but this does not correspond to the size of the LCD screen. Physical width of the screen is $w_{lcd}$ = 0.14976 m and the centers of both half-screens are 0.5 $w_{lcd}$ = 0.07488 m apart. This value differs from $L_{IPD}$, so each image must be shifted towards the center of the display by h in meters:

$$h_m = \frac{w_{lcd}}{4} - \frac{L_{lcd}}{2} \qquad (5)$$

With real cameras, this shifting can be done in pixels by:

$$h_p = W \frac{h_m}{w_{lcd}} \qquad (6)$$

where W is the horizontal resolution of the Oculus LCD screen in pixels. For VR cameras, it can be simply applied to the projection matrix (plus sign for the left eye, minus sign for the right eye):

$$\mathbf{P}' = \begin{pmatrix} 1 & 0 & 0 & \pm\frac{4h_m}{w_{lcd}} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \mathbf{P} \qquad (7)$$

### E.3.3.3 Distortion and Chromatic Aberration

The lenses in Oculus Rift create a significant pincushion distortion of the image, which can however be cancelled out by creating appropriate opposite (barrel) distortion in software before sending the pictures to the HMD device.

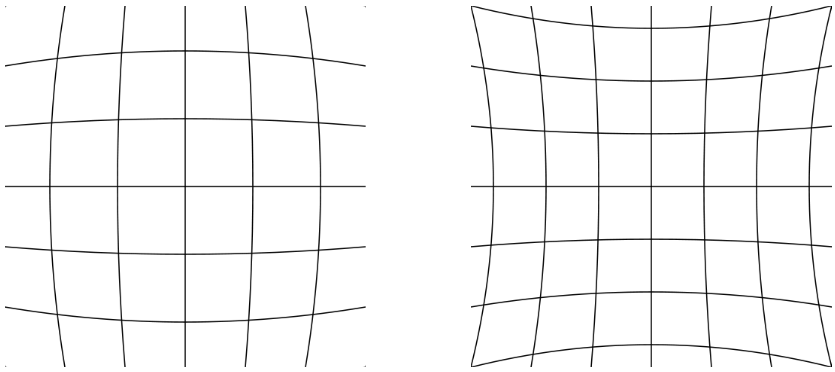

**Figure E-26: Barrel and Pincushion Distortion.**

The lenses also introduce the visual defect *chromatic aberration*, which is caused by varying refractive index of different wavelengths of light. Fortunately, also this unwanted effect can be significantly improved by an appropriate pre-transformation. Together with the barrel distortion, it can easily be done in a post-processing pixel shader, at the cost of some additional GPU processing time. The code for the pixel shader is available in the Oculus SDK documentation and samples [36].

#### E.3.3.4 Convergence

As was already mentioned, the cameras are required to have parallel axes, with the convergence point in infinity. They should not be angled towards each other (so-called "toe-in") and also *Horizontal Image Translation* (*HIT*) should not be performed. Because of how the HMD optics works, the user does not have the sense of watching the LCD screen of the device, his eyes are naturally focusing on individual objects in a virtual world in front of him. If an object is very far away (almost infinitely) in reality or in the rendered 3D virtual world, it appears at the same position on both half-screens and thus both eyes look parallel to focus on it. Similarly natural it feels to watch objects in closer distances.

### E.3.4 Design of a Mobile Robot Teleoperator User Interface

A HMD device (Oculus Rift) can be used to display stereovision images to the operator of a mobile robot, either a physical one (images from real cameras), or a virtual one is a simulator.

The first obvious solution is to directly display the images from cameras onto the screen of the HMD device, left camera on the left half and right camera on the right half. This creates a virtual reality for the HMD wearer so that he feels like if he was standing at the position of the mobile robot. There are however multiple complications in this case.

First, according to the previous chapter, the cameras need to have very specific lenses to exactly or at least very closely match the quite big FOV of the device, which is 98°. This value can be achieved by using ultra-wide angle or fish-eye lenses, because standard cameras typically have FOV only between 40 and 60 degrees [37]. Another complication is the uncommon aspect ratio of the Oculus half-screens (4:5), where height is larger than width. Pictures from the cameras would need to be cropped and the operator would be able to see less of the world around the robot than with the current flat screen without stereovision.

It is still possible to use the existing cameras with normal lenses, without any cropping, if the pictures are scaled down so that they occupy only the middle portion of each half-screen, which exactly matches the corresponding fraction of the total FOV. Practical testing proved that this solution works quite well and a good 3D illusion is achieved, but only a part of the whole FOV is used, which denies one of the main advantages of Oculus Rift.

The biggest problem with direct display of camera images is that it caused nausea to most testing subjects (this applies to both situations – with and without the accurate FOV). The reason behind this is that Oculus Rift makes the user feel really immersed in the VR and so his brain expects all input information from eyes and the vestibular system in his inner ear to match. A possible way how to reduce this source of nausea is to use the head-tracking sensors of Oculus and rotate the physical cameras exactly the same way, with as low latency as possible. The Oculus Rift documentation recommends the maximal latency to be around 40 ms [36], but this is almost impossible to achieve, because during this time we need to process the head tracking data, send a corresponding camera rotation command to the robot, the cameras must mechanically rotate, new images must be read from the camera and transmitted to the operator and finally displayed in the HMD device. Even if the data transfer is very fast, dynamics (acceleration) can possibly be the biggest source of lag. This is the case especially if cameras are mounted on the manipulator arm and the only way how to look around is to move the whole arm. The acceleration and deceleration times can be too high and also the maximal velocity can be not large enough to follow head movements in real time.

There is even a bigger problem if the robot moves, because in this case the cameras are moving in a way completely unrelated to the head movement of the operator. And especially on uneven terrain when the images shake, it is extremely inconvenient to look through the robot cameras using a HMD.

### E.3.4.1 Virtual Operator Station

Because of the described problems, a new system was developed – a *virtual operator station*. The operator wearing HMD is put to a virtual space (“room”) created completely in a computer and can freely look around by head movements. This virtual room contains several 3D objects, primarily a big rectangular plane with images from the stereovision cameras displayed on it. The room itself is fully black, to provide as little distraction as possible.

Watching the video from the cameras this way feels for the operator as naturally as watching a television or cinema screen with a 3D technology in real life. The biggest source of nausea is removed for most testing subjects, because the brain feels to be part of the virtual room and thus expects the virtual screen to be fixed in space, or to move naturally with head movements, which can easily be accomplished.

The virtual room is watched from a pair of imaginary stereovision cameras configured according to the Oculus requirements. This pair of cameras is fixed in one point in the room (see the camera symbols on Figure E-27) and can rotate (look around) in all three axes (yaw, pitch, roll) based on user’s head movements.

