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Army Science Board
Fiscal Year 2016 Study

Robotic and Autonomous Systems-of-Systems Architecture

Final Report
January 2017

Department of the Army
Office of the Deputy Under Secretary of the Army
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March 13, 2017

DUSA-ASB

MEMORANDUM FOR SECRETARY OF THE ARMY

SUBJECT: Final Report of the Army Science Board, "Robotic and Autonomous Systems-of-Systems Architecture"

1. I'm pleased to forward the final report of the Army Science Board (ASB) study titled "Robotic and Autonomous Systems-of-Systems Architecture." The study sought to identify which Army formations have the greatest potential to benefit from adopting robotic and autonomous systems (RAS) technology in both the near and long terms. The scope of the study included a review of current investments in autonomy software and the integration of RAS into manned and unmanned teams. The study team also made a compelling case for the Army to increase its development of RAS by identifying some intractable warfighting challenges posed by near-peer adversaries and demonstrating how RAS opens the design space for solutions that, coupled with innovative CONOPS, change the character of warfare and present multiple dilemmas to the adversary.

2. For this effort, the ASB brought subject matter experts in Electrical Engineering, Computer Science, Aeronautical Engineering, Mechanical Engineering, Telecommunications, Physics, ISR, Air Defense, Modeling & Simulation, Analytics, Robotics, and a variety of military operations and technologies, as well as former Army leaders. During its seven months together, the study team conducted over thirty visits and interviews among Army and DoD agencies, Federally Funded Research and Development Centers, Academe, and commercial industry.

3. As a result of their work, the study team made a number of findings. The most significant detailed how the weaponization of RAS technology will be inexorable and will change the character of warfare. Regardless of what the Army does, adversaries are aggressively pursuing RAS and Soldiers will face it on the battlefield. To counter this reality, the study team recommended the Army begin a campaign of learning to evaluate the operational utility of RAS and to begin developing CONOPS and TTPs. The findings and recommendations were adopted by unanimous vote of the ASB on July 16, 2016.

4. I hereby endorse the findings and recommendations in this report.

James A. Tegnelia
Chairman

TABLE OF CONTENTS

Executive Summary 1

1 Introduction 7
- 1.1 Terms of Reference (TOR), Team, and Information Sources 7
- 1.2 Study Approach and Lines of Inquiry 7
- 1.3 The RAS Environment 9

2 Autonomy 11
- 2.1 Key Terms and Definitions 11
- 2.2 Cognitive Functionality 12
- 2.3 Advances in Autonomy 13
  - 2.3.1 Limitations of Current Autonomous Systems 13
  - 2.3.2 The Future of Autonomy 13

3 RAS Concepts and Benefits 16
- 3.1 Intelligence Warfighting Function 17
- 3.2 Mission Command Warfighting Function 17
- 3.3 Movement and Maneuver Warfighting Function 18
- 3.4 Fires Warfighting Function 18
- 3.5 Protection Warfighting Function 19
- 3.6 Sustainment Warfighting Function 19

4 Counter-Armor RAS Concept 20
- 4.1 The Challenge 20
- 4.2 RAS Counter Armor Capability as a Potential Solution 21
- 4.3 CONOPS for High Lethality Unmanned System Application 24
- 4.4 Autonomy Evolution 25
- 4.5 Campaign of Learning 26

5 RAS Counter-IAD Concept 28
- 5.1 The Challenge 28
- 5.2 The RAS C-IAD Concept 29
- 5.3 Concept of Operations 32
- 5.4 Evolution of Autonomy 35
- 5.5 Campaign of Learning 35

6 RAS Architecture 37
- 6.1 RAS Architecture Requirements 37
- 6.2 Systems-of-Systems Interfaces and Interactions 38
- 6.3 Modular Open Systems Architecture 39

7 Research and Development (R&D) 42

7.1 Human-RAS Collaboration 42
7.2 Countermeasures 44

8 The Way Ahead 46
8.1 Advocacy 46
8.2 Trust 47
8.3 Verification and Validation, Test and Evaluation 47

9 Findings and Recommendations 50
9.1 Findings 50
9.2 Recommendations 53

APPENDICIES

A. Terms of Reference 55
B. Study Team Members 57
C. ASB Approved Briefing, Findings & Recommendations (July 28, 2016) 58

LIST OF FIGURES

1.1 Study Team Visits and Interviews 8
2.1 The Future of Autonomy 14
4.1 Man/Unmanned Vehicle Comparison 21
4.2 Combat Vehicle Lethality and Laden Weight 23
4.3 Robotic Armor Concept 24
4.4 Robotic Vanguard CONOPS 25
4.5 Evolving Levels of Autonomy 26
4.6 Campaign of Learning 26
5.1 J-SEAD vs. IADS 29
5.2 RAS Offers Convergence of J-SEAD Functionality in Small Attritable UAS 30
5.3 Modular Payload UAS 31
5.4 Nominal UAS Payloads with Small SWaP 31
5.5 UAS Design Space 32
5.6 Counter IADS CONOPS 1 33
5.7 Counter IADS CONOPS 2 33
5.8 Counter IADS CONOPS 3 34
5.9 Evolving Levels of Autonomy 35
5.10 Campaign of Learning 36
6.1 RAS System-of Systems Architecture 39
6.2 Modular Software Partitioning 40
6.3 Upgrading RAS Cognitive Functionality 41
8.1 T&E to Build Trust in RAS 49

EXECUTIVE SUMMARY

This report summarizes the 2016 study conducted by the Army Science Board (ASB) on "Robotic and Autonomous Systems-of-Systems Architecture." The study was requested by the Secretary of the Army under the sponsorship of the Commanding General, U.S. Army Training and Doctrine Command (TRADOC). Among the tasks requested by the Terms of Reference (TOR) for the study, ASB was asked to define the operational benefits to Army formations from adopting Robotic and Autonomous Systems (RAS) technologies, and to Investigate the operational and systems architecture that would provide the best disruptive and innovative capabilities.

Autonomy likely to change the character of warfare

The impetus for this study lies in the dramatic growth of unmanned systems and autonomy over the past decade. Most observers would agree that the world has experienced a "tipping point" in the application of autonomous technologies in both the civil/commercial and military sectors. Also, it's widely accepted (as is the case with most disruptive technologies) that this tipping point will inevitably lead to a dramatic increase in demand and generate new capabilities, new businesses, and new ways of doing business - or of waging war.

The Army has already benefitted from the introduction of RAS on the battlefield, but with limited autonomy. Unmanned Aircraft Systems (UAS) were initially used for Intelligence, Surveillance and Reconnaissance (ISR) purposes. The introduction of both sensor and shooter capability on a single UAS (e.g., Predator) has demonstrated the capabilities of UAS beyond ISR applications and has opened the door for a variety of other UAS applications. Unmanned Ground Vehicles (UGVs) were initially deployed as tele-operated systems for detection and disposal of explosive ordnance and improvised explosive devices (IEDs) in response to Joint Urgent Operational Needs (JUONS) in OEF and OIF. However, they have evolved to the point where they show potential to contribute to a variety of other applications, from autonomous ground convoys to remotely controlled tanks.

Adversaries have also deployed RAS and appear intent on taking advantage of ubiquitous RAS technology to counter U.S. capabilities. This initial, limited use of RAS by both US Joint Forces and adversaries has already started to change the character of warfare, but even greater changes seem inevitable as autonomy continues to improve. Both friendly and adversarial nations will continue to develop and adopt new uses for battlefield autonomy. How the Army chooses to respond to adversaries' RAS capabilities, whether proactively or reactively, will shape how the Army fights in future conflicts.

The underlying technologies for RAS are ubiquitous. Private sector investment in autonomous and collaborative technologies is growing and will likely far exceed military spending in the future. The US does not necessarily have an asymmetric advantage in these technologies, nor is it likely to gain a disruptive advantage as the trends toward globalization and commercialization continue. Consequently, disruptive capability will rely on both technology and the Concept of Operations (CONOPS) that dictate how the technology is used.

Potential Opportunities and Representative Point Designs

The study endeavored to understand the operational benefits of RAS to the Army, and the underlying attributes of RAS contributing to these benefits. The study determined that there are two fundamental factors that allow RAS to augment military formations and provide better solutions to difficult warfighting challenges than manned systems and/or more traditional solutions. The first benefit's that RAS opens the design space for material solutions. This greater design space allows smaller, lighter and more affordable solutions with equivalent or greater effectiveness than manned system. But, perhaps even more important is the second factor; the ability for Joint Force Commanders to innovate with CONOPS and Tactics, Techniques and Procedures (TTPs) that aren't viable with manned systems.

The study postulated and defined two advanced RAS capability concepts to better understand how these two fundamental factors—opening the design space and enabling innovative CONOPS—contribute to operational effectiveness in the context of tough warfighting challenges that traditional, manned systems cannot efficiently solve. One concept examined adding a remote controlled, counter armor UGV (i.e., a robotic tank) to a Stryker Brigade Combat Team (SBCT) to enable the SBCT to defeat enemy armor formations without compromising deployability or maneuverability. The second concept evaluated the use of UAS to conduct localized Suppression of Enemy Air Defenses (SEAD) against capable threat Integrated Air Defense Systems (IADS).

To understand the operational benefits and technical feasibility of the concepts at a concrete level, point design instantiations of each were formulated. In the case of the counter armor UGV, the design space is opened by eliminating requirements for crew survivability or other crew-imposed environmental factors (e.g., overpressure from a gun, 6-watt ride, nuclear, biological and chemical gear, etc.), leading to a smaller, lighter and lower cost system than a manned vehicle. The point design selected for evaluation was a 25-ton class, robotic UGV with lethality equivalent to an M1-A2 tank, survivability equivalent to a Bradley armored vehicle, and deployability and maneuverability equivalent to or better than a Stryker armored vehicle. This material solution enables innovative CONOPS and TTPs by providing an SBCT with a capability it lacks to counter massed armor and the ability to use autonomy for a variety of maneuver, targeting and direct fires functions as technology advances.

For the Counter IAD RAS, the design space is opened through several factors, beginning with reducing the size, weight, and cost by removing people from the platform. In addition, continued advances in autonomy and electronic miniaturization allow for the convergence of ISR, signals intelligence (SIGINT), electronic attack (EA) and kinetic attack payloads in a small Size, Weight and Power (SWaP) form factor. The point design instantiation of this concept was a modular, low cost "attritable" loitering UAS platform capable of carrying a variety of field replaceable modular payloads. The modularity provides a multi-mission, mix-and-match payload capability that enables Joint Force Commanders the flexibility to tailor the capabilities for each mission based on the specific threat and mission objectives, which facilitates

innovative CONOPS. A CONOPS was postulated for one specific mission to illustrate this flexibility. The mission utilized the loitering UAS with its various payloads to open a temporary local corridor though the threat's mobile tactical IADS to allow for Army combat aviation to conduct a deep shaping CAS mission.

These two RAS point designs and their associated CONOPS were selected as representative of the wide spectrum of ways RAS can address Army warfighting challenges. Both were based on mature RAS technologies to provide near-term initial operational capability. Moreover, if architected correctly from the beginning, they can easily capitalize on new, autonomous technology developed by private industry or the government in the coming years to provide a growth path for continuous capability improvement.

Overcoming Impediments to Adoption

Despite these operational benefits, the mature technology status for near-term deployment and a path for continuous improvement in autonomous capabilities, the Army plans for future RAS Programs of Record (PORs) are modest at best. Therefore, in addition to answering the question "why RAS?" the study addressed the equally important question of why the Army is not more aggressively transitioning autonomous system technologies into PORs. The principal factor appears to be a lack of advocacy for RAS by Army leadership, with an attendant lack of funding.

The study concluded that there are three factors underlying the lack of advocacy and funding. First, authority and responsibility for RAS in the Army is fragmented. Second, the Army's Total Obligation Authority (TOA) is unlikely to grow to provide Research and Development (R&D) and procurement funding for new RAS PORs, so there's the typical, organizational resistance to reallocating funds away from current PORs to initiate new PORs. The third factor is a lack of trust among Army leaders that RAS can fully realize the capability gains many RAS proponents claim.

To address the underlying factors for developing advocacy, Army leadership must be convinced that the promise of RAS can indeed be realized. A campaign of learning is required to build this compelling case. Objectives for the campaign of learning should include validating operational value, evaluating innovative CONOPS and TTPs, maturing critical hardware and software and system interfaces, informing capability needs as input to a future Army Requirements Oversight Council (AROC), and, most importantly, building the trust of leadership.

Simulation, prototyping, experimentation and operational assessments all play important roles and will need to be coordinated into a single integrated program. Experimentation should start by using surrogate vehicles for demonstrations of operational interfaces and communications to control costs and speed the process of learning. Successful concepts, appropriately modified with feedback from the experimentation program, could then progress to prototyping of critical components and capabilities, again using surrogates as appropriate, and culminate with rapid prototyping of purpose-built systems for evaluating integrated capability against a live-OPFOR.

For each campaign of learning (Armor and C-IAD), the speed of development, a firm (non-tradeable) cost target, and a willingness to fail, learn, and improve are essential.

RAS Architecture: the key for growth

An autonomous system will operate as one system within a system-of-systems (SoS) environment. Other systems with which a RAS must interface and interact include the controller/collaborator, higher echelon commanders, data consumers (e.g., Processing, Exploitation and Dissemination (PED) cells), the external environment (which the RAS senses and sometimes manipulates), off-board collection and information systems, other RAS, and the larger, data "cloud." The RAS itself will continuously evolve within this SoS environment, but so will the other SoS entities. While the RAS POR manager will have control of the RAS, the manager will generally not have control of the other entities. Therefore, it will be important for the RAS architecture to ensure interoperability of the interfaces and interactions with the other entities as they continuously evolve. Efforts are underway to define the open system standards and protocols for these interfaces and interactions, but it will be important for a single, multi-service set of open system standards to emerge from several different efforts currently underway.

RAS are inherently software intensive. The software that controls all system functions is generally written by the system prime contractor and often highly coupled to platform-unique dynamics (e.g., inner control loops) and other platform specific design attributes (e.g., signatures, failure modes). Also, there's typically no requirement to functionally partition the software architecture into separate and isolated platform-unique functions versus mission functions. The software may also contain proprietary code. These conditions make it difficult to upgrade software or to add new capabilities on a schedule commensurate with electronics maturation cycles without expensive coding, verification and validation (V&V) and regression testing by the prime contractor. Thus, to fully exploit advances in autonomy and human-RAS collaboration, it's essential for the RAS software to have a modular, functionally-partitioned, open systems architecture that enables a continuous insertion of "best of breed" cognitive software modules from independent developers.

Findings

To summarize, the ASB study team made the following findings:

1. Regardless of how Army proceeds, the application of ubiquitous RAS technology on the battlefield is inexorable and will change the character of warfare; adversaries are aggressively pursuing.

2. Technology alone will not provide an asymmetric advantage; CONOPS also need to be innovative and disruptive.

3. RAS offers solutions to difficult warfighting challenges because it opens the design space and enables innovative CONOPS.

4. Counter-Armor RAS and Counter-IAD RAS are excellent points of departure for understanding RAS operational utility by integrating mature technology.

5. Three factors limit advocacy and funding for RAS with greater autonomy:
   - Fragmented authority and responsibility for RAS.
   - Organizational resistance to reallocation of funds from current PORs.
   - Lack of trust.

6. An integrated campaign of learning is needed to evaluate innovative CONOPS, validate operational value, develop next generation autonomy, inform capability needs for future AROC, and to build trust.

7. RAS architecture is important to:
   - Ensure the interoperability of RAS in a continuously evolving Systems-of-Systems environment; many open architecture systems in development.
   - Allow for independent development of high order cognition software (S/W) applications and facilitate insertion of "best of breed" applications into current and future RAS.

Recommendations

Based on these findings, the study developed two recommendations. The first addresses those findings associated with lack of Army leadership advocacy for new RAS with greater autonomy and collaboration. Advocacy must start from the top and build on convincing evidence that RAS can deliver as promised. Among the actions that must be taken to build the evidence are a RAS-focused campaign of learning and advanced concept design. Given the operational benefits inherent in the two concepts studied, it's recommended that the Counter Armor and Counter IAD concepts be used as the advanced concept design activity. As they become available, results from these efforts, which should be conducted in parallel, should be consolidated and synthesized into a set of initial capability requirements for future RAS.

1. CSA issue an EXORD that:
   - Establishes a RAS focused Army Campaign of Learning for evaluating operational utility of RAS and developing RAS CONOPS and TTPs. The campaign should include simulation, prototyping, limited fielding, experiments & warfighting assessments
   - Initiates the advanced concept design of a) an attritable robotic counter-armor capability and b) an attritable, autonomous loitering UAS with a modular payload design that provides a counter IAD capability
   - Establishes an AROC committee to develop requirements based on inputs from the campaign of learning and the concept design

- Designates a central RAS advocate

The second recommendation provides the essential building blocks for future RAS development. These building blocks include an inter-service modular open system architecture that enables RAS interoperability within a system-of-systems environment and that facilitates continuous insertion of independently developed, autonomous software over the life cycle of a RAS. The other essential element is a high-fidelity simulation toolset for RAS, which is critical for all life cycle phases of a future RAS, from initial design and development through V&V and test and evaluation (T&E), and for operator or collaborator training. Simulation will be particularly important for understanding RAS behavior and calibrating trust in RAS behavior in complex environments.

2. ASA(ALT):
   - Working with Joint Services, define a modular open system architecture that allows for independent development of high order cognition S/W applications and that facilitates insertion of “best of breed” applications into current and future RAS.
   - Develop a high-fidelity simulation toolset for understanding RAS behavior in complex environments; for calibrating trust confidence levels of RAS under dynamic conditions; and for design, development, V&V, T&E, training and life cycle management.

1 INTRODUCTION

This report summarizes the 2016 study conducted by the ASB on "Robotic and Autonomous Systems-of-Systems Architecture," which was requested by the Secretary of the Army under the sponsorship of the Commanding General, U.S. Army Training and Doctrine Command (TRADOC).

The motivation for studying an expanded role of RAS in Army operations grew out of the dramatic developments around the use of unmanned systems and the advancement of autonomy in both civil/commercial and military applications. The spread of information sciences and related technologies has driven the global growth of RAS, which will ultimately reshape the character of warfare. The way the Army responds to this inexorable shift toward greater autonomy will determine how it fights future conflicts.

The Bottom Line

The Army finds itself at an impasse on developing and deploying more capable RAS, even while RAS is becoming globally ubiquitous and adversaries are developing and deploying them.

1.1 TERMS OF REFERENCE (TOR)

Specific tasks the Secretary of the Army requested the ASB to accomplish under the TOR (Appendix A) included:

- Defining the benefits from adoption of Robotic and Autonomous Systems (RAS) technology.
- Investigating the operational and systems integration or architecture that will provide disruptive and innovative capability.
- Identifying approaches to human-system collaboration demonstrated in the research community and recommend further research.

The ASB study team members came to understand that to address these tasks, they needed to answer the more fundamental question: "why RAS?" That is, to adequately answer the TOR, the benefits of RAS needed to be studied on a more concrete, operational basis.

1.2 STUDY APPROACH AND LINES OF INQUIRY

The ASB study team (Appendix B) had a broad level of expertise in the evaluation, development, acquisition and testing of RAS, including both Unmanned Air Systems (UAS) and Unmanned Ground Vehicles (UGVs). Members also brought experience in many of the supporting technologies, including command/control, communications, platform design, mission systems, avionics and electronics, software, on-board processing, and data analytics.

Lines of inquiry were established with numerous Army, Navy, Air Force, Office of the Secretary of Defense (OSD) and Joint Staff offices to gain an understanding of the current RAS environment, including Science and Technology (S&T) initiatives, development and deployment of Programs of Record (PORs), operational experiences, and strategies and plans (Fig 1.1). In addition, a wealth of information was available to the study from several other recent studies on RAS conducted by the private sector, as well as government agencies and advisory boards, to include the Defense Science Board (DSB).

Army
- **DASA(R&T), G3/5/7**
- **TRADOC ARCIC, G2, G9, TRAC**
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Other Services
- **Air Force Research Lab (AFRL), A3**
- **Office of Naval Research (ONR), Naval Air Warfare Center (NAWC)**

Joint
- **Joint Staff, J8**
- **OSD PD ASD(R&E), CAPE, DARPA**

Other
- **Software Engineering Institute (SEI)**
- **Industry RFI**
- **Studies, Roadmaps, and Strategy Docs**

Figure 1.1 Study Team Visits and Interviews

In settling on a study approach and methodology, scope became a concern. While the operational benefits of RAS are well understood at a general and abstract level (i.e., using RAS for dull, dirty and dangerous missions), the study team determined they needed to define RAS concepts within the context of specific warfighting challenges and functions. The problem with this approach, however, is that there are numerous potential RAS applications; and the operational benefits of each are functions of many independent variables, including type and phase of conflict, mission, scenario, task and threat sophistication, etc. Clearly, an exhaustive evaluation of all the possible combinations of RAS applications was not feasible.

The study team settled on a two-level approach to the evaluation. At the first level, RAS concepts were postulated for each of the six Army Warfighting Functions at a top level of definition, with generalized benefits identified on a conflict/scenario independent basis. From

these, two representative concepts were selected (one UAS and one UGV) for more detailed definition and evaluation. A representative point design instantiation of each concept (out of many possible instantiations within the concept design space) was developed to examine operational utility within a representative vignette. The vignettes were selected within the context of a scenario representative of a near peer adversary, with highly capable Integrated Air Defenses (IAD) and highly challenging armor and indirect fires (IDF) capabilities.

The point designs were also used to examine the autonomy and human-RAS collaboration capability needs of each concept and the likely evolutionary path of autonomy improvements for each (Sections 4 and 5 below). They were also used to identify system-of-systems and system-level architecture attributes required to ensure that the concepts could continuously improve autonomous functionality and collaboration from the near-term through the far-term (Section 6 below).

1.3 THE RAS ENVIRONMENT

Currently, DOD is conducting significant research in RAS, which includes research performed in the Army's S&T enterprise. This work presents pioneering developments in autonomy and human-RAS collaboration technologies that will be critical to the future growth of autonomous systems in Joint Force applications. But while the S&T activity is impressive, the transition from S&T to a POR has been modest to date. The Army has several UAS and UGV PORs, but the autonomous functionality and human-RAS collaboration of these systems is limited, relative to the full potential that can and will eventually be achieved.

Advances in RAS technology and applications aren't limited to the defense sector. Commercial industry investment in RAS has grown substantially over the past decade. Within the commercial ground vehicle sector, autonomous functionality in automobiles (e.g., hands-off parallel parking and automatic braking for collision avoidance) has developed at a consistent pace. Several companies are investing heavily in driverless cars. In terms of air platforms, the FAA has had to release guidance for the use of small UAS to allow companies to operate them for commercial purposes. Companies are now operating small UAS for multiple commercial applications, ranging from precision agriculture to critical infrastructure monitoring and inspection. In most cases, the UAS companies selling small platforms have embedded autonomous functionality within the flight control system to facilitate control from laptop-type interfaces, replacing the need for training and dexterity in manual stick-and-throttle types of controls.

Development of autonomous systems technology and the production of unmanned systems is global and ubiquitous. The best-selling commercial UAS is a Chinese product. If this technology follows other pervasive technologies that were spawned in the defense sector, it's very likely that commercial industry research and development (R&D) in RAS will far exceed military or defense R&D. The significant implications for the U.S. will be that it won't enjoy a competitive advantage in RAS technologies or applications in the commercial arena, nor will it maintain a competitive advantage in RAS technology in the future.

These trends have led to an important thesis in this study: that U.S. Joint Forces will have difficulty gaining a disruptive advantage over adversaries based on the development and advancement RAS technology alone. In other words, U.S. forces can't rely on the nation's industrial base as their predecessors had in past wars. Innovative Concepts of Operation (CONOPS) that integrate RAS into the force and deploy/employ RAS on the battlefield will be more effective than the latest developments in technology.

Following that line, the study found several warfighting challenges where conventional, manned systems couldn't accomplish the mission, but RAS provided potential solutions. Among these are: (1) the loss of air superiority against the capable Integrated Air Defense Systems (IADS) of near peer adversaries; (2) deployability and maneuverability difficulties for Armored Brigade Combat Teams (ABCTs); and (3) limited lethality of Stryker Brigade Combat Teams (SBCTs) and Infantry Brigade Combat Teams (IBCTs) against massed armored forces.

RAS offers potential responses to these challenges by opening the design space for material solutions with equivalent or better effectiveness than those offered by manned systems. For example, RAS assets can be attritable. RAS also provide size, weight, power, and fuel consumption advantages that improve deployability and maneuverability while reducing the logistics burden. The material advantages open the door for innovative and disruptive CONOPS that can change the character of warfare and present multiple dilemmas to adversaries.

While the Army has fielded some UAS and UGV systems and used them successfully in recent conflicts, it's widely acknowledged that these systems have limited autonomy and therefore represent the tip of the iceberg in terms of the full potential that greater autonomy and human-RAS collaboration can achieve. Impressive S&T work has laid the foundation for leap-ahead capabilities and numerous warfighting experiments have evaluated the operational utility of advanced RAS capabilities. However, despite these S&T activities, the transition to acquisition programs has been limited and there's been little funding for RAS PORs with greater autonomy. This drove the study's second key question: what's preventing the full-scale engineering development and fielding of RAS with greater autonomy and disruptive capabilities?

The study team concluded a lack of institutional advocacy within the Army is the fundamental hurdle, and three factors underlie the lack of advocacy and funding: (1) authority and responsibility for RAS in the Army is fragmented; (2) the Army's Total Obligation Authority (TOA) is unlikely to increase to provide the funding for new RAS PORs due to the organizational resistance inherent in any effort to reallocate funds from current PORs, which have strong advocates, to new PORs, which have fewer advocates; and (3) the lack of trust that the promise of RAS will be fully realized (see Section 8.2).

2 AUTONOMY

Any study of RAS requires a clear understanding of "autonomy" and related terms relevant to the application of autonomy to unmanned systems.

2.1 KEY DEFINITIONS AND TERMS

The term "autonomy" evokes widely disparate perceptions among different practitioners and audiences. Scholars have developed a considerable body of knowledge on the subject over the past decade, but have yet to form a consensus on the best definitions. The study team didn't attempt to add its own unique definitions to this burgeoning field, but rather adopted definitions from several recent reports which best capture the meanings used for the study,[1] including the following:

- **Autonomy** – the level of independence that humans grant a system to execute a task within specified boundaries. It's the condition or quality of being self-governing to achieve an assigned task based on the system's own situational awareness (SA) (integrated sensing, perceiving, analyzing), planning and decision-making. Autonomy is a spectrum of automation in which independent decision making can be tailored for a specific mission, level of risk, and degree of human-machine teaming

- **Artificial Intelligence (AI)** – the capability of a computer system to perform tasks that normally require human intelligence. Big data analytics, computer vision, pattern recognition, speech recognition, and natural language are among the applications for which AI is particularly adept.

- **Expert System** – an approach to AI in which human domain expertise is captured in the form of rules and criteria, which are translated into software code. Expert system algorithms are generally deterministic, i.e., results from the same set of inputs are repeatable.

- **Machine Learning** – an approach for achieving AI in which the computer does not follow specifically coded software instructions, but is trained (by means of massive data inputs) to learn how to perform tasks when ingesting and manipulating new data under unspecified conditions. Machine learning algorithms are typically non-deterministic, i.e., different results may be generated by the same inputs or stimuli. The variability of results is a natural consequence of the computer continuing to learn as it processes new information.

- **Cognitive Function** – an analysis, planning or decision activity that make up a complex task. Cognitive functions can be allocated to either the human operator or the

[1] Primarily from the Defense Science Board Summer Study on Autonomy, June 2016, and the National Science and Technology report "Preparing for the Future of Artificial Intelligence," October 2016

computer, either a priori or during the mission. Independent actions resulting from allocated computer cognitive functions are restricted by human imposed constraints.