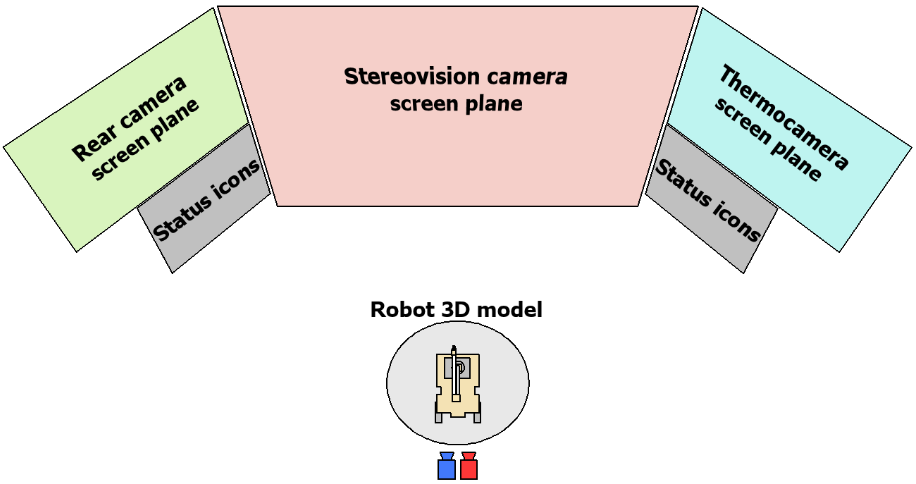


**Figure E-27: Schema of the Virtual Operator Station.**

The biggest rectangle is a virtual screen plane with images of the stereovision cameras; this rectangle is rendered differently for the left and right eye – each time with the appropriate camera image. The screens on left and right sides display pictures from a secondary (rear) camera and from a thermovision camera. Right in front and slightly down is rendered a 3D model of the mobile robot with the arm at the real actual position, which helps the operator a lot to during manipulation tasks. Additional necessary information about the robot, as operating modes, sensor data etc., are displayed below the smaller camera images. Because of the low resolution of the Oculus SDK version, visual representations of information (icons, symbols, images) are preferred, or a large font must be used for text. After some testing of usability, we decided to display the control elements twice – once on each side, so that they are in the operator's sight most of the time. Important icons can be also displayed over the camera image, as for example the gripper icon on Figure E-28.

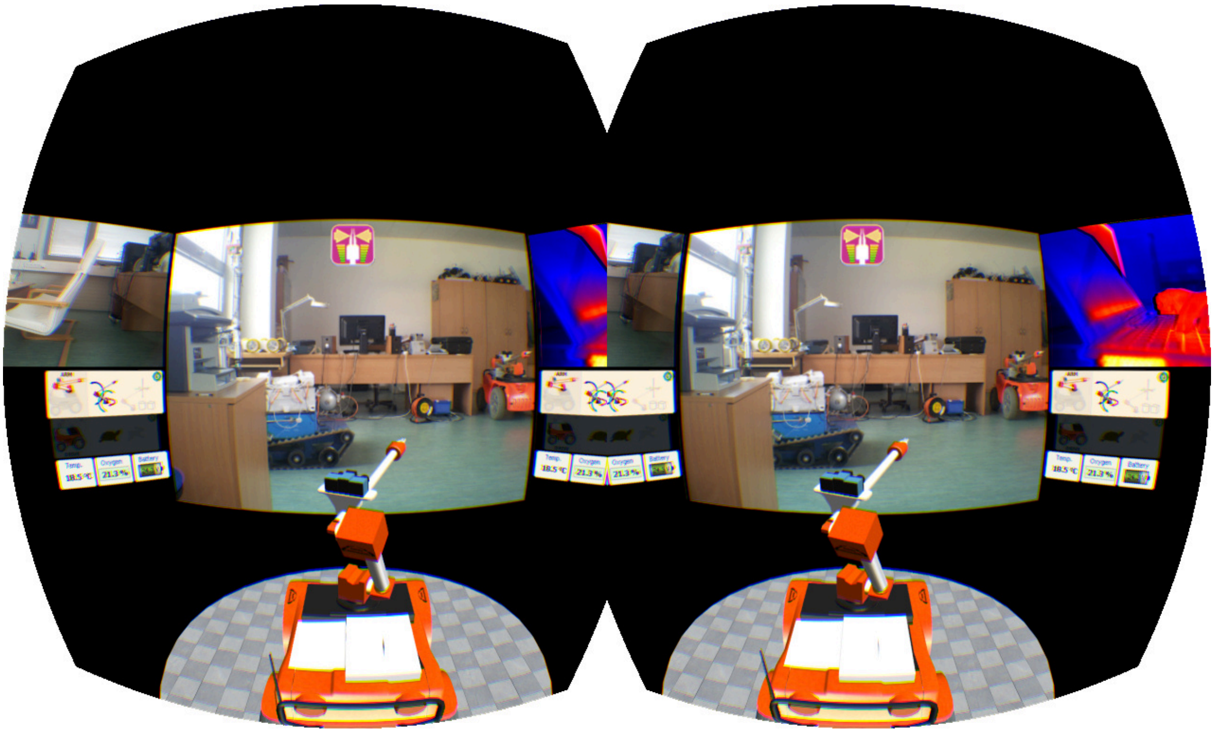

**Figure E-28: Image Displayed on the Oculus Rift Screen – Operator is Looking Ahead.**

All rectangular planes with textures (camera images or control elements) are oriented vertically in the virtual world, so that their normal vector is perpendicular to the vertical axis of global coordinate system. And at the same time the planes are rotated towards the virtual head position (Figure E-31).

The previous images show the actual view of the virtual world with applied distortion and chromatic aberration, as it is sent to the HMD device LCD. On Figure E-28 the user is looking straight ahead towards the big screen, on Figure E-29 the user is looking to the left to focus more on the rear camera and then to the bottom to better watch the robot model. The robot model on the last image is rotated sideways, which is a feature that the operator can control manually by a gamepad.

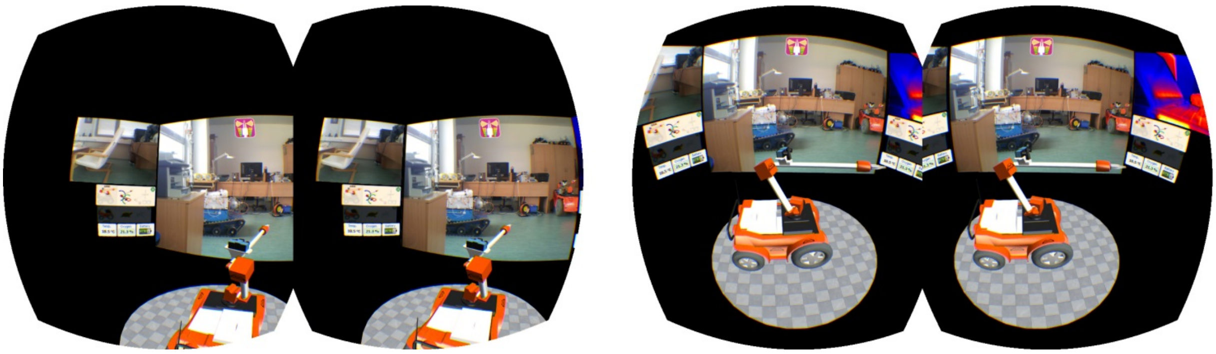

**Figure E-29: Images Displayed on the OR Screen – Operator Is Looking to the Left and Down.**

### E.3.4.2 Visibility

Only a part of the Oculus LCD can be easily seen through the lenses. The visible part of Figure E-28 is highlighted on Figure E-30. Content of the virtual room was carefully configured based on testing, to show comfortably the whole plane with the main camera image and the robot arm in front of it, in a very convenient location. The operator can look just slightly to the left or right and will be able to see also most of the secondary camera image and all additional information about the robot.

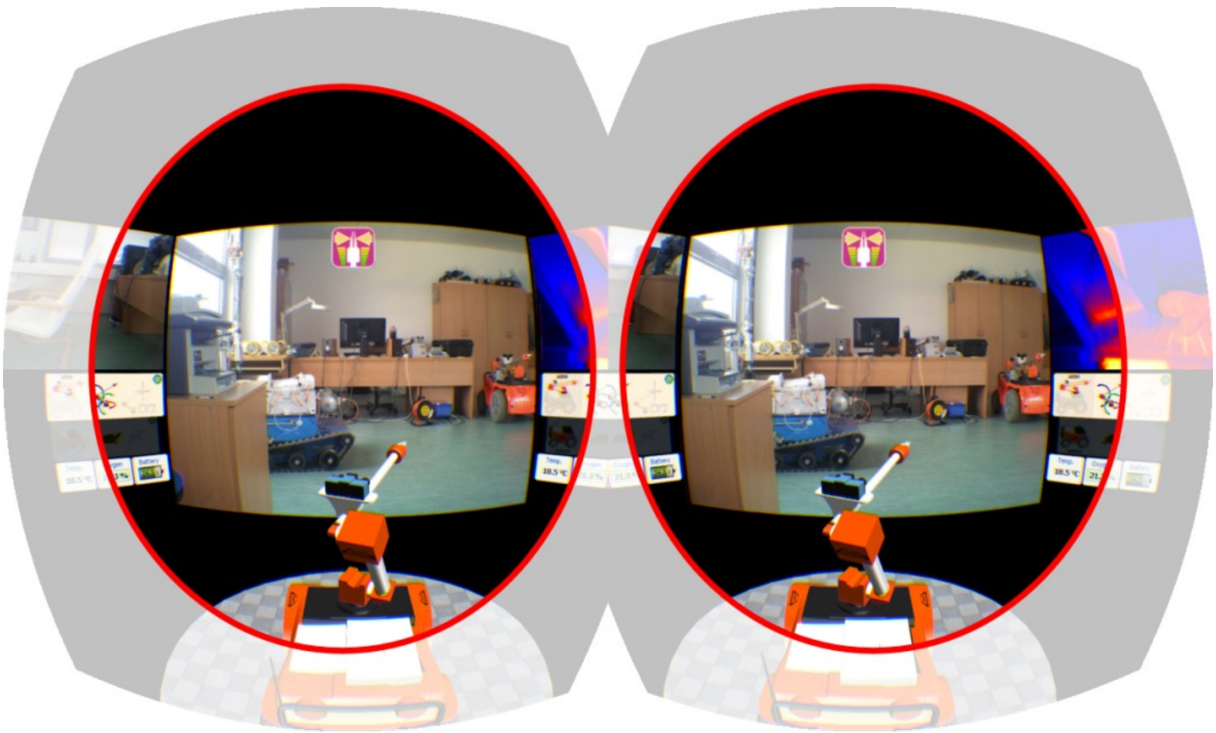

**Figure E-30: Physically Visible Section of the Rendered Image.**

The virtual operator station also provides a "zoom-out" mode, in which all screen planes move away from the user so that they all are visible at the same time without having to look around, at the cost of being smaller and thus less detailed. Frequent transition between the two modes is however not recommended, as it is a potential source of nausea or eye-strain. All screens are still oriented towards the virtual cameras, as shown on Figure E-31.

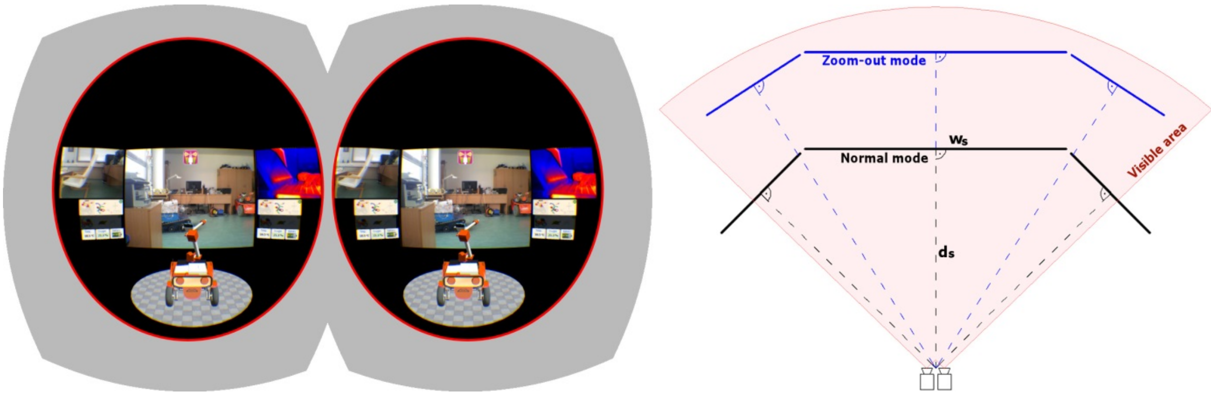


**Figure E-31: The Zoom-Out Mode with Schematic View of the Screen Rotating Towards the User.**

It may be necessary to display some crucial information, for example error messages or symbols, on a floating plane which is in front of any other object and also is moving in the virtual world to be always clearly visible to the operator, regardless how his head is actually rotated. This also must be done with caution and only when really needed, because any similar violations of the expected behavior can be inconvenient for the user.

### E.3.4.3 Stereovision Cameras

As already mentioned, the images from stereovision cameras are displayed on the biggest virtual screen. This however is not so straightforward, as attention must be paid to convergence.

In the virtual scene, the screen plane is $w_s$ = 3 m wide and is rendered in a distance $d_s$ = 2.4 m from the user (in the normal mode, Figure E-31). To focus on this object, the user's eyes naturally converge on it just like if it was a real object 3 meters far away.

There is a stereovision image displayed on this screen, which creates the illusion of additional depth – the objects on the picture appear at different distances than the screen itself, exactly as in a 3D cinema. An object on the image is placed exactly at the distance of the virtual screen if it is at the same pixel position on both images. For physical cameras with parallel axes and the point of convergence in infinity, this is valid only for objects in infinity, or very far away. This in fact means that the whole scene "thrusts out" of the screen into the space in front of it.

This is not very good for immersion, because the 3D model of the robot appears to collide with the image, although it is located in front of the screen, and there is also unmatching depth information near the side edges of the virtual screen, where the edge seems to be at two different depths at the same time.

A possible partial solution is to apply HIT before placing the images on the virtual screen plane, to change the convergence point. This does not violate the rule mentioned earlier, because now the camera images are not displayed directly in the HMD.

The images must be shifted outwards (the left one to the left and vice-versa), to put the convergence point further away. There is one very important limitation to the translation, because if the images are shifted too much, the convergence point of a particular pixel on the image could be "behind infinity" in the HMD virtual world and the eyes would have to rotate outwards to focus on such a point, which is physically not possible. This creates a lot of eye strain, because the brain is not used to this situation and ineffectually keeps trying to focus.

The maximum allowed translation is equal to the parallax pmax of the screen plane in VR, so that objects infinitely far on the camera image appear at infinite distance in the HMD:

$$d' = \frac{W}{4\tan\frac{\phi_x}{2}} \tag{8}$$

$$p_{\max} = \frac{L_{IPD} d'}{2d_s} \tag{9}$$

where $w_s$ represents the width of the virtual screen plane, $w'$s is the width of the plane in pixels as it is displayed on the LCD and $W_c$ is horizontal resolution of the camera images.

Shifting the images by this fixed amount does not fully solve the problem with closer objects thrusting out of the screen plane, but at least improves it by placing some objects behind the plane. A better solution would be to analyze the camera images, detect the furthest objects and shift according to them. If the furthest detected objects are not very (infinitely) far way, the HIT may be larger than pmax. The value can also be increased without image analysis if the robot is for example designed only for indoor environment, where the maximal possible depth is limited to few meters.

## E.4 ROBOSIM

RoboSim [40] is a simulation system for tele-operated mobile robots.

Mobile service robots are relatively often used not only for operations associated with safety engineering such as firefighting, chemical accidents, terrorist attacks, disposing of explosives, surveying of hazardous and cramped areas, searching for earthquake victims, but also in the commercial and science sectors, e.g. checking and maintenance of piping, exploration of planets. Also military applications cannot be neglected.