- **Dynamic Autonomy** – the active allocation of cognitive functions to RAS and the adjustment of imposed constraints on the cognitive functions in response to changing battlefield conditions, levels of risk and rules of engagement

Several points need to be emphasized to understand the study team's use of the term "autonomy" and to clear up some common misconceptions about autonomy that have arisen in popular media. First, autonomy involves the cognitive functionality granted by humans to RAS and supervised by humans at some level. The supervision may vary from extremely tight (man-in-the-loop) to very loose (man-on-the-loop), depending on specific applications and missions. Second, allocation of cognitive functionality can and should be dynamic to match changing battlefield conditions. Third, humans constrain each allocated autonomous function by imposing boundaries on the actions each RAS can take. From this study's perspective, RAS always operates within rules established by human operators and/or collaborators; autonomy is neither unbounded nor unsupervised. Last, autonomy is neither binary, nor even a quantum set of discrete "levels," but a continuous spectrum of capabilities resulting from an almost infinite variety of cognitive functions, allocations and constraints.

2.2 COGNITIVE FUNCTIONALITY

The catalyst behind public concerns over RAS developing a "will" of its own, particularly for applications employing machine learning, lies in the notion of cognitive functionality. Cognitive functions allocated to RAS will evolve over time in several different dimensions or domains. In the first of these domains, functionality may be characterized as non-kinetic or kinetic, or what the DSB has referred to as autonomy at rest and autonomy in motion. The non-kinetic domain is functionality that operates in the electromagnetic (EM) spectrum and/or is used for digital processing of information. The kinetic domain includes both lethal and non-lethal applications. A second dimension in which cognitive functionality may be characterized is the extent to which AI is used, spanning a spectrum from deterministic rules-based expert system algorithms to functionality employing non-deterministic machine learning. A third dimension is the extent of human-RAS collaboration enabled by the cognitive functions, spanning a range from non-collaborative functionality, in which the RAS is employed strictly as a "tool" of the human operator, to fully collaborative, in which the human and RAS are equal partners, sharing a common world view and situational understanding, but otherwise acting independently to achieve mutual goals (e.g., commander's intent).

The cognitive functions of current Army RAS fall to the far "left" of the AI and collaboration dimensions. This results in operational limitations which restrict the potential benefits of RAS to the warfighter. However, cognitive functionality is expected to advance rapidly to the "right" of these spectrums due to the tremendous investments in AI and machine learning across the globe.

2.3 ADVANCES IN AUTONOMY

The limitations of current RAS are easy to quantify. More difficult, but nonetheless possible, are the likely evolutionary paths RAS will follow within the kinetic and EM/digital domains, which will unleash the full potential of RAS from its current limitations.

2.3.1 LIMITATIONS OF CURRENT AUTONOMOUS SYSTEMS

The Army has successfully deployed RAS on the battlefield. While these systems have been useful, they have limited autonomy, which places limitations on the battlefield effects they can produce. These limitations include:

- Manning: Operating and maintaining a single RAS generally requires multiple skilled Soldiers, and forward deployed units must generally dedicate Soldiers to operate a RAS, taking them out of the fight.

- Supervisory Control: Tight supervision is required, with near-constant control of the RAS. To date, control stations are typically unique to each RAS due to proprietary technology and the lack of a common open architecture.

- Communications: The current communications architecture generally requires a dedicated high bandwidth RF link between RAS and operator that is potentially vulnerable to jamming and cyber-attack. Dissemination of RAS data to other echelons is limited.

- Mission Flexibility/Adaptability: A RAS is generally dedicated to a single mission in low tempo operations. While there have been some notable exceptions recently (e.g., Predator, Gray Eagle), the current generation of RAS are generally not easily adaptable to other missions or to unanticipated environments at least in part due to proprietary software architectures.

- Collaboration: RAS is usually operated as a stand-alone entity at safe distance from Soldiers. RAS is used as a tool rather than a collaborative entity.

2.3.2 THE FUTURE OF AUTONOMY

Advanced autonomy offers the promise to overcome the limitations of current RAS and thereby provide much greater operational utility to the warfighter (Figure 2.1). Current capabilities are limited by functionality that falls within the rules-based (deterministic) and non-collaborative ends of the spectrum (for both kinetic and non-kinetic applications), but will improve through greater use of AI and collaboration. However, this evolution of autonomy is not binary (e.g., not all functions are either rules-based or use machine learning). A broad spectrum of cognitive functionality is possible between the extremes. The Army can benefit from improved autonomy in the near-term and shouldn't wait for the "holy grail" of machine learning functionality to be

fully realized to develop and deploy RAS that would otherwise have much improved effectiveness over currently deployed systems.

The Future "Promise" of Autonomy

Parameter	Current	Far Term Future
Manning	Many soldiers to few RAS	Many RAS to few soldiers
Supervision	Tightly controlled	Little to no control
Communications	Constant RF link	Intermittent RF; use of natural language/gestures
Operating Environment	Low tempo; fairly static	High tempo; complex & dynamic
Proximity	Safe distance	Close to soldiers
Scale	One or few RAS	Multiple RAS
Collaboration	None	Human-RAS and multi-RAS

But, Army does not need to wait until the full promise is realized. Operational Effectiveness of RAS can be improved in near to mid term through evolutionary advances in autonomy

Figure 2.1 The Future of Autonomy

In the non-lethal, kinetic domain, current functions include autopilots, waypoint navigation and if-then vehicle contingency management (e.g., if loss of communication control link, then return to base). Within this domain, more advanced functionality that may be expected in the next decade may use a mixture of deterministic and non-deterministic algorithms include collision/obstacle avoidance in complex environments and/or terrains, and coordinated multi-agent maneuvers. Far-term non-lethal kinetic functionality will be largely AI-enabled, including self-organizing, multi-agent collaboration (e.g., swarms) and human-RAS collaborative motion with RAS in close proximity to Soldiers.

In the lethal, kinetic domain, current functionality is limited to remotely controlled human-in-the-loop operations (e.g., "eyes-on-target" weapons release from Predator or fire authority for fire-and-forget weapons), which conforms with DOD policy. In the near- to mid-term, human-in-the-loop fire control will continue, but some autonomous functionality, such as "slew-to-source-of-fire" on a remotely controlled robotic armor vehicle, may be implemented. It's highly contentious whether DOD policy for human-in-the-loop control of robotic weapons will ever be waived, even if adversaries develop and deploy fully autonomous lethal robotic systems. Regardless of whether lethal authority will ever be delegated to RAS, in the far term, more AI-enabled functions, such as intelligent maneuvering and multi-RAS collaboration (e.g., synchronized fires) can be anticipated.

The EM and digital processing domains are the most fertile for rapid advancement of cognitive functions utilizing AI and machine learning. Currently, EM and digital functions include RF signal processing, image processing (e.g., autonomous target recognition) and signal recognition for electronic attack (EA) within a prescribed library of signals-of-interest (SOI). One of the most exciting advances expected in the near to mid-term is "cognitive EW," in which adaptive threat signals are analyzed and with a nanosecond, the software determines the most effective Electronic Countermeasure (ECM) to activate. Protection against cyber intrusion is also possible in the near to mid-term. In the far-term, numerous functions may evolve, including multi-agent collaboration for wireless beamforming for very large scale synthetic aperture arrays.

Advanced cognitive functionality will likely be fully utilized and deployed in the EM/digital domain before the kinetic domain, especially for lethal actions. There are several reasons for this likely progression. First, human response time is generally too slow to be effective in the EM and digital domain. Functionality such as cognitive electronic warfare (EW) and cyber protection requires responses in the nanoseconds, which can only be achieved without a human in the loop. Second, the consequences of incorrect or inappropriate actions taken in response to RAS cognitive functions are generally more severe in the kinetic domain, in which AI enabled actions may cause harm to Soldiers or civilians near the RAS. Some advances in kinetic functionality can be implemented in the mid-term, but they should be part of an evolutionary approach to learn and calibrate trust (see Section 8.2) in advanced cognitive functions in the EM/digital domain and in certain "no-harm" kinetic functions before implementing those functions which pose the greatest risk to humans.

Just how much of this promise can be realized in the near to mid-term (5-10 years) and how much needs to wait until the far future is debatable. What can be said with high level confidence is that autonomous functionality will continue to evolve rapidly and globally. The rate at which the Army will take advantage of this inexorable evolution is a function of numerous factors, including fiscal, cultural and exogenous forces. Certainly, a key factor will be how well Army leadership believes that RAS can indeed offer disruptive capabilities to solve tough warfighting challenges that can't be solved through standard past approaches.

3 RAS CONCEPTS AND BENEFITS

RAS has long been recognized as an ideal operational solution for dull, dirty and dangerous missions. In the most recent OSD Roadmap for Unmanned Systems,[2] these missions are characterized as follows:

- Dull – ideal for unmanned systems because they involve long-duration undertakings with mundane tasks that are ill-suited for manned systems; for example, surveillance missions involving prolonged observation. Unmanned systems currently fulfill a wide variety of "dull" mission sets, and the number will increase in all domains as unmanned systems capabilities improve.

- Dirty – have the potential to unnecessarily expose personnel to hazardous conditions; for example, chemical, biological, and nuclear detection missions. Unmanned systems can perform these types of missions with less risk exposure to the operators.

- Dangerous – with ongoing advances in performance and automation, unmanned systems will curtail and even eliminate Soldiers' exposure to risk by fulfilling capabilities that are inherently dangerous, such as the detection and removal of unexploded ordinance and obstacle clearance.

The DSB's 2016 Study on Autonomy established the following categorization for ways that autonomy can benefit DOD missions:

- Required decision speed – having more autonomy is valuable when decisions must be made quickly (e.g., cyber operations and missile defense).

- Heterogeneity and volume of data – autonomy works well in high volume data environments and when there's a variety of data types (e.g., imagery; intelligence data analysis; intelligence, surveillance, reconnaissance (ISR) data integration).

- Quality of data links – more autonomy is valuable when communication is intermittent (e.g., times of contested communications, unmanned undersea operations).

- Complexity of action – autonomy is well-suited to multimodal activity (e.g., an air operations center, multi-mission operations).

- Danger of mission – autonomy can reduce the number of warfighters in harm's way (e.g., in contested operations; chemical, biological, radiological, or nuclear attack cleanup).

[2] DOD Unmanned Systems Integrated Roadmap, FY2013-2038

- Persistence and endurance – more autonomy can increase mission duration (e.g., enabling unmanned vehicles, persistent surveillance).

These frameworks are useful for a broad, high-level understanding of RAS operational benefits. However, to adequately answer the TOR in defining the benefits of RAS for Army formations, the study team determined it needed to address benefits in a more concrete context. To do so, the study team adopted two lower levels of definition. The first, still at a general level, consisted of many possible RAS concepts, but in the context of specific Army warfighting functions and formations (Sections 3.1-3.6 below). The second level consisted of more detailed descriptions of two selected RAS concepts, in the form of representative, point design instantiations of the concepts. These were developed to better understand a technically feasible RAS design approach, its capabilities, how the RAS might be used (CONOPS) in the conduct of a mission, and the role and evolutionary approach of autonomy (Sections 4 and 5 below).

3.1 INTELLIGENCE WARFIGHTING FUNCTION

The principal application of UAS on the battlefield for all US military services has been ISR. The Army has deployed several UAS that were used successfully for ISR in support of the Army Intelligence warfighting function. Thus, the operational benefits of RAS for collecting intelligence are well known. Its success has dramatically increased the number of personnel working Processing, Exploitation and Dissemination (PED) cells necessary to evaluate the massive amount of information (especially full motion video) and to convert the data into actionable intelligence. Even with the expansion of PED, massive amounts of information go unexamined. Improvements to automated analysis of images (still and full motion video) would potentially make better use of the massive data collected by flagging the information most likely to be important for further human analysis. Also, autonomous functionality will allow much of the PED image processing to eventually move from the ground to the RAS vehicle, reducing the communications bandwidth required for downloading the unfiltered ISR data to ground control stations.

3.2 MISSION COMMAND WARFIGHTING FUNCTION

Real time ISR is also useful for mission command. As small UAS continue to be deployed at lower echelons, the SA available to small unit commanders/leaders also improves real time decision making. Within the near-term, Soldier portable, hand-launched small/micro UAS could carry an EO/IR camera and direct downlink to provide squad level, real time SA within its radius of action. The enhanced SA would enable more rapid movement and maneuver and mission command. If designed with hover and/or perching capability, the micro UAS might prove particularly valuable in urban operations to provide SA within buildings or within congested alleyways. The cognitive functionality of the RAS can build over time, starting with the RAS as a simple tool for the Soldier and transforming into a collaborative concept in which the RAS has both UAS and UGV components which share SA with the Soldiers and perform autonomous

actions aligned with commander's intent. In addition to ISR/SA benefits, UAS can also contribute to mission command as an aerial communications layer, strengthening mesh networks. The communications payload would link isolated or "RF-obscured" dispersed, small units to each other and to higher echelon entities, thereby enhancing mission command synchronization among small dispersed units. It could also provide high data rate access to dismounted units, as well as back-haul access to the Global Information Grid (GIG).

3.3 MOVEMENT AND MANEUVER WARFIGHTING FUNCTION

There are several warfighting challenges and multiple applications for RAS within this function. The continued growth in weight of ABCTs and the related increase of an ABCT's logistics footprint make it difficult to both deploy the ABCT and, once in theater, to maneuver it. Armor UGVs teamed with manned supervisor vehicles can provide lethal capabilities at much reduced size, weight, fuel consumption and manpower, relative to equivalent lethality of manned armor vehicles. When teamed with an ABCT, UGVs can provide an outer layer of survivability triggering adversary ambushes, obstacles, or absorbing the first rounds fired by adversaries. This capability would be especially valuable in protecting ABCTs conducting bridging operations, which are increasingly likely missions due to the inability of many civilian bridges to support 80-ton tanks.

The massed armor capabilities of potential near-peer competitors introduce additional challenges to Army maneuver forces. Current limitations in ABCT force structure identified by the National Commission on the Future of the Army suggest the Army may need to rely on light and medium forces to counter massed armor of near peer forces. Lethal UGVs can increase both the survivability and lethality of SBCTs without compromising the deployability and maneuverability of these units. The UGVs could be designed to be air dropped, thereby increasing the lethality of an IBCT for expeditionary, forced entry operations.

Multiple other RAS applications can be envisioned. For example, small unit UGVs can reduce dismounted Soldiers' physical burdens to improve freedom of maneuver. They may also enhance lethality by carrying weapons that Soldiers can't transport. The survivability and mission effectiveness of Combat Aviation Brigades (CAB) can be improved by means of Manned-Unmanned (MUM) teaming with UAS wingmen.[3] The distributed functionality of the manned-unmanned team adds an outer layer of survivability to the manned system, degrading threat MANPADS or SAM detection/tracking systems, and increasing mission effectiveness by allowing specific effects to be directed against specific threats in closer proximity.

3.4 FIRES WARFIGHTING FUNCTION

Near peer competitors also present two other tough challenges to joint forces: massed IDF that outrange and out-gun current Army fires; and a highly capable IADS. Integrated air-ground RAS offer a potential solution to counter the IDF threat (as well as massed armor). The air

[3] Army Science Board 2015 Study on The Future of Army Aviation

component might consist of a loitering UAS that hovers over designated threat areas and detects and geo-locates threat armor and/or artillery by means of appropriate on-board sensors. A UGV could provide the ground-based fires with shoot-on-the-move and automatic reload capabilities. The air and ground components would be networked to allow seamless collaboration under meaningful human supervisory control. The loitering UAS component could also be used to provide a counter-IAD capability. Field interchangeable payloads, including ISR, SIGINT, signature augmentation (spoofing), EW, kinetic attack, communications and cyber, could provide a mix-match mission tailoring capability to disrupt, degrade or destroy threat IADS.

3.5 PROTECTION WARFIGHTING FUNCTION

Tele-operated UGVs have already proven their value in protecting Soldiers while inspecting and disposing of suspected explosive ordnance, improvised explosive devices (IEDs), and chemical, biological, radiological and nuclear threats. The utility of these RAS will continue to grow and provide greater capability better safer stand-off distance for Soldiers as improved autonomous functionality develops. RAS will also grow into CONOPS for protecting Forward Operating Bases and other secure installations using UAS for perimeter monitoring, improved automated alerts and supervised, lethal UGVs for defense.

3.6 SUSTAINMENT WARFIGHTING FUNCTION

Ground convoy operations represent an ideal application for RAS, with clear operational benefits for reducing casualties and manpower. Leader-follower technology is well proven; and fully autonomous operations are on the near-term horizon by taking advantage of investments in driverless vehicles in both the military and industry sectors. The last mile problem for point-of-need delivery of consumables (e.g., water, fuel, ammunition) can be solved using rotorcraft UAS, which provide runway independent operations that can deliver supplies in austere or congested areas of operation directly to dispersed units. A reliable rotorcraft UAS has the potential to deliver “just in time” supplies that would allow units to leave some “just in case” items at an assembly area to enable faster and more effective patrols–an impractical option with current manned systems. An integrated air-ground capability, utilizing both autonomous UGVs and rotorcraft UAS, could also provide main base to battlefield point of need capability that reduces the burden on manned convoys and manned rotorcraft for sustainment operations.

4 COUNTER-ARMOR RAS CONCEPT

Despite the development of precision anti-tank guided weapon systems – either man portable or mounted on lighter combat vehicles – the centerpiece in the defeat of entrenched adversary armor on the battlefield remains US heavy armor systems such as the M1A2 Abrams main battle tank. Although very capable due to both high lethality and high levels of survivability, the Abrams solution is increasingly challenged in several areas. Thus, for the first point design instantiation demonstrating RAS concepts, the study team chose to address the counter-armor problem.

4.1 THE CHALLENGE

A long-standing concern with the M1A2 has been the challenge of deploying the system to the battlefield. The weight of the system, approaching 80 tons, limits deployment to either slow, ship based options or to transport of single M1A2 vehicles on C-17 aircraft (which come with challenges for loading and unloading). Rapid deployment to the battlefield is impossible, and the build-up time for heavy forces is long. The situation has grown worse as upgrades to the M1A2 have increased weight over time. On the battlefield, where maneuver corridors are limited, the M1A2's weight often exceeds the limits for most bridges. The heavy weight also punishes the structural chassis and drive, requiring more frequent and extensive maintenance than other combat vehicles. A cascade of additional maintenance and logistics concerns arise from poor efficiency and the demands to resupply fuel.

A second concern relates to the sheer number of adversary armor faced on the battlefield. The drawdown of Army force structure has significantly reduced the total ABCT force totals.[4] In offensive operations that require the re-taking of territory from a well-entrenched adversary, the typical numerical advantages sought for success are no longer guaranteed. Under current force levels, even if all U.S. ABCTs could get to the fight in time, SBCTs and IBCTs would be needed to fight enemy armor formations and would suffer heavy casualties.

Finally, ensuring survivability of a main battle tank is becoming more challenging due to the increasing lethality of adversary weapon systems, mines, and IEDs. Survivability improvements to counter that lethality are not guaranteed and often create additional challenges with regards to weight, maintenance, logistics, and tactics.[5] In the case of the latter, for example, maneuver to contact with a hidden, entrenched adversary, the loss of vanguard vehicles is more likely. Attrition of these expensive, heavy capabilities is extremely costly.

The potential to address and/or avoid these issues make a complementary robotic counter-armor capability attractive. The RAS capability would augment lighter forces (e.g., SBCT units) to provide additional, heavy lethality force structure. However, the augmentation must be done

[4] National Commission on the Future of the Army, 2016, 54. Available at www.ncfa.ncr.gov.

[5] Advanced protection systems (APS) have been around for years but generally avoided due to concerns that APS activation can cause friendly causalities when armor forces operate with infantry forces – standard U.S. tactics.

so that it neither reduces the deployability of SBCT units, nor impedes SBCT maneuver options on the battlefield. Furthermore, the challenge is to provide this capability at a low cost, offering both a more economical option than additional ABCT units, as well as a more palatable option from the perspective of likely battlefield attrition.

4.2 RAS COUNTER ARMOR CAPABILITY AS A POTENTIAL SOLUTION

Compared to current, manned tanks and armored vehicles, a robotic vehicle has several distinct advantages (Fig. 4-1) in both operational characteristics and constraints.

	Manned Solution	Unmanned Solution
Survivability	• High survivability required to protect crew in armor vs. armor fight; increasingly difficult to achieve	• Survivability tradeable for other capabilities (cost/lethality/weight); fewer requirements (NBC, 6W ride)
Lethality	• Shock from gun limited due to crew presence	• Higher local shock from gun permitted but constrained by weight
Volume	• Hull volume needed to accommodate crew; adds weight and size	• Smaller hull volume possible; greater magazine depth possible as trade
Logistics	• Above factors lead to heavy solution increasing vehicle wearing, maintenance, and fuel needs	• Smaller & lighter vehicle more deployable; less vehicle wearing, maintenance, and fuel needs
Training	• Heavy expensive vehicle represents substantial asset; greater training needed to "qualify" crew	• Less expensive vehicle potentially allows lighter training to "qualify" crew; more natural interface possible

Unmanning of tank opens design space & offers potential for lighter, less expensive, lower logistic footprint vehicle with lethality matching or exceeding M1A2

Figure 4.1 Man/Unmanned Vehicle Comparison

The comparison begins with differing constraints on survivability. In the case of the manned system, survivability is not tradeable, and significant survivability must be assured to protect the crew and to increase the likelihood of their survivability even in cases where the vehicle system is destroyed. People also require more internal volume, which increased the size of the vehicle. These requirements lead to the need for more armor, increasing weight and overall cost and limiting the deployment and corridor maneuverability of the vehicle. Cost and complexity are also driven by the need for nuclear, biological, and chemical (NBC) protection for the crew of the manned system.

In contrast, unmanned systems may trade survivability to achieve lower cost, improved deployability or enhanced battlefield corridor maneuverability. Furthermore, unmanned systems offer other design options with alternate approaches to survivability. For example, with no need for turret volume to support the crew, the physical cross section of the vehicle may be reduced, making the vehicle a smaller target by about one-third. Similarly, the operational speed of a lighter, unmanned vehicle could be substantially greater.

The trade of survivability for other characteristics becomes more desirable in cases where enemy capabilities challenge the survivability of even a very heavily armored vehicle. Take for

example the case of maneuver to contact against an entrenched, highly lethal adversary armor unit. As anti-armor weapons become more powerful, survivability may become more aligned with reduced armor protection, smaller size, more maneuverability with better acceleration and deceleration, and a level of lethality that forces adversary forces to react and expose their location. With this robotic system approach, vehicles will still be attrited – something no different from the manned armor case – but the cost will be lower, both due to the lower vehicle cost and the fact that the remote crew will survive. There's also reason to believe the number of losses could be fewer, given the advantages a fully unmanned vehicle can exploit.

RAS Counter Armor Concept

A UGV with the deployability of a Stryker, the survivability of a Bradley, and the lethality of an Abrams.

Advantages of the unmanned system extend to other areas where the design space is opened. For example, in the design of the gun, overpressure and shock are no longer issues as they are with manned systems and more lethal options are possible – including beyond-line of sight fires and the direct engagement of targets in elevated, urban buildings. The hull size can also be reduced in the unmanned case, or a greater portion of the volume used to expand magazine depth.

Unmanned system advantages also cascade into the areas of logistics and training. A lighter, equally lethal unmanned system produces less wear on the drive train, which requires less maintenance. Fuel consumption would be similarly reduced, translating into further logistics savings and exposing fewer convoys to potentially dangerous supply routes. Finally, since the vehicle is less costly, the training required to "entrust" a vehicle to a crew might be relaxed. Combined with a more natural control interface to the vehicle, it might be possible to train more personnel.

Advantages of an unmanned autonomous vehicle approach are aggregated in the weight/lethality/ survivability graph in Fig. 4-2, which plots the three key Army manned armored fighting vehicles (Stryker, Bradley, and Abrams) along with the proposed unmanned system. A robotic UGV can be designed anywhere within this weight-lethality-survivability design space, depending on specific requirements. For purposes of concept evaluation, a specific point design instantiation was selected from the broader design space.[6] The proposed design is one with a weight slightly less than that of a Stryker, hence sharing the Stryker's flexibility in deployment to theater, but with the survivability of a Bradley and the lethality of an M1A2. Survivability and lethality could be enhanced at the expense of greater weight (survivability) or by considering more advanced weapon technology (lethality). In all cases, however, it's clear that the unmanned approach allows set levels of survivability and lethality to be achieved at a significantly reduced overall weight.

[6] The broader design space and UGV options within the design space are explored in a companion 2016 ASB study on Armor Anti-Armor Competition

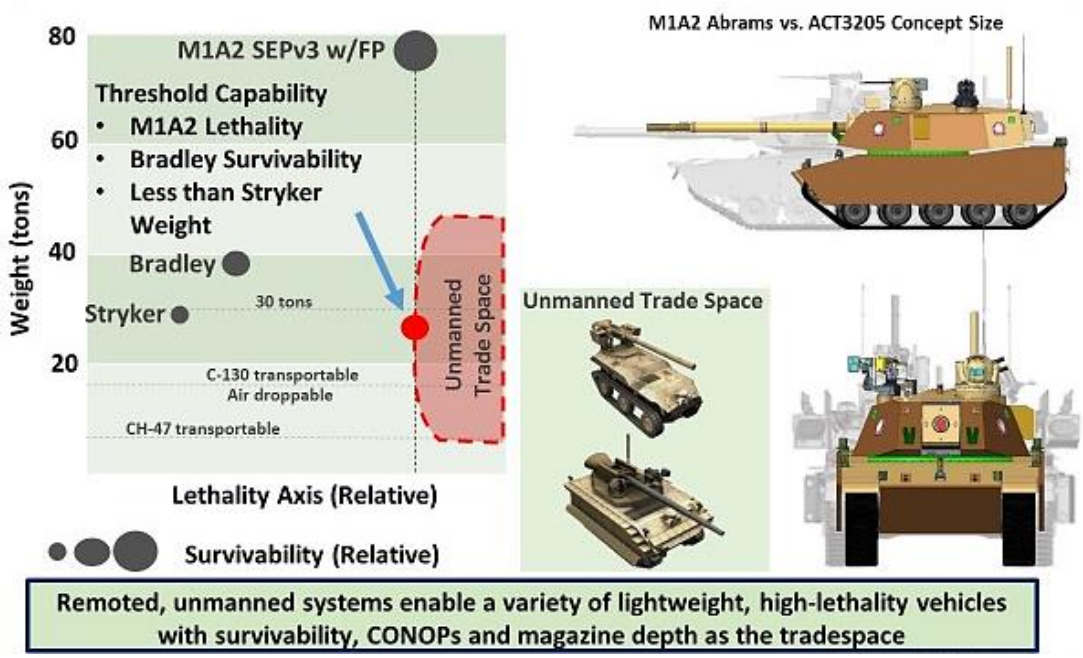

Figure 4.2 Combat Vehicle Lethality and Laden Weight

The point design, developed by TARDEC in support of this study (Fig. 4.3), is centered on a XM360 120mm gun with lethality similar to an Abrams that uses existing and future planned 120mm rounds. The vehicle carries 36 rounds for this main gun. Lethality of the main gun is supplemented by a 0.50 cal. Advanced Remote/Robotic Armament System. Survivability is set to counter a medium cannon as well as rocket-propelled grenade/contact explosive and explosively-formed penetrator. Because of the reduced size, weight, and complexity of unmanned ground system, it's expected that the cost would be approximately $2-3M each.

A representative operational concept would pair two of these unmanned systems with two Stryker vehicles acting as command vehicles for the autonomous vehicles. Two personnel in each Stryker would act as driver and gunner for the unmanned system, controlling both via tele-operation (e.g., semi-autonomous operation) using video links from the unmanned vehicles, and using virtual reality headsets and controllers in the Stryker. These controls would be designed such that the driver/gunner crews could dismount from the Stryker and continue to operate the unmanned system. Units could add a Soldier as the tank commander if experimentation indicates a tank commander is needed.