Vast majority of the above applications use mobile robots remotely controlled by a human operator. Compared to autonomous robots, this is still the cheaper and above all more reliable solution. Algorithms of robot artificial intelligence and sensory systems still have not reached the level when it would be possible to use a robot for tasks when human lives are at stake.

Owing to the immense range of possible applications, the mobile robotics field is subject to continuous development and innovation. The development process of a new mobile robot requires a lot of time and funds, and therefore it is convenient to use virtual prototyping – in an ideal case the resulting first physical prototype developed would meet all requirements and no additional modifications would be required. As for the mechanical construction of a robot, the existing CAD/CAM systems may be used. However, these systems usually do not allow complex simulation of behavior of the whole mobile robot in the conditions similar to reality. So a situation may occur when a physical prototype would be fully operational in terms of its mechanical aspects but due to an unsuitable concept, the mobile robot would be difficult to control in the required conditions, the camera subsystem would not provide the operator with sufficiently clear images, and suchlike.

The possibility to carry out extensive testing on a virtual prototype of a whole robot in a simulated real environment may make the whole development process much faster, much more efficient, and especially cheaper. The virtual model may be further used even when the robot is physically manufactured, fully tuned, and used in practice – the virtual model may be used for training of operators without the necessity to use the actual robot.

### E.4.1 Basic Structure and Properties of the Simulator

There are a great number of simulation systems available, for example [10]-[16]. However, most of them focus on testing of various algorithms of autonomous behavior, and therefore they offer advanced possibilities of programming of robot control systems. However, creation of a program code is also necessary even for basic tasks, unless one of the ready-made mobile robots based on actual commercial robots is used. It is quite difficult to install and commission the systems, which is given particularly by their composition of various more or less independent modules and libraries. The primary view of the 3D simulated scene is from top, but there usually is a possibility to define virtual robot cameras and use them to monitor the scene. The graphic output is average, created using basic principles and simple shadowing is usually the most advanced effect.

*RoboSim* simulation system described in this article tries to excel compared to the competition of the already existing systems particularly in the following areas:

- Short time needed to start working with the system, application with ease of use even for designers and other professionals not skilled in programming.
- Possibility of quick verification of the concept and kinematics of the mobile robots plus easy modifications.
- Advanced simulation of virtual cameras, superior virtual presentation for more realistic feel for operators when controlling virtual robots.
- Specialization in verification of the ease of operator control and navigation in an unknown or complex environment.

Simulation requirements may be divided into two large groups:

- Movement physics (driving properties, handling in various terrains, stability, ability to avoid various obstacles, turning radius and manoeuvrability in general, speed, power, etc.).
- Navigation (ability of the operator to control the robot using only the feedback from the cameras and sensory subsystem, verification of the required quantity, placement and the type of cameras, benefits of stereovision, etc.).

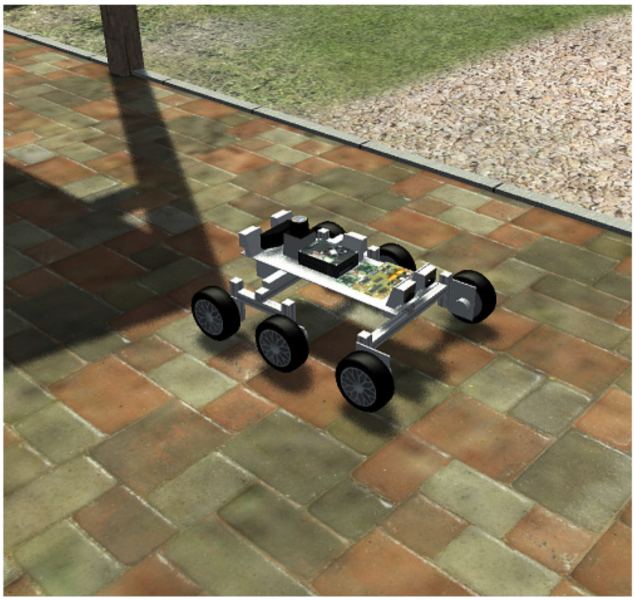

**Figure E-32: Six-Wheeled Mobile Robot Displayed in the Simulator.**

The application is based on our own application core and is programmed in Visual C++. The Direct3D Application Programming Interface (API) is used for graphics [37] and the *Havok* engine for rigid objects physics simulation [29].

The rendered virtual scene consists of a greater number of separate entities (these are usually separate bodies), where each of them has its visual and physical properties [38], [39]. Various relations and dependencies may be defined between the entities. Rendering of entities is optimized for maximum speed and therefore suitable filtering is applied according to visibility and the rendered objects are also ordered for more efficient calling of Direct3D functions. Hardware acceleration of rendering is a matter of course. Therefore, a graphic chip supporting at least Shader Model 3.0 (DirectX 9.0c) is required to run the application.

### E.4.2 Kinematics and Dynamics of Movement

Comprehensive simulation of Newton physics of a mobile robot is achieved through proper use of the above-mentioned *Havok* engine. The mobile robot is divided into individual parts (entities) with suitably adjusted physical properties. The entities are then connected by appropriate physical links and action parts (e.g. driven wheels) are complemented with physical actions (drives). When the mobile robot defined this way is placed in a virtual environment also containing entities with a physical component (at least a floor or ground), complex simulation of robot behavior is secured.

The current version of the simulator uses only rigid body dynamics from the *Havok* library, and therefore it is impossible to simulate e.g. flexible wheel tyres. However, simulation of springs for sprung wheel suspension is possible. Each rigid body (entity) has particularly the following properties:

- Weight, center of gravity position, inertia moments;
- Shape for detection of collisions;
- Restitution (degree of energy loss upon collision);
- Friction; and
- Linear and angular damping (degree of energy loss when moving without effect of external forces).

Body shape is used for detection of collision with other objects and calculation of correct reaction to these collisions. Calculation of collisions is an operation whose complexity rises significantly with the complexity of body shapes. Therefore, it is desirable to define the collision shape of the body as simple as possible while preserving sufficiently accurate behavior. Therefore, in most cases a different shape is used for visual representation of an object (rendered triangular mesh with many details) and for collisions (Figure E-15). Examples of some shapes ordered starting with the least demanding: sphere, capsule, box, cylinder, general convex body, and general concave body.

Restriction of movement of two bodies against each other may be achieved by links. *Havok* allows definition of new arbitrarily complex links but it also contains ready-made links of which the following are the most suitable for undercarriages, handling superstructures or other parts of mobile robots: *hinge* – axial rotation, *limited hinge* – restricted rotation, *wheel* – rotation round one axis, optional rotation round another axis (steering) and optional translation along a third axis including a spring and dampening (wheel suspension) and *prismatic* (translation).

Behavior of objects in a certain way is affected by *actions*. Analogous to links, new actions also may be easily defined according to actual needs. Rotational and translation motors in particular belong to the prearranged actions. A new link was created for the needs of RoboSim, simulating behavior of a DC motor including characteristic dependence of torque on speed.

### E.4.3 Simulation of Camera and Sensory Subsystem

With regard to the primary designation of the simulator for testing of operator con-trolled robots particularly when using a feedback from a camera subsystem, great attention was paid to correct simulation of cameras.

The simulation system allows fitting of the robot with an arbitrary number of virtual cameras, which may be used for monitoring of the robot surroundings. These cam-eras may be visually rendered as a 3D model (Figure E-33).


**Figure E-33: Virtual Mobile Robot with 2 Stereovision Cameras and One Rear Camera.**

Each camera needs to have specified the basic optical properties – viewing angle, resolution in pixels, or even for example parameters of barrel distortion of the image.