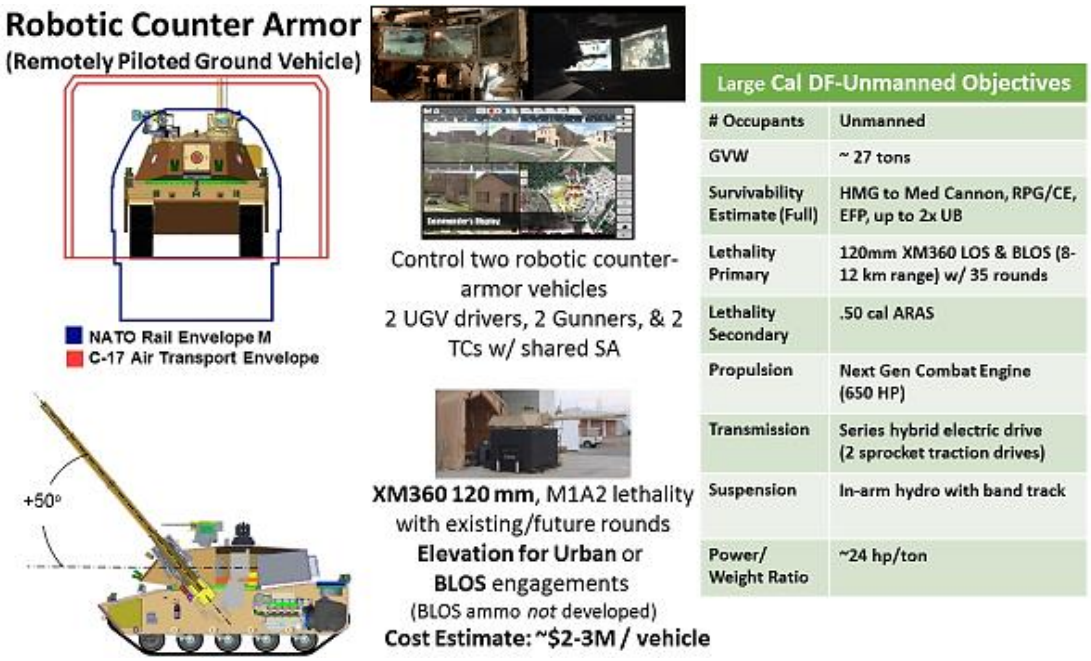

Figure 4.3 Robotic Armor Concept

4.3 CONOPS FOR HIGH LETHALITY UNMANNED SYSTEM APPLICATION

A variety of CONOPS for the unmanned system could be explored, each leveraging its unique benefits. A specific mission was selected by the study team for evaluation: maneuver to contact against an entrenched armor force of unknown location (Figure 4.4). In this vignette, the unmanned systems are used as the vanguard while the manned Stryker vehicles controlling these unmanned systems remain sufficiently to the rear to ensure their safety. The unmanned vehicles advance in a bounding over watch formation until contact is made. The surviving unmanned systems rapidly respond to fires from enemy armor using automated slewing techniques coupled to man-in-the-loop triggering.

Several advantages of the unmanned system emerge in the mission vignette. First, the new unmanned capability represents an advance in lethality over the Stryker vehicles and evens the mismatch between an entrenched adversary force and the attacking U.S. unit. Second, because the new capability is unmanned, personnel are not put at direct risk as part of this vanguard capability. Should the vehicles be attrited, the crews are preserved, and if a resupply of the unmanned systems themselves can be accomplished, the enhanced SBCT could continue at full strength. Third, survivability in the scenario is uncertain, even with more heavily armored manned tank systems, so the unmanned approach places less costly resources at risk. And finally, the partial automation of the unmanned system offers further combat advantages. Multiple unmanned vehicles can be “networked” in the sense that they can cooperate in a semi-autonomous fashion. For example, if one vehicle takes fire, another can automatically slew at high speed to help human operators return fire quickly. With a beyond line of sight capability, vehicles returning fire could be separated by terrain features. Fires from multiple unmanned systems can be coordinated allowing greater lethality by, for example, synchronizing

rounds from multiple shooters to overwhelm adversary countermeasure and active protective systems.

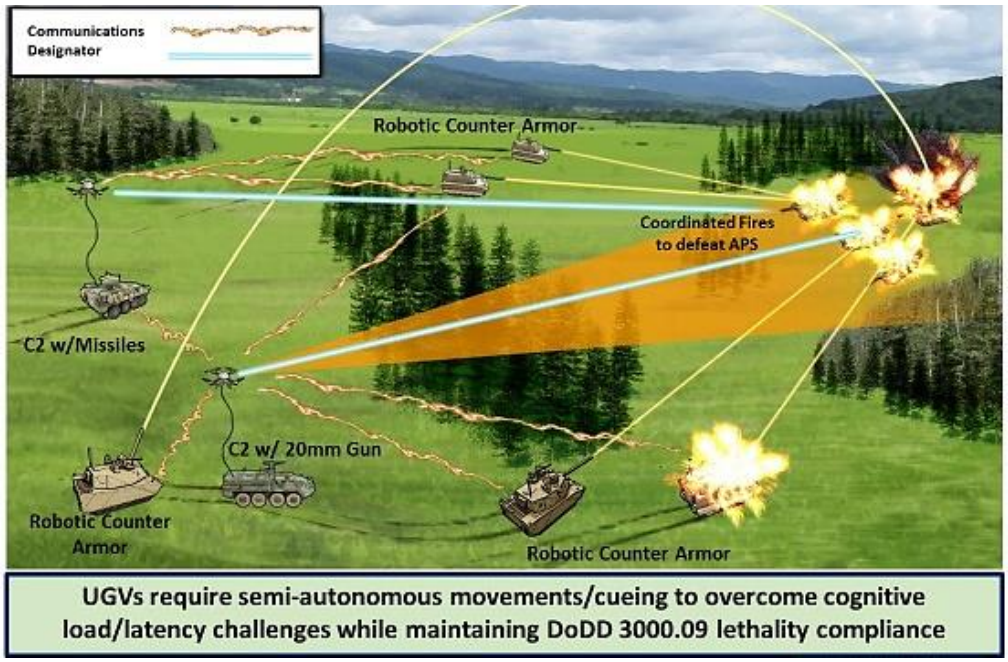

Figure 4.4 Robotic Vanguard CONOPS

4.4 AUTONOMY EVOLUTION

While providing a substantial complementary capability to existing manned systems, the unmanned counter armor capability does not initially require advanced autonomy. A baseline capability could be implemented using existing, proven remote operation technology; relying on tele-operation of both the vehicle and the vehicle's weapon systems (Fig. 4.5). If implemented with the correct open architecture approach, the autonomy of the vehicle could then be enhanced over time to allow greater supervised vs. tele-operated approaches to both movement and weapons engagement. In accordance with current DOD Directive 3000.09, Autonomy in Weapon Systems, it's assumed that weapons operation would always involve meaningful human control for lethal actions.

	Timeframe	Maturity	Autonomy Offered
Baseline Concept	Now	Mature	• Remotely tele-operated vehicle & gun • Follow-me robotic drive for convoy to frontline • Semi-automated gun (e.g., automated slew to source of fire - adapted Boomerang equivalent)
	< 5 years	Maturing	• Supervised autonomy • Automated evasive maneuvering • Supervised coordinated fires to defeat APS
	5-10 years	R&D	• Voice command driving • Cross country, fully automated driving
	10+ years	R&D	• Intelligent autonomous maneuver

Strategy allows fielding of unmanned tank with currently mature technology; open architecture approach allows path to evolve level of autonomy in the future

Figure 4.5 Evolving Levels of Autonomy

4.5 CAMPAIGN OF LEARNING

To develop the RAS counter armor concept, the Army would need to initiate a campaign of learning (Fig 4.6). The intent would be to reduce overall concept risk while progressively developing and hardening autonomy and man-machine interfaces.

Hardware & Software Development
CONOPS & TTP Development
Exercises & Operational Assessments

- Phase 0 – Surrogates
  - Concept exploration with surrogate vehicles (e.g., Stryker as unmanned vehicle)
  - Interfaces: Remote operation shown effective; initial development of man-machine interface; etc.
  - Table VI (in testing) to Table VIII operational capability
  - Initiate driver autonomy software development
  - Develop simulations

- Phase 1 – Component Prototyping
  - Systems integration lab
  - Early prototype (e.g., integrate reduced recoil XM360 120mm gun on Bradley chassis)
  - Weapon related prototyping and automation demonstrated (e.g., autoloader, remoted 50 cal, fire control system for 120mm gun)
  - Universal remote control demonstrated on vehicle similar to final capability
  - Engagement modelling and simulation development
  - Command and control software development

- Phase 2 – System Prototyping
  - Prototype purpose-built, robotic system
  - Platoon-size force-on-force exercises to show integrated end-to-end capability
  - Electromagnetic dense environment testing
  - CTC experimentation using OPFOR

Figure 4.6 Campaign of Learning

Phase 0 of this campaign would use surrogate vehicle capabilities to allow exploration of the proposed unmanned system CONOPS, as well as demonstration of some of the key technologies (tele-operation) and the communication link needed to support remote control. A modeling and simulation toolset for the system would also be initiated, which would be improved upon and validated in subsequent phases.

Phase 1 of the campaign would focus on component prototyping. For example, on integrating the proposed gun component on a surrogate (e.g., Bradley) chassis. Testing with the more realistic surrogates of this stage would allow higher fidelity exploration of the operational concepts, and would inform the requirements for a full system prototype.

Finally, Phase 2 of the campaign would then develop the full prototype, purpose built as a robotic system for counter-armor capability.

5 RAS COUNTER-IAD CONCEPT

For decades, U.S. armed forces have enjoyed freedom of maneuver enabled by air superiority. With the advent of highly capable IADS by adversaries, air superiority can no longer be assured or assumed in Joint force planning. A lack of air superiority has profound implications for Joint Force operations in future conflicts.

5.1 THE CHALLENGE

Robust adversary IADS pose a lethal threat to the Army's organic combat aviation assets (e.g., AH-64, UH-60 and FVL), which in turn creates cascading vulnerabilities throughout maneuver forces. Task Force Hawk in the Kosovo conflict provides a good example of the reluctance of Joint Force Commanders to utilize Army combat aviation in the face of robust Serbian air defenses. Commanders never employed the Apaches that were deployed because the "risks were determined to be too great relative to the payoff."[7] In a later mission in 2003, Iraqi air defenses shot down one Apache and damaged the remaining Apaches, forcing them to retreat without accomplishing their deep attack mission. Only seven of the brigade's AH-64s were ready for combat a week later.[8] The current capabilities of near peer competitor IADS and of weapons available to other potential adversaries far exceed those of the late 1990's Serbian or 2003 Iraqi IADS, which were sufficient to damage and/or reduce the use of Army combat aviation.

The lack of air superiority is compounded by a lack of IDF superiority, which combine to create a perfect storm for Joint Force capability against near peer competitors. The erosion of the IDF advantage stems from a reduced need for IDF in most recent conflicts and from a strategic decision to pursue precision over mass. The combination of range and numerical disadvantage in fires has left the Joint Force highly vulnerable to massed IDF. The net result is a greater reliance on close air support (CAS) to provide long range fires, but CAS assets will have difficulty accomplishing in a contested air environment.

Fixed- and rotary-wing aircraft perform CAS operations against hostile targets proximate to friendly forces and require detailed integration of each air mission with the fire and movement of those forces.[9] Operations include shaping, close combat, and joint security area operations. In shaping operations, Commanders may employ CAS to support deep operations, which may include SOF or conventional forces.

Against a capable, near peer IADS, Suppression of Enemy Air Defenses (SEAD) missions are required to neutralize or degrade the IADS sufficiently enough to reduce risk to friendly forces conducting CAS missions (Fig. 5.1). The IADS provides a large three-dimensional bubble in which

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[7] John Gordon, Bruce Nardulli, and Walter Perry, "The Operational Challenges of Task Force Hawk," *Joint Forces Quarterly*, no. 39 (2001): 55, http://www.dtic.mil/dtic/tr/fulltext/u2/a403513.pdf.
[8] Tim Ripley, *Air War Iraq* (Pen and Sword, 2004), 97.
[9] Joint Publication 3-09.3, Close Air Support, dated 25 November 2014

anything that flies does so at high risk. Within the large bubble are numerous surface to air missile batteries that vary from high altitude, long range SAMs protecting strategic targets to mobile tactical SAMs and MANPADs (represented in the figure by the smaller bubbles). The targets that Army maneuver forces and combat aviation brigades engage are generally within these mobile tactical bubbles. The RAS concept provides an organic Army capability to degrade localized IADS in support of the J-SEAD mission[10] and to allow survivable Army Combat Aviation CAS operations. This also helps Joint Force combat aircraft concentrate on J-SEAD missions against high priority strategic targets and has the potential to create safe lanes for Joint air missions against deep targets.

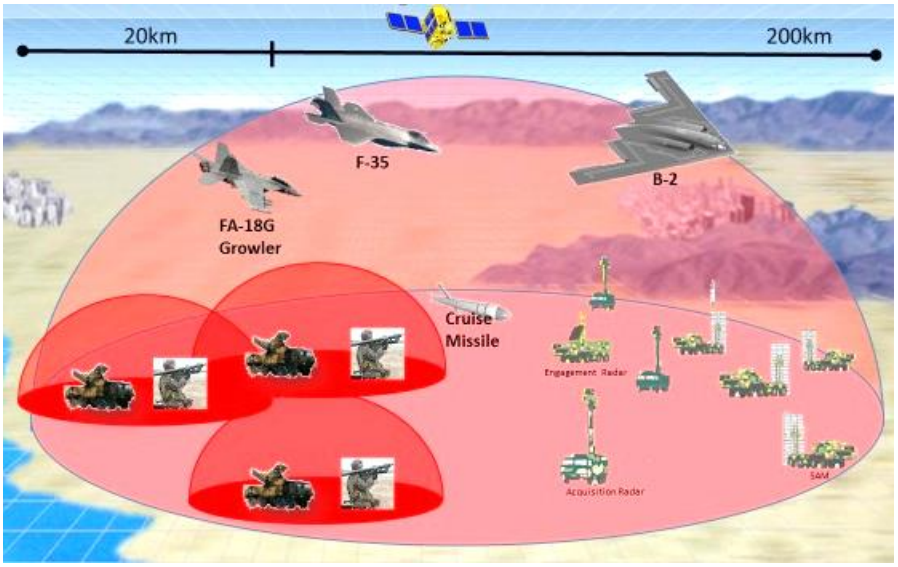


Figure 5.1 J-SEAD vs. IADS

5.2 THE RAS C-IAD CONCEPT

The J-SEAD mission requires an ability to collect data to know where the targets are located and an ability to then attack the targets either electronically or kinetically (Fig. 5-2). While manned aircraft have been consolidating toward 4th and 5th generation systems in each of these domains, unmanned systems, including both UAS and missiles, have been taking on greater roles for ISR and SIGINT collection and both forms of attack. The Predator was among the first to combine ISR and attack on a single platform, but advancements in autonomy and electronics miniaturization now allow convergence of the ISR/SIGINT, EA and kinetic attack domains in a single vehicle. This emerging capability forms the basis for the postulated RAS concept.

[10] Joint Publication 3-01.7, JTTP for Joint Suppression of Enemy Air Defenses (J-SEAD), 25 July 1995

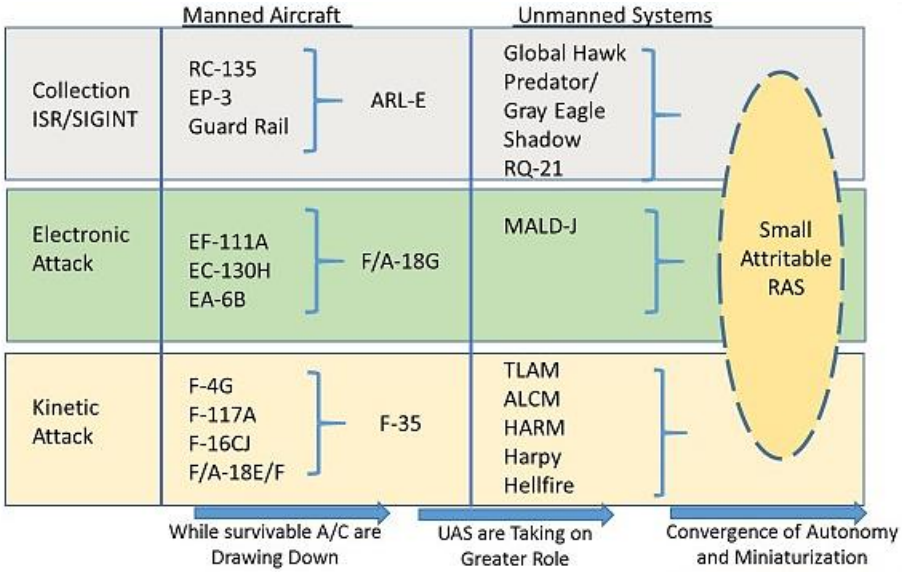


Figure 5.2 RAS Offers Convergence of J-SEAD Functionality in Small Attritable UAS

The point design instantiation of the counter IADS concept selected for study was a small, low cost loitering UAS that can carry a variety of field replaceable payloads, including ISR, SIGINT, signature augmentation or spoofing, EW, lethal kinetic, communications and cyber (Fig. 5.3). The payloads and the vehicle would be designed with standard structural, power, electrical and data bus interfaces so that the payload modules are interchangeable and field replaceable. The modularity of the system provides commanders a great deal of flexibility in terms of mixing and matching the payloads to specific mission needs and to operate several of them simultaneously in multiple domains.

It's desirable for the UAS platform to be as small as possible for several reasons. First, cost is highly correlated to size and weight. If sufficiently low in cost, the vehicle may be considered attritable, which allows CONOPS in which the vehicle is used in a sacrificial role. Second, smaller systems allow less complex launch and recovery operations and runway independence. Third, the radar cross section of small vehicles is inherently less than larger ones, which improves survivability when operating under the IADS "bubble" and/or in proximity of other weapons systems.

RAS Counter IADS Concept

A low-cost/attritable UAS supporting modular, "plug-and-play" payloads capable of operating in multiple domains (ISR, SIGINT, spoofing, EW, lethal/kinetic, C2, cyber, etc.).

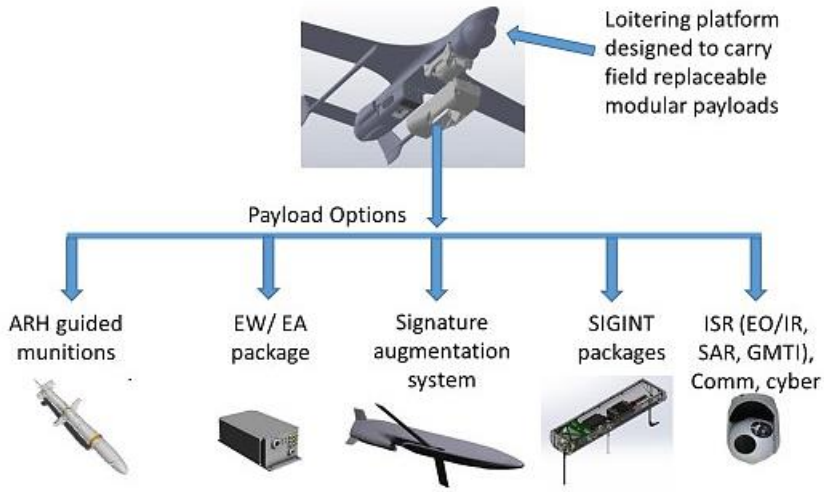


Figure 5.3 Modular Payload UAS

The size of the vehicle will be determined mainly by the size, weight and power (SWaP) of the payload (Fig. 5-4). Based on various desired payloads, the study team determined a reasonable weight goal for the payload would be 20 to 30 pounds. There's strong rationale for believing payload weight can fall below 20 lb., based on demonstrated R&D of Digital Radio Frequency Memory (DRFM) capabilities on a single integrated circuit card.

Type	Exemplar	Capability	Approximate Weight – lb.
Signature Augmentation	MALD	Replicates the RF signatures of A/C, creating multiple "ghost" images	5 (electronics)
Electronic Attack	MALD-J	Radar jammer to degrade IAD emitters	5 (electronics)
SIGINT	Spectral Bat Cylon Smoke	RF/DF for localization of emitters Simultaneous collection of SOI	2 + Antenna 20
ISR & RSTA	Split Aces	Dual Band (UWB & Ku) for SAR/GMTI	20
Warhead	Hellfire Javelin MLRS APKWS/M247	HEAT HEAT DIPCM (compliance issue) HEAT/HEDP	20 20 <1 each 9

Figure 5.4 Nominal UAS Payloads with Small SWaP

The design space for a low cost, loitering UAS can be defined within the correlation of payload weight to vehicle gross weight for several existing unmanned air vehicles with endurance of several hours (Fig. 5.5). That level of endurance matches the time required for several deep shaping missions. It also reduces the frequency of launch and recovery operations. Based on this correlation, the study team believes a 30-lb. payload requires a UAS platform of around 100-lb.; or a 20-lb. payload requires a 70-lb. platform. As indicated, there are several existing vehicles in this weight class. Consequently, there should be no technical issues associated with

developing the vehicle. A “stretch” cost goal for this 70-100 lb. vehicle of $100,000 seems reasonable, if produced in sufficiently high volume.

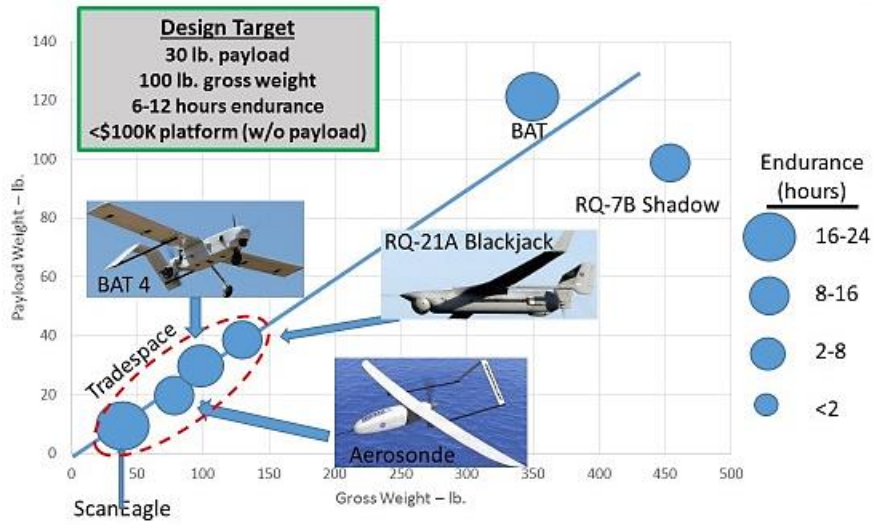


Figure 5.5 UAS Design Space

5.3 CONCEPT OF OPERATIONS

Although small UAS concept can provide multi-domain capabilities for a wide variety of tasks, the study team focused on one specific J-SEAD task to illustrate the operational value of a small UAS contributing to the J-SEAD mission. The intent is to create a temporary corridor in the tactical IADS to allow Army combat aviation to conduct deep shaping CAS in support of joint maneuver forces and to free up USAF and USN aircraft to focus on strategic missions (Figs. 5.6-5.8).

The study team postulated a layered IADS with overlapping mobile, tactical IAD bubbles that are networked together, and with higher echelon command and control (C2) nodes. In the accompanying figures, the targets for the deep shaping combat aviation mission are located within the deepest bubble, requiring manned aviation assets to penetrate several layers of the IADS.

Note that the mix of RAS payloads changes as the mission progresses. During initial phases of the operation (including defer and shape phases prior to hostilities) the payloads are mainly ISR and SIGINT as part of the overall collection process for intelligence preparation of the battlefield (IPB). These assets will focus on developing the best picture of the threat order of battle in the localized area of operations, while other intelligence assets are developing the larger and deeper picture.

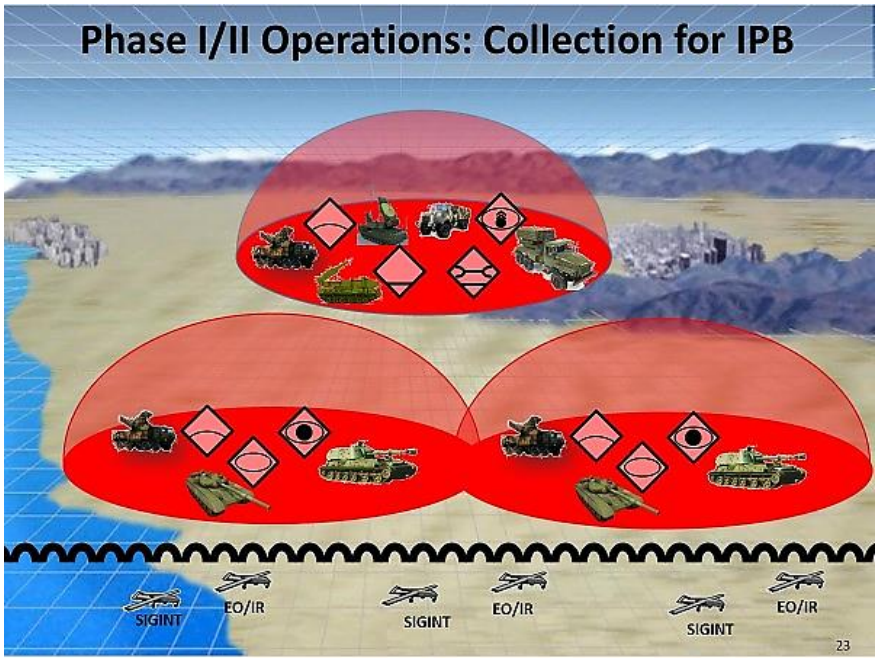


Figure 5.6 Counter IADS CONOPS 1

At the beginning of hostilities (Fig. 5-7), vehicles with the electronic and kinetic attack payloads will join the ISR and SIGINT assets. The EW vehicles will probe threat IADS to identify and geo locate emitters and C2 nodes to determine preferred EA techniques. Kinetic attack vehicles will use anti-radiation homing guidance to destroy emitters and supplement IDF against targets. Key objectives are to degrade the IADS as much as possible and to get a clear picture of which azimuths of attack would be preferred for the subsequent combat aviation mission.

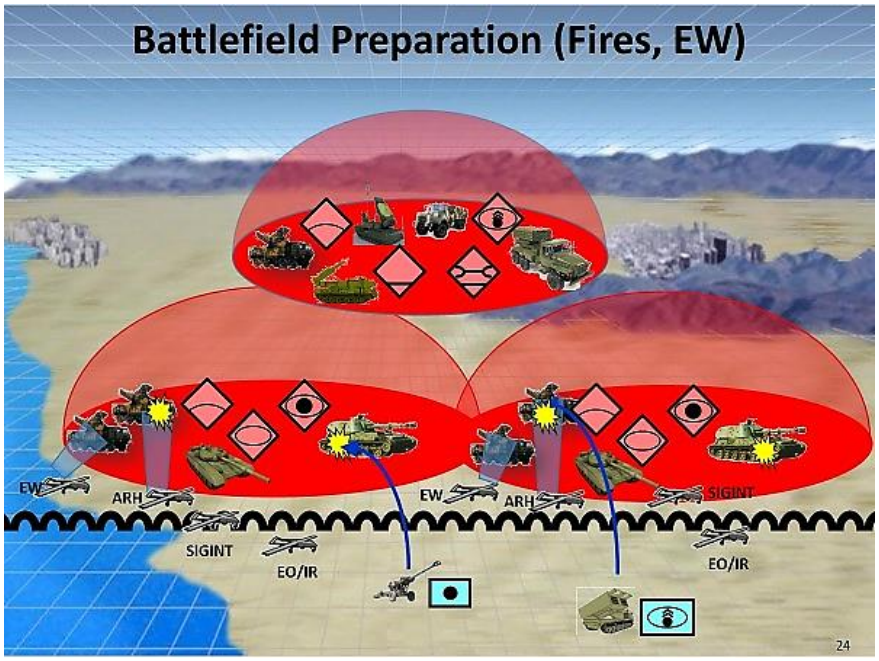


Figure 5.7 Counter IADS CONOPS 2

In the deep shaping phase (Figure 5-8), signature augmentation or spoofing payloads are added to the mix. ISR and SIGINT vehicles continue flying to enrich overall SA in the local area of operations for the entire joint force. he spoofing payloads create ghost images of the Apaches along 3 or more axes, of which 2 (or more) are feints and 1 of which will be the actual Apache attack ingress corridor. These payloads stimulate the IADS and cause it to exercise C2 links to activate track radars of designated fire control units, allowing other systems to identify emitters and C2 nodes for targeting by lethal and EW systems, in turn creating safer corridors for ingress and egress.