The actual optics of cameras usually does not have sufficient depth of field to cover large distance range of viewed objects, and therefore focusing is implemented. The objects outside the focused depth of field then appear to be blurry. This effect may substantially affect operator's ability to navigate in a complex environment using only the cameras and therefore RoboSim includes simulation of depth of field (Figure E-34). When rendering a scene, this visual effect is achieved using a special *pixel shader*. It is not an exact physical simulation of this optical phenomenon but only its rough and simplified approximation.


**Figure E-34: Depth of Field Effect.**

When using *stereovision* it is necessary to specify a pair of cameras with suitable mutual position and identical optical parameters (Figure E-33). Stereovision may then be viewed in the following ways:

- *Anaglyph* – encoding images for individual eyes to different colors and subsequent filtration using simple passive spectacles with colored glasses through which the monitor is viewed [30].
- *Head-Mounted Display (HMD)* – various types of active displaying devices placed directly on user's head [31]. Two general methods of displaying are supported –interlacing and image alternating.
- *Oculus Rift* – new HMD with exceptional properties and very low price. This device requires a specific way of rendering when the images for both eyes are placed next to each other and software barrel distortion is applied to them to eliminate the opposite distortion created subsequently in the device optics [34].

Simulation of sensors is only simple in the current version of *RoboSim*. There are three types of sensors available – *linear* (measuring linear distance to one point of an obstacle, simulation of IR and suchlike sensors), *conical* (measuring distances in a cone and returning the smallest value, simulation of ultrasound sensors, etc.) and *planar* (measuring distances in a fan pattern on a plane and providing a set of measured values, simulation of laser scanners). All sensors are sending imaginary mathematical beams and detect intersections with object in the scene. In order to prevent unrealistic absolute accuracy, it is possible to add random noise.

### E.4.4 Realistic Testing Environments

Besides the possibility to define completely new environments, RoboSim also offers three predefined scenes covering various conditions of possible applications of robots – a family house (complex interior with narrow spaces and a large number of obstacles, Figure E-35), an outdoor scene (open space, uneven terrain with various sloping, Figure E-32 and Figure E-34) and a special testing laboratory (various exactly defined sizes of corridors, door openings, obstacles, stairs, inclined planes, ramps, etc., Figure E-33 and Figure E-36).

**Figure E-35: One of the Rooms in the Family House Testing Environment.**

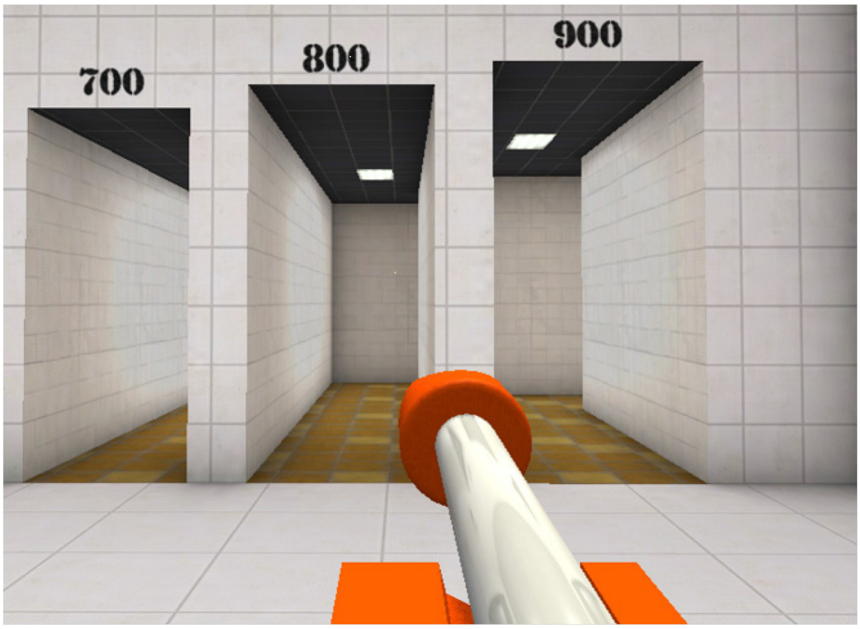


**Figure E-36: Demonstration of the Advanced Lightning Model Used in the Simulator.**

In order to provide the most authentic feel of the view available from the mobile robot cameras, the testing environments are created with emphasis placed on the visual quality and details using some advanced methods to achieve realistic 3D graphics. Common graphics applied in CAD systems and in most of the existing simulation systems uses only simple dynamic lighting and possibly textures. The resulting uniform color surfaces and repeating textures do not provide the operator with sufficiently authentic image when testing navigation using the camera subsystem and the result may be biased due to this fact – it is much more difficult for the operator to find his/her way in the virtual environment than in reality.

The advanced techniques used in RoboSim include for example:

- *Shadows* – very important for understanding the mutual spatial relations between objects. The used technique is shadow mapping including an optional degree of smoothing (Figure E-32).
- *Lightmapping* – replacement of real-time dynamic lighting by much more accurate pre-calculated model simulating even reflected light (walls on Figure E-36).
- *Environment mapping* – simplified simulation of highly reflective materials (robot arm on Figure E-36).
- *Normal and specular mapping* – simulation of uneven and diverse surface using a suitable lighting calculation without the necessity to create a very complex 3D model (Figure E-32).
- *Multitexturing, texture layers* – alleviating of undesirable effect of repetition of texture patterns, adding of imperfection, impurities, etc.

To compare simulation with reality, virtual models of several actual robots were created and their behavior was tested (Figure E-37). Although the simulation of dynamics in real time implemented by Havok system is quite realistic, it is not fully physically accurate, which is given by the necessary simplifications in order to allow sufficient calculation speed.

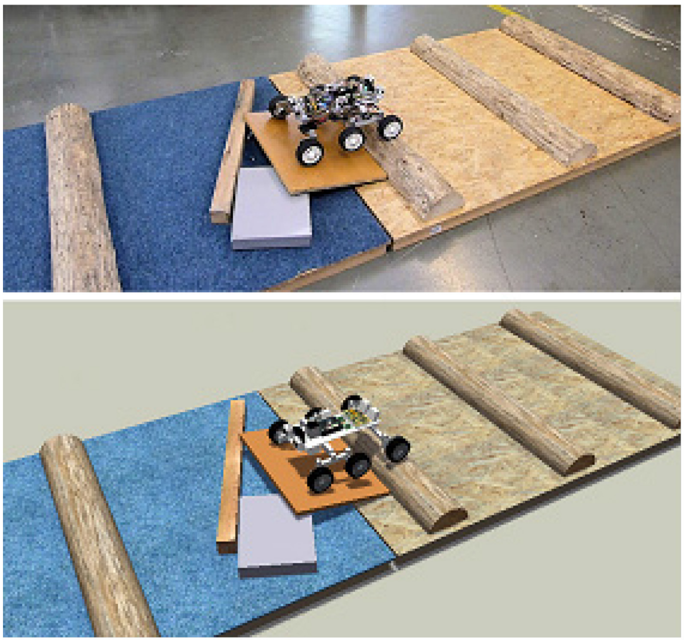

**Figure E-37: Mobile Robot on an Obstacle Course in Reality and in the Simulator.**

The basic simplification directly concerning wheeled mobile robots is the replacement of simulation of soft rubber of wheels (or even air filled tyres) with ideally rigid objects. Neither is it possible to simulate accurately the tyre tread and so the possible shape contact of the wheel with an obstacle is replaced by mere friction of a cylinder against an obstacle. Despite that, the behavior of robots in the simulation is depicted relatively accurately in particular in terms of manoeuvrability and ease of control.