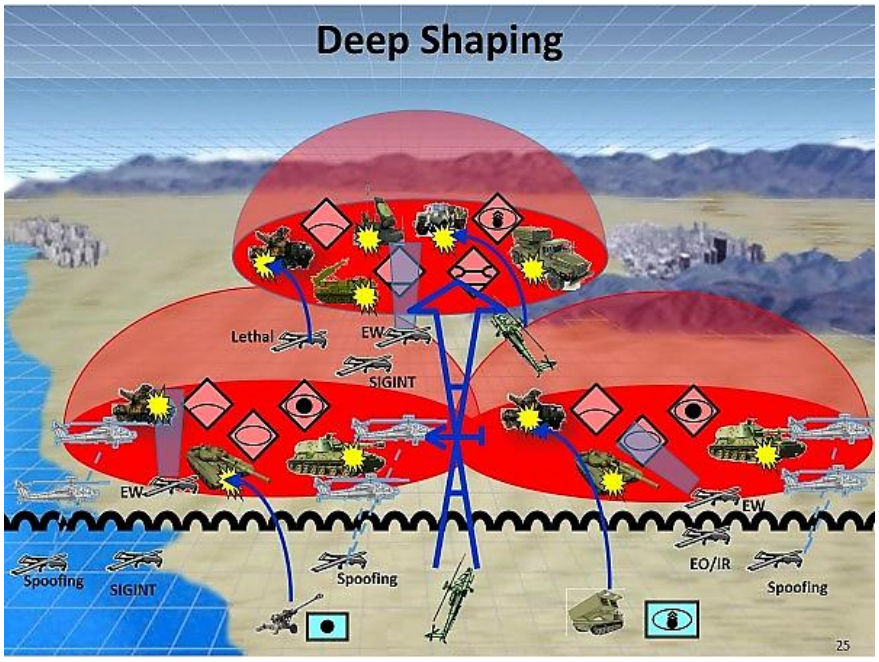


Figure 5.8 Counter IADS CONOPS 2

Several attributes of the RAS counter IAD concept contribute to the effectiveness of J-SEAD. Among other things, the small size/radar cross section of the vehicle may allow it to operate near IAD nodes to conduct stand-in jamming. Size also allows runway independent launch and recovery, making it more difficult for threat ISR to locate the base of operations. Its low cost allows the UAS to be considered an attritable asset when necessary. Modularity allows field replaceable tailoring of the payload mix to mission specific needs. It's also possible to operate ISR and SIGINT simultaneously in multiple EM bands, allowing for real time data fusion.

The RAS counter IAD concept focuses on disruption and degradation of the active emitter components of an IADS. While it doesn't specifically address passive systems within the IADS, it does help reduce the effectiveness of passive systems by disabling C2 nodes which may be cueing or directing passive units. Also, there are alternate approaches for the use of RAS that directly contribute to degradation of passive systems that may be considered as a complement or supplement to the loitering UAS counter IAD system. Among these are an approach that was

recommended in the 2015 ASB study on Army Aviation.[11] In that concept, the UAS is designed to fly in formation with manned aviation assets to escort them through areas of operation which are known or suspected to have a high density of passive systems (e.g., MANPADS). Aviation survivability equipment (ASE), including Infrared Countermeasures (IRCM) and decoys that replicate the signatures of the manned rotorcraft, are distributed on the escort unmanned air systems, thereby providing an extra, external layer of survivability around the manned platform.

5.4 EVOLUTION OF AUTONOMY

The RAS counter IAD concept can be deployed in the near term with currently mature autonomous functionality (Fig. 5.9). These functions include guidance, navigation and control (GNC), emitter identification via an onboard library of signals of interest, automated target recognition and automated launch and recovery. If the RAS is designed from the outset with an open system architecture, more advanced functionality can be easily inserted in the mid-term. This could include cognitive EW, which provides the ability to identify adversary emitters employing adaptive pulse and other techniques that make current EW operations difficult. In the long term, multi-agent collaboration can be added, which would allow wireless distributed beamforming arrays for high resolution synthetic aperture radar and improved jamming techniques.

	Timeframe	Maturity	Autonomy Offered
Baseline Concept	Now	Mature	• Flight Guidance, Navigation and Control (take-off, ascent, waypoint navigation, loiter & search patterns) • Emitting target ID via library • Non-emitting target image recognition • Automated launch and recovery
	< 5 years	Maturing	• Mission contingency management • Cognitive EW, cyber protection, adaptive SOI ID • False target rejection • Enhanced ATR for targets in camouflage/deception environments • Automated evasive maneuvering
	5-10 years	R&D	• Swarming, multi-agent collaboration • Coordinated fires • Wireless distributed beamforming arrays for high resolution SAR and jamming

Figure 5.9 Evolving Levels of Autonomy

5.5 CAMPAIGN OF LEARNING

As with the counter armor concept, a campaign of learning will be required to take RAS counter IADS from the concept to prototype level, to understand its operational utility, to develop

[11] ASB FY 2015 Study: Army Science and Technology for Army Aviation 2025-2040; Feb. 2016.

CONOPS and TTPs, and to build trust that the RAS can perform as predicted (Fig. 5.10). Major elements of the campaign include simulation, prototyping, experimentation and operational assessments. As before, the campaign may utilize three overlapping phases that start with heavy use of surrogates and progress to higher levels of component and system level prototyping and simulation.

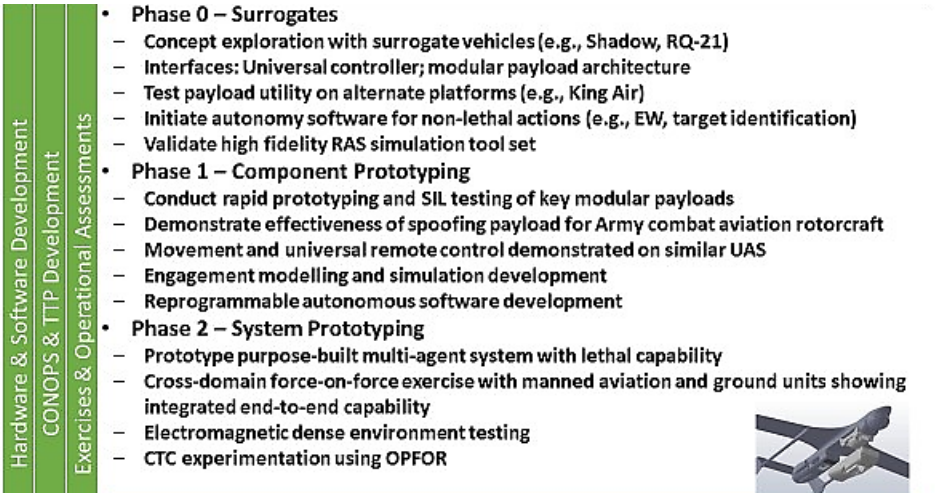


Figure 5.10 Campaign of Learning

Phase 0 would consist of experiments using surrogate vehicles to demonstrate command, control and communications interfaces with the intent of reducing risk of failure between system-of-systems interactions. There are several existing UAS that could be used as surrogates, including Shadow, BAT 4, Aerosonde and RQ-21. It might also be useful to employ manned aircraft, such as a KingAir, as a surrogate to carry alternative communications and mission payloads. Autonomous software modules would be hosted in on-board computers of the surrogates to develop an understanding of the roles and benefits of autonomy to mission effectiveness. Experimental results would be used to evaluate, refine and validate a RAS simulation, which would be used throughout the campaign to extrapolate RAS operational utility to a full spectrum of environments and conditions beyond the test set.

Phases 1 and 2 would progressively introduce higher fidelity component level and system level prototypes of the RAS, while continuing to refine and expand the simulation toolset and to increase the complexity of the experimentation environment. A system integration lab (SIL) could be used to test and evaluate functionality and performance of the prototype components with simulated or actual hardware and software interfaces. Unique mission payload capability (e.g., spoofing electronics and software) would be developed and evaluated in the SIL before integration on the surrogate or prototype UAS platforms. Likewise, autonomous software would continue to be developed, evaluated in the SIL, and ultimately integrated into a system-of-systems experiment and demonstration on the test range. Test range threat capability would continuously be improved, to include the capacity to simulate a highly dense and complex EM environment. The experimental and assessment program would culminate in a CTC type of operational assessment exercise against an OPFOR.

6 RAS ARCHITECTURE

The RAS concepts described in Sections 4 and 5 above illustrate the value of an autonomy evolution path, which allows the concepts to be developed and deployed with mature but limited autonomy in the near term, while providing for growth to greater autonomous capabilities over time.

6.1. RAS ARCHITECTURE REQUIREMENTS

An architecture that facilitates an evolutionary growth in autonomy is critically important to unlock the full potential of RAS. Some of the key capabilities that need to be provided by the RAS architecture include:

- Interoperability – RAS will operate in a system-of-systems (SoS) environment, with interfaces and interactions with multiple external entities. It will be important to ensure that RAS remains interoperable with these entities as they continuously evolve outside the control of the RAS program office.

- Modular Open Systems – Like manned aircraft and ground vehicles, autonomous system platforms will have long life times, spanning decades in most cases. Because of long DOD acquisition cycles, new, platform-based systems are often fielded with obsolete electronics/avionics. Moreover, closed, proprietary architectures on prior DOD platforms limit the ability to continuously insert state-of-the-art electronics and software as technology advances and to integrate with other systems in an interoperable SoS environment. With autonomous systems, it's especially critical to ensure the architecture is modular and open to facilitate the insertion of independently developed "best-of-breed" cognitive functionality, because both autonomy and cognitive functionality development will continue to rapidly advance on a global basis while the RAS platform remains relatively static.

- Dynamic Autonomy – RAS architecture should allow for reallocation of cognitive functions between operator and RAS and across echelons during a mission in response to changing battlefield conditions.

- Assured Communications – Communications between operator/collaborator and RAS, as well as between RAS and other entities with which it interacts in the SoS environment, must be assured when needed. Two opposing trends in communications are evident as autonomy continues to advance. On the one hand, as AI enabled autonomy facilitates greater human-on-the-loop vs. human-in-the-loop operations, the frequency and bandwidth of communications between operator and RAS can be significantly reduced, allowing for low probability of intercept (LPI) intermittent data transfer. On the other hand, in fully collaborative human-RAS operations, near continuous communications between human and RAS collaborative agents may be necessary in dynamic battlefield conditions to ensure shared SA. In either case, jam

resistant LPI communications systems and techniques are critical to continued development and deployment of RAS.

- Cyber Security – RAS must be protected against cyber intrusions. RAS cognitive functions in the EM and digital domains (e.g., cognitive EW) provide the means to counter cyber intrusions in real time (human on the loop because of slow human response time). It's important for the RAS physical, software, communications and data-bus architectures to be well integrated to function coherently and provide continuous real time cyber responses.

- Scalability – As autonomy advances, RAS operations will transition from single or multiple operators for every RAS to a single human directing multiple RAS and multiple RAS interacting with each other (e.g., swarms). To accommodate this transition, the RAS architecture must be scalable for multi-agent collaboration.

- Transparency and Shared World View – Future RAS applications in which RAS and humans truly collaborate as partners (as opposed to the RAS being only a supervised tool) will require that the human and RAS collaborators share a common world view and understand each other's intentions and physical/cognitive states. Such a collaborative environment will rely on trust between the agents, which, in turn, requires transparency between the agents. The RAS architecture must ensure transparency in terms of full disclosure of SA, physical and cognitive states and understanding of rationale behind decisions.

The study team found the key architecture features required for achieving these attributes are SoS interfaces and modular, open systems architecture.

6.2 SYSTEMS-OF-SYSTEMS INTERFACES AND INTERACTIONS

RAS will need to interface and interact with various external entities as one component in a system-of-systems. The SoS entities with which a RAS may interact include the external environment (e.g., sensing, manipulation), off-board systems (e.g., GPS, ISR), other RAS (e.g., multi-agent collaboration, swarms), the cloud (e.g., databases), consumers of RAS products (e.g., processing, exploitation and dissemination cells), higher echelon command (e.g., RAS state, status), primary controller/operator/collaborator (e.g., command and control), and secondary operators/collaborators (Fig. 6.1). As with most SoS, the interactions are almost exclusively information exchange, and the interfaces are principally communications transmitters and receivers.[12] The information exchange content and communication link requirements (e.g., frequency, bandwidth) will vary considerably, depending on the type of RAS and its autonomous capabilities, as well as the mission and battlefield environment.

[12] An exception is a RAS that manipulates or alters the environment by means of manipulation appendages or kinetic effects.

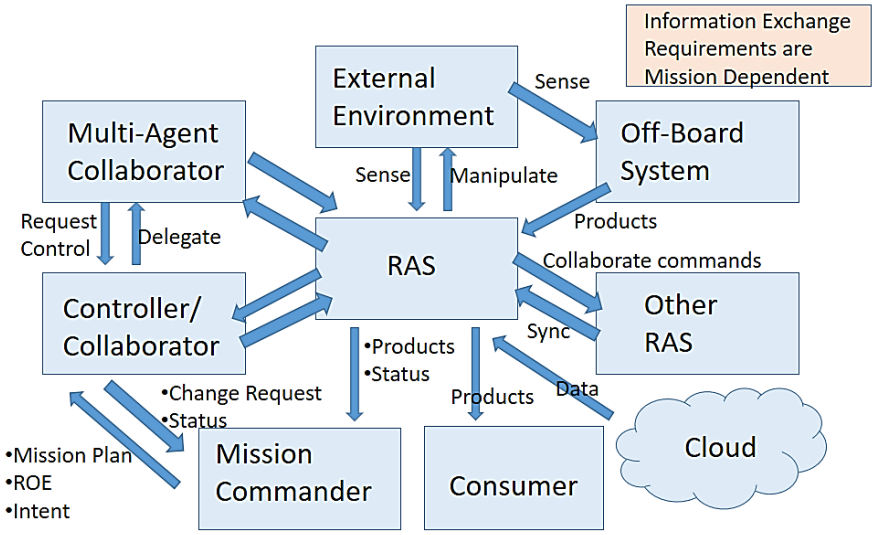


Figure 6.1 RAS System-of Systems Architecture

From an architecture standpoint, the driving capability need is to accommodate the change in information exchange between the RAS and the other SoS entities as the autonomy of the RAS evolves and as the other SoS entities change. The counter armor and counter IAD RAS concepts provide examples of how the information exchange may be expected to evolve.