The strongest point of *RoboSim* – simulation of camera subsystem – brought several interesting findings even during the development of the simulator. It was successfully used for optimization of camera position on a developed mobile robot and this SW was also used for testing of stereovision and particularly its usability for navigation.

The application is currently being extended by a more convenient and fully graphical editor of mobile robots and testing scenes and adding of simulation of tracked chassis would be also desirable. There is also a plan for the possibility to control the virtual robot in the simulator using the operator’s station for the actual robot, which instead of the real robot would establish connection with the PC with the running simulation.

## E.5 ANTI-COLLISION SYSTEM FOR MANIPULATORS

For more complicated tasks, mobile service robots can be equipped with a manipulation arm to extend their applicability also for example to defuse explosives, transfer barrels or containers with dangerous chemical substances, gas bottles, radioactive materials. The more degrees of freedom such an arm has, the more useful it may be, but at the cost of more complex handling required from the operator.

A manipulation arm with strong motors can easily damage itself or some delicate components of the mobile robot (cameras, sensors, communication antennas …) situated in the operating area of the arm. When the robot is out of direct sight from operator, the operator has only very limited feedback from the robot in the form of video from robot camera(s). Actual angles of all arm joints usually are not clear from camera view and thus the operator cannot be fully responsible for prevention of collisions and the control system must assist him.

The mobile robot *Hardy* (Figure E-38) serving as an example of practical application of anti-collision system in vision assisted remote control of a service mobile robot is a heavy-duty tracked mobile robot with 5-degrees-of-freedom manipulation arm and 2 additional significant degrees of freedom in the gripper. Because of very complicated kinematic structure of the arm and the strength of the arm (max. load is 300 kg), automatic anti-collision system was crucial for this robot.


**Figure E-38: Heavy-Duty Mobile Robot Hardy.**

Collision detection and prevention in mobile robotics has been the subject of numerous articles and research projects, but typically in the context of movement of an autonomous robot in unknown environment, obstacle avoidance, path finding etc. Manipulator arms on mobile robots are often quite simple with low number of joints or relatively week and thus collision avoidance is either very straightforward or not needed at all.

Many researchers have described collision detection techniques based on continuous monitoring of the torque applied to the arm actuators. These values are then compared with the torque expected for the actual movement and if the difference is above a specific threshold, a collision is signaled [41], [42]. This however requires a perfect mathematical model of the arm and even then it cannot detect the collision before there is a physical contact. This method is used especially on industrial robots even to prevent human injuries, but is unacceptable for very strong and heavy arms with longer deceleration (braking) times.

Self-collision detection with prevention has been proposed primarily for humanoid robots, using protective hulls bounding volumes generated by a CAD software or other accurate methods [43], [44], or for general robotic arms, for example with capsules and octree hierarchies [45]. These solutions are more accurate but also more complicated to implement and more computationally demanding.

Our goal is to find a new simple, fast and easy-to-implement solution with adequate detection accuracy and with good collision prediction and prevention even for heavy arms with long reaction times [52].

### E.5.1 Methods of Collision Detection

For simple arms with about 2 degrees of freedom, it can be sufficient to just properly limit range of motion of individual joints in software control system or even by hardware end limit switches. With increasing complexity of the manipulator, this solution quickly becomes unusable, because the permitted range of movement of one joint will be a function of actual angles of other joints, and the function may be impossible or very hard to explicitly define.

The other extreme is to provide the control system with full 3D model of the whole robot and perform collision checks between individual parts. This solution would be very accurate, but even with a simplified 3D model stripped of insignificant details (see Figure E-39) the computations would require inadequate amount of CPU processing power on the computer running the control system. This is a problem especially because control systems run real-time, usually on small embedded PCs or light notebooks, instead of high-end desktop workstations. Such a system is also hard to implement and, after all, the absolute accuracy is not really necessary in common applications.

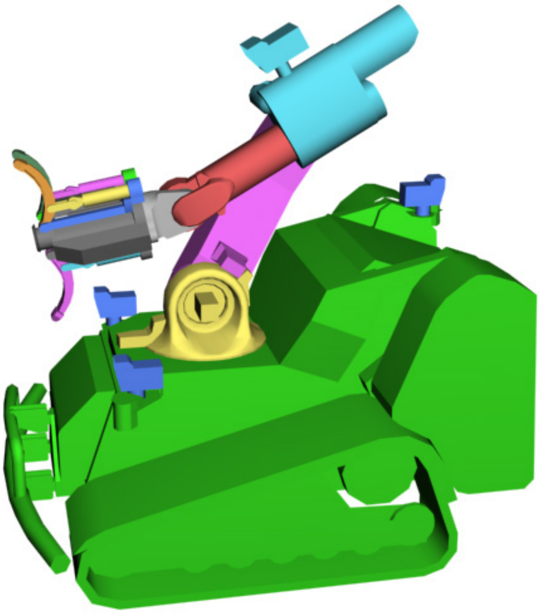

**Figure E-39: Example of a Simplified 3D Model for Accurate Collision Checking.**

Another possible concept is to use radically simplified representations of individual moving parts, built from basic geometric primitives like cylinders, spheres, blocks or lines [41]. These primitives offer much easier ways of mathematical intersection check at the cost of lower collision prevention accuracy, because the real shape of mechanical parts cannot be fully replaced by a reasonable number of basic primitives.

### E.5.2 Bounding Boxes

Blocks (boxes) are good primitives for bounding envelopes because of their variability (three dimensions can be set independently) and primarily because of their mathematical simplicity. They are often used in computer algorithms to quickly check some basic conditions. There are two commonly used forms of bounding boxes [46], [47]:

- Axis-Aligned Bounding Box (commonly abbreviated AABB) – the edges of the box are parallel to the used Cartesian coordinate axes and every box is defined by its position (3 coordinates) and dimension (3 lengths).

- Oriented Bounding Box (OBB) – the box can be arbitrarily oriented and is defined by three more coordinates (3 orientations).

AABBs are very fast in intersection calculations, but cannot properly represent slim bodies at general orientations, which makes them absolutely unsuitable for manipulation arms. OBBs are computationally more expensive, but are better at representing shapes at arbitrary orientations (Figure E-40).

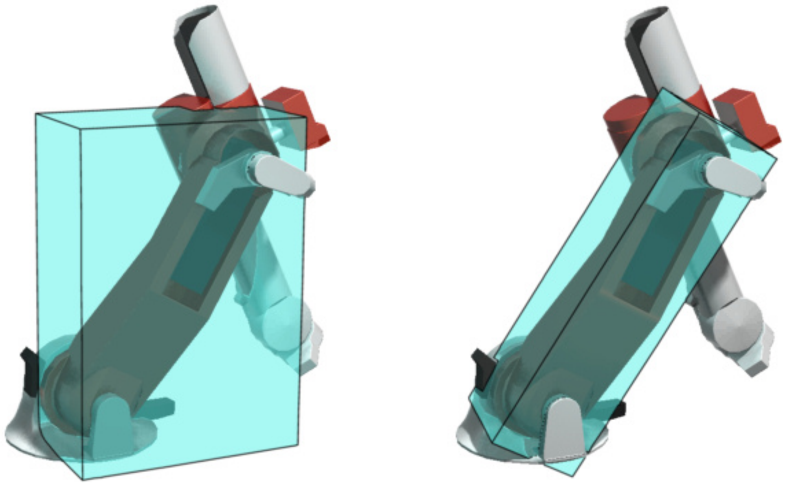

**Figure E-40: AABB and OBB Representation of an Arm Link.**

If needed, every movable part can be represented by a set of boxes, to make the envelope more accurate. The boxes also do not have to be strictly enclosing the whole volume of the body, important are just the parts that can possibly collide with other objects. An actual set of oriented bounding boxes for the real robot *Hardy* can be seen on Figure E-41. Green boxes are moving together with corresponding links of the arm, yellow boxes are stationary – but most of them are still arbitrary oriented and not axis-aligned. Some parts of the robot are not enclosed in any box, because it is impossible for them to collide with anything, given the mechanical limits of all joints. The goal is to use as few boxes with as small dimensions as possible to adequately represent critical parts.