Initially, the robotic armor UGV may interact only with the supervisor, receiving targeting data and maneuver steering and fire commands from the supervisor and sending back status and SA information (possibly full motion video). Over time, the robotic vehicles may also exchange information among themselves to optimize coordinated maneuver and synchronize fire, and send/receive information into a network with other direct and indirect fire assets. Also, the information exchange with supervisory systems will expand as the autonomous functionality to understand the environment and situation improves.

For the counter IAD concept, the UAS vehicles will exchange information with the mission controller and PED centers. Information sharing among the RAS vehicles may be initially limited to flight geo-location data to ensure safe separation between adjacent vehicles. Over time, the exchange among vehicles will increase to allow formations to self-organize in real time for optimum mission performance by correcting for attrition or contingencies.

6.3 MODULAR OPEN SYSTEMS ARCHITECTURE

The RAS concepts demonstrates the value of physical modularity. The ability to interchange payload modules on a common platform enables multi mission capability and provides flexibility to mix and match payloads to optimize RAS vehicles for specific scenarios and threats. The key to payload modularity is a set of structural, power, electrical and data-bus interface

standards that allows payloads to be easily interchanged in the field. Similarly, the counter armor concept uses a 120mm gun to allow ammunition interoperability with the M1A2 Abrams and other NATO tanks, simplifying logistics and reducing operations costs. Ensuring physical modularity with other programs is important for limiting costs, easing field repairs and resupply, and encouraging more advanced development. For the counter armor concept, other common systems could include active protection systems (APS), sights, sensors, etc.

Software modularity in an open systems architecture is the principal enabler to autonomy evolution in a RAS, as outlined above (counter armor, Section 4.4; counter IADS, Section 5.4). A functional partitioning of software in a modular software architecture allows for cognitive functions to be separated and isolated from software modules that are tightly coupled to platform-specific dynamics and inner loop control modules (Fig. 6.2). This partitioning allows cognitive functions to be developed independently of the platform, and enables continuous insertion of autonomy improvements as they become available from any source, not just the platform prime contractor. This is an important feature since it will allow "best-of-breed," non-proprietary cognitive functions to be integrated into any RAS without the encumbrance of integration and regression testing of each upgrade with prime contractor-unique proprietary software and processes.

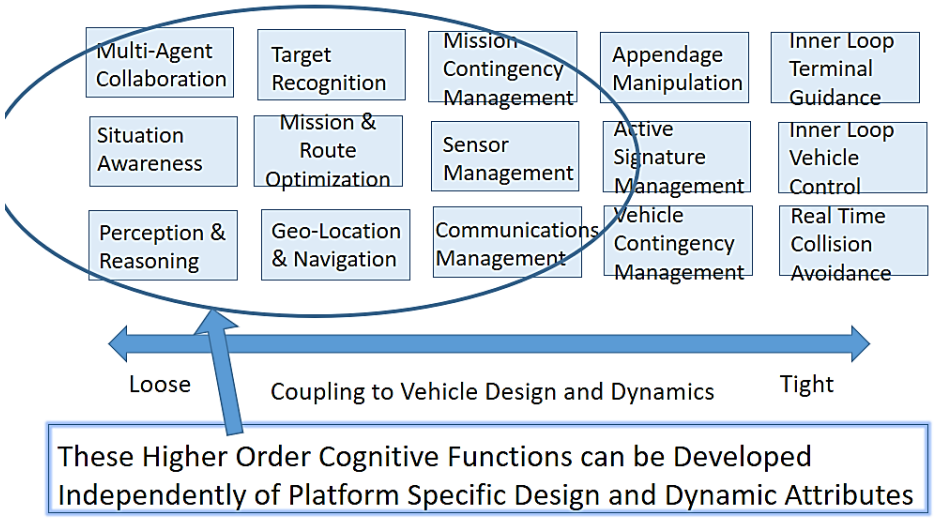


Figure 6.2 Modular Software Partitioning

An open systems software architecture is required to implement this modular software approach. The modular software functions need to be isolated from the RAS platform operating system (OS) by means of middleware, along with well-defined application interfaces (APIs), to enable independent cognitive function application software development and integration. The middleware can introduce latencies that might not be acceptable for inner loop control functions on high performance RAS, but are not normally significant for outer loop control or cognitive functions. In these cases, the architecture may be a hybrid open system, in which cognitive functions are open and reside on the middleware, while tightly coupled dynamic

control software may be "closed" (i.e., platform unique and potentially proprietary) and reside on a dedicated low latency bus.

Modular, functionally partitioned, open system architecture provides the path to independent development and insertion of "best-of-breed" cognitive function upgrades and the means for implementing autonomy evolution (Fig. 6.3).

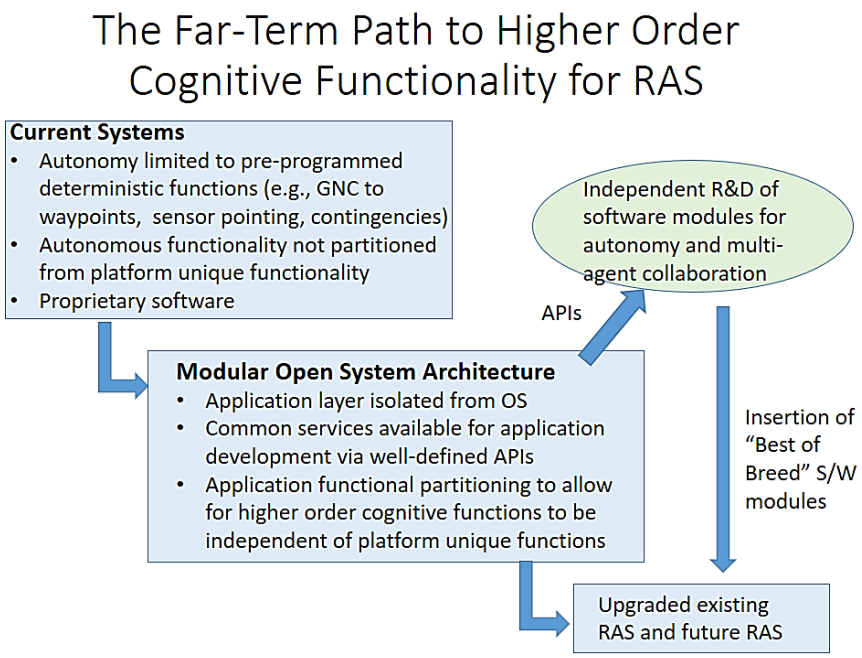


Figure 6.3 Upgrading RAS Cognitive Functionality

7 RESEARCH AND DEVELOPMENT (R&D)

Considerable RAS related R&D is being conducted within the Army, across DOD, in the civil and commercial sectors, and within academia. This R&D is global in scope and can be expected to rapidly advance RAS capabilities in all technology domains. Several recent reports and briefings provide excellent summaries of developments and R&D requirements for RAS technologies in support of DOD applications,[13] [14] [15] as well challenges and strategies for R&D investment across the U.S. Government.[16] No attempt was made to summarize this expansive field of R&D in this report. Instead, the following sections focus on two technology areas specifically highlighted in the TOR: Human-RAS collaboration and countermeasure robustness.

7.1 HUMAN-RAS COLLABORATION

Military systems are a combination of both human and machine subsystems. Much work and progress had been done in academia, commercial industry, and DOD labs in the areas of computing, robotics, sensors, and artificial intelligence (AI). Twenty years ago, many of today's ubiquitous AI capabilities were major challenges that needed to be solved. Real time computer vision, image, gesture and face recognition, speech, language translation, autonomous navigation, and machine learning are all capabilities now being incorporated into civilian and military robots. In fact, AI provides a clear, new path for advancing the capabilities of weapons systems and protecting Soldiers by reducing the cognitive and physical burdens on them. As discussed earlier, autonomy also opens the design space for weapons developers because it's a rapidly advancing technology that allows trade-offs among survivability, weight, and lethality.

Despite these advances, the team believes robotic weapons systems cannot stand apart from Soldiers. Humans, at some level will always be involved as part of a team. As demonstrated in the work done at ARL for the Robot Collaborative Technical Alliance (RCTA) and DARPA's Squad X programs, robots introduce new synergies, given the appropriate CONOPS. One of the main goals of Squad X is making the squad more autonomous (with respect to platoons and companies) by increasing squad members' real-time knowledge of their own and teammates' locations through collaboration with embedded unmanned air and ground systems.[17]

RCTA is attempting to develop highly capable systems, which have a set of intelligence-based capabilities sufficient to enable the teaming of autonomous systems with Soldiers. To act as teammates, robotic systems will need to reason about their missions, move through the world in a tactically correct way, observe salient events in the world around them, communicate efficiently with Soldiers and other autonomous systems, and effectively perform a variety of

[13] DOD Unmanned Systems Integrated Roadmap, FY2013-2038
[14] DOD Autonomy Roadmap, Autonomy Community of Interest, NDIA 16th Annual Science and Engineering Technology Conference, 24-26 March 2013
[15] Defense Science Board, The Role of Autonomy in DOD Systems, July 2012
[16] The National Artificial Intelligence Research and Engineering Strategic Plan, National Science and Technology Council, October 2016
[17] http://www.darpa.mil/program/squad-x-core-technologies

mission tasks. Four focus areas for RCTA include:[18]

- Adaptive Tactical Reasoning – robots understand the concept of a mission or task, including stages of progress and measures of success. They work with Soldiers, using the shared concept of METT-TC: mission, enemy, troops, terrain, time, and civilian considerations.

- Efficient Proactive Interaction with Humans – robots interact with each other and especially with Soldiers in an efficient and proactive way relevant to the evolving situation.

- Safe, Secure, and Adaptive Movement – robots move on orders or on their own from one tactical position to the next with little or no reliance on metric inputs (i.e., GPS).

- Interaction with the Physical World – robots observe objects at close quarters to enable 3D interaction with them.

Humans set the constraints (physical, ethical, or legal) and the goals implicitly through system designs or explicitly through commander's use and intent. Robots will be subject to rules of engagement when employed in combat like any military system. Moreover, Soldiers will either be "in the loop" making decisions on employment and actions or "on the loop," monitoring the behavior and consequences of robotics systems.

The study team expects to see an evolution of systems, e.g. "creeping autonomy," where autonomy isn't immediately self-evident but an additional feature of a platform. An example is the approach by auto companies to slowly introduce autonomy with a "cruise control" system which is improved with each software patch and eventually transforms into a self-driving car. In the case of a tank, autonomy will grow in sub-systems such as driving, evasive maneuvers, and "slew-to-que" where the gun is automatically cued to likely threats.

Given the nascent understanding of the role of robots in tactical formations, they should operate, initially, within strict bounds of performance. CONOPS developed through the campaign of learning will eventually exploit their full capabilities. Some autonomous systems will have little immediate interaction with Soldiers because they will be designed to counter threats faster than humans can react, e.g., APS on a tank or a "cognitive EW" system.[19]

As robotics develops, learning will become more important and robots will have to express to humans what they have learned and why. The relationship and balance between Soldiers and robots will be dynamic and adapt to the military situation. As RCTA is demonstrating, robots will also have to work as member of a team and share common goals.

[18] http://www.arl.army.mil/www/pages/392/RCTA_FY12_APP.pdf
[19] http://www.darpa.mil/program/behavioral-learning-for-adaptive-electronic-warfare

7.2 COUNTERMEASURES

Threats to unmanned systems will vary based on platform and mission, but may include ground fire, artillery, air, air defense, or any other type of conventional or unconventional attack. As demonstrated in the Ukraine, Iraq and Afghanistan, adversaries can be very creative in their approach to reducing unmanned systems capabilities. There are several potential countermeasures and promising venues for additional research.

The primary threats to unmanned systems are very similar to manned systems. Physical damage and/or destruction can be caused by enemy combatants using bullets (including armor piercing); anti-armor munitions (hand held high-explosive anti-tank munition) and anti-material sniper rifles; directed energy systems (high-powered radio frequency and laser); surface and subsurface munitions and mines; indirect fire (rockets, mortars and artillery) with improved conventional munitions and precision guided munitions. In most cases, these threats are defeated by standard protection systems (APS, active armor, coatings, system/hull shape that use void spaces and channels to route blast pressure around critical components, etc.). The Army should continue research into materials and vehicle designs to reduce the effects of physical damage and apply any solutions to both manned and unmanned systems.

Electronic attack will potentially threaten communications, data link, and position navigation systems. Computer network operations could threaten associated networks. Adversaries will possess a wide variety of target acquisition means from the intercept of unencrypted traffic, through image intensification (active and passive infrared), and thermal imaging systems. These types of attacks will be common to manned and unmanned systems. For unmanned systems, these attack types pose an additional level of risk because the commander of the system may lose contact and not know its status. This loss of SA by the vehicle commander reduces the usefulness of the system in an engagement. Research should continue in developing secure and redundant communications. The Army currently has systems that can operate in several different communications denied environments, but as adversaries continue to develop new threats to communication systems, it needs to continue to evolve countermeasures.

Electronic attack can also take place in the form of a cyber-attack, whether as a directed attack over RF, as an attack over the network, as an insider attack, or as a Trojan horse lying dormant in the software. These types of attacks can occur in manned or unmanned systems. For unmanned systems, the Army should continue to build tools to identify these attacks and to develop automated responses. These can include simply shutting down and rebooting the operating system when an anomaly is identified, an automated way to respond to and overcome the attack, or returning to a preprogramed location or state.

Adversary employment of various camouflage, concealment, cover, denial, and deception techniques (such as obscurants, nets, and coatings) will complicate intelligence collection missions and timely tele