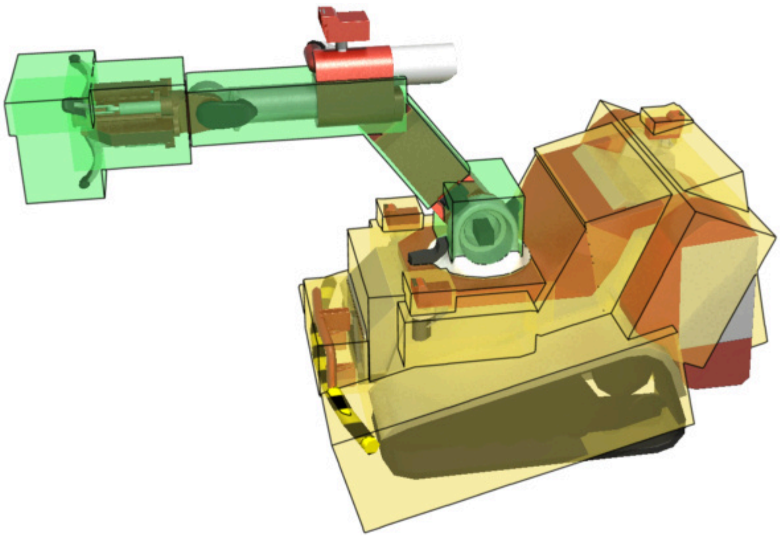

**Figure E-41: Collision Boxes for the Robot Hardy.**

Intersection tests can be executed on a pair of OBBs at a time. The theoretical number of tests needed to check intersections between *n* boxes is:

$$c = \binom{n}{2} = \frac{n!}{2 \cdot (n-2)!} \tag{10}$$

but it is obvious that all the tests are not necessary, because some pairs can never collide (especially the fixed boxes) and some pairs even must not be tested at all, because they are always intersecting (in the cases where more boxes are used to represent a single body). The number of collision boxes for *Hardy* (Figure E-41) is $n = 15$, which gives the maximum number of tests $c = 105$, but the actual number of checked pairs is only 43.

### E.5.3 Separating Axis Theorem

The separating axis theorem can be used to test intersections between any two convex bodies. The theorem says that for any two convex bodies there exists a line onto which their projections will not overlap if and only if the objects are not intersecting [46], [48]. This line is called the Separating Axis (SA). All lines parallel to a SA are also separating axes and are considered to be a single SA.

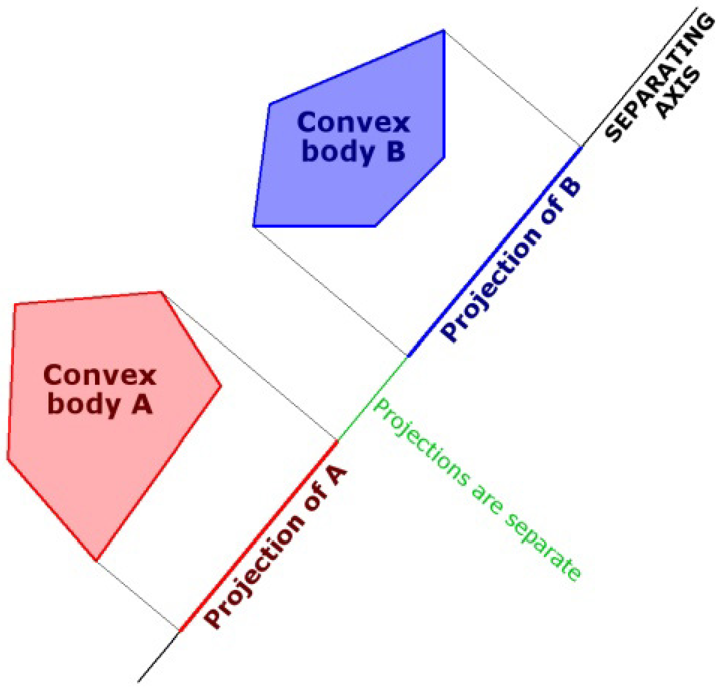


**Figure E-42: Separating Axis Theorem.**

To rule out intersection, at least one axis needs to be found. But to prove intersection, it is necessary to verify that none of all potential separating axes exists.

For oriented bounding boxes, there are only 15 potential separating axes [49], [50]:

- 3 basic axes of the first OBB;
- 3 basic axes of the second OBB; and
- 9 cross-products of the previous axes (one axis from each object).

Figure E-43 shows a 2D view (for simplicity) of two oriented bounding boxes with center points A and B, each with corresponding half-extends ("radii") $a_i$ and $b_i$ and basic axes represented by unit vectors $\mathbf{a}_i$ and $\mathbf{b}_i$, where $i = 1, 2, 3$. The distance vector between centers of both boxes is:

$$\mathbf{d} = \mathrm{B} - \mathrm{A} \tag{11}$$

and its projection onto the separating axis defined by unit vector $\boldsymbol{s}$:

$$r = |\mathbf{s} \cdot \mathbf{d}| \tag{12}$$

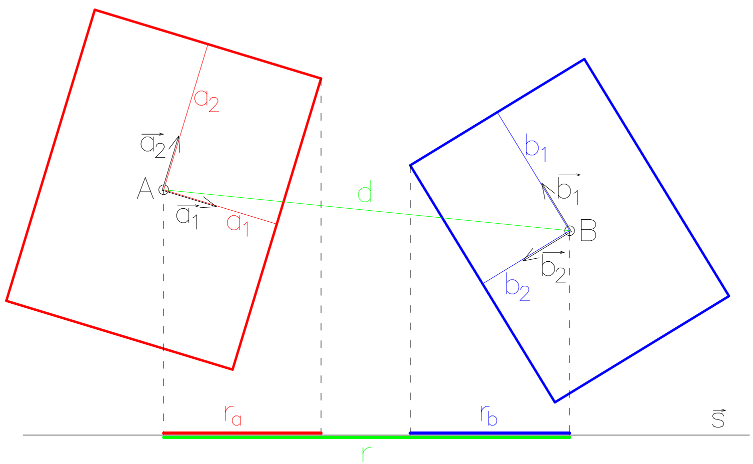


**Figure E-43: Separating Axis *s* for Oriented Bounding Boxes A and B.**

The total radius of projection of a box onto the SA is a sum of projections of all three radii:

$$r_a = \sum_{i=1}^{3} |a_i \mathbf{a}_i \cdot \mathbf{s}| \qquad r_b = \sum_{i=1}^{3} |b_i \mathbf{b}_i \cdot \mathbf{s}| \tag{13}$$

The projections are not overlapping (**s** really is a separating axis) if:

$$r > r_a + r_b \tag{14}$$

For the first three tests where the basic axes of box A are taken as potential separating axes, the calculations are simplified to:

$$\mathbf{s} = \mathbf{a}_j \tag{15}$$

$$r_a^j = a_j \tag{16}$$

where $j = 1, 2, 3$ is number of the test. Similar simplification applies to $r_b$ during the next 3 tests.

For the last 9 tests, potential separating axes are cross-products of basic axes:

$$\mathbf{s}_{i,j} = \mathbf{a}_i \times \mathbf{b}_j \tag{17}$$

where $i = 1, 2, 3$ and $j = 1, 2, 3$. Equation (13) applies without the simplification mentioned in equations (15) and (16).

### E.5.4 Implementation

Finding an existing intersection between two OBBs would mean that the real arm already probably is in collision – which is too late. Algorithm in the control system of *Hardy* uses extrapolation of actual angular velocities of all arm joints to predict position of the joints after a chosen constant time $t_{ext}$:

$$q_i^{ext} = q_i + v_i t_{ext} \tag{18}$$

where $q_i^{ext}$ is the extrapolated angle, $q_i$ is the real actual angle and $v_i$ is the actual angular velocity.

There are two phases of collision check. In the first phase $t_{ext}$ = 0.2 s and if a collision is found, the arm can still continue moving, but all velocities are lowered to 20 % as a precaution and warning against an impending collision. In the second phase, $t_{ext}$ = 0.05 s and if now a collision is found, the arm is immediately stopped. The second phase is completely skipped if the first phase did not find any collisions.

Each OBB has a constant local homogeneous transformation matrix defining position and orientation of the box relatively to the local coordinate system (LCS) of its parent – the corresponding arm joint. In every cycle (“frame”) of the control system loop, joint angles are updated from extrapolated values and for every joint a global transformation matrix is calculated. This matrix is then multiplied by local matrices of all OBBs belonging to the arm link, which results in global transformation matrices of the OBBs:

$$\mathbf{T}_{OBBj}^{g} = \mathbf{T}_{OBBj}^{i} \cdot \mathbf{T}_{i}^{g} \tag{19}$$

where $\mathbf{T}_{OBBj}^{g}$ is transformation matrix from the $j^{th}$ OBB to the global coordinate system (GCS), $\mathbf{T}_{OBBj}^{i}$ is transformation matrix from the $j^{th}$ OBB to the LCS of the $i^{th}$ arm link and $\mathbf{T}_{i}^{g}$ is transformation matrix from the LCS of the $i^{th}$ link to GCS.

Relevant rows of the matrices $\mathbf{T}_{OBBj}^{g}$ are then directly used as unit vectors $\mathbf{a}_i$, $\mathbf{b}_i$ and center points A, B.

### E.5.5 Practical Performance Test and Analysis

Only one phase of collision check will be considered for simplicity. Up to 43 OBB pairs must be tested for intersections. All these 43 tests will be performed if there are no collisions; if a collision is found in an early pair, the rest of the phase can be skipped. It thus may seem to be more efficient to start with the pairs that have the highest probability of collisions during normal operation of the robot, but there will be a potential positive effect of this step only when a collision really occurs. In any case, the order of pairs is not crucial and the pairs are not intended to be sorted online.

For every OBB pair, up to 15 separating axes will be checked. A big advantage of the separating axis theorem is that all 15 axes need to be verified only very rarely. If the boxes are not penetrating and a valid separating axis is found for example in the second step, the remaining 13 steps can be completely skipped.

A practical test on the robot *Hardy* was executed with statistical data being written to a log file. The test was 70 seconds long and during this time the arm was navigated to various positions in the whole operating range, simulating intensive use of the robot. The control system was running at approx. 88 Hz and 6160 frames were calculated and written to the log file.

Collision was detected in 303 frames, which is 5% of the running time. Operator is notified of a collision and usually changes his commands, so this relatively small number of frames with collisions is common. All 43 OBB pairs were tested in frames with no collision and 24.2 OBB pairs in average were tested in frames with a detected collision.

The most important indicator is the number of separating axes checks. Average number of separatix axes checked every frame is 77.7 and average number of SA checked for every OBB pair is 1.87 (out of the maximal 15 possible separating axes for OBB–OBB test).

Effectiveness of the algorithm is evident from Table E-1, where all individual OBB-OBB intersection tests were aggregated. The table shows total number of times when the separating axis theorem finished after *n* axes (*n* = 1, 2, ... 15). The maximum number of axes ever tested in case of no collisions was 10. The 303 occurrences of all 15 SA tests correspond to the 303 frames with collisions, because collision can be proven only after going through all 15 SAs.

**Table E-1: Statistical Data of Complexity of 259175 Intersection Tests.**

| Sep. Axes | Occurrence |
|---|---|
| 1 | 126201 |
| 2 | 56713 |
| 3 | 73839 |
| 4 | 66 |
| 5 | 1009 |
| 6 | 543 |

| Sep. Axes | Occurrence |
|---|---|
| 7 | 277 |
| 8 | 20 |
| 9 | 27 |
| 10 | 177 |
| 11 | 0 |
| 12 | 0 |
| 13 | 0 |
| 14 | 0 |
| 15 | 303 |

Another interesting fact is that 99.1 % of all OBB–OBB tests finished after checking only up to 3 separating axes and 99.7 % during the first six checks. This is very good for performance, because the first 6 possible separating axes are faster to calculate, see equations (15) and (16).

Average duration of the whole anti-collision algorithm in one frame, including matrix transformations from equation (10), is approximately 20 µs on a low-end CPU Intel Celeron 430 (1.8 GHz), which is a negligible time.

Collection of oriented bounding boxes is a sufficient replacement of real shapes of mechanical components of a robot and if higher collision accuracy is needed, it is possible to use bigger number of smaller boxes instead of one large. Bounding boxes can also be arranged in a hierarchy (tree) [51] with quick preliminary tests eliminating whole subsets (branches). The separating axis theorem used to test intersections between pairs of oriented bounding boxes is very efficient and requires insignificant amount of CPU processing time if implemented properly.

This method is very versatile and flexible and can be applied to any manipulator arm or similar mechanical device mounted on a mobile robot as you can see in Figure E-44, or even for example to industrial robots.

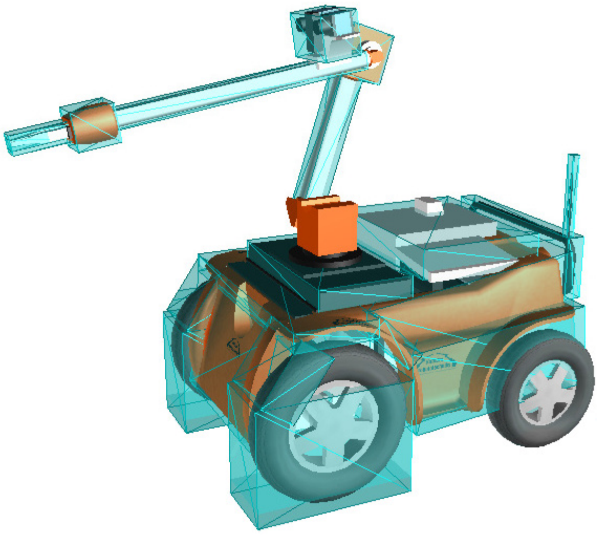

**Figure E-44: Simplified OBB Representation of the Mobile Robot.**

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The work of the NATO Task Group SAS-097 took place from January 2012 to January 2015, and its achievements were: analyzed the gap between operational requirements and technological possibilities and described it in the report; contributed to bridging the gap between cutting edge of technology and military operational needs by participating at several meetings and exhibitions; provided experimentation support for robotics concept development and testing (TARDEC, Czech military project TAROS, being in touch with two European Commission funded research projects NIFTi and TRADR, dual-use of technologies); organized NATO supported workshops in Prague in 2012, Paris in 2013, in Prague in 2013, in Rome in 2014; created and supervised bidirectional working links to the European Commission R&D activities in dual-use of robotics (the talks with European Commission and its public-private-partnership vehicle in robotics euRobotics AISBL were positive); and opened possibilities for the new robotics research motivated by military needs and funded by third parties.

People from 10 NATO member countries contributed to SAS-097 results.

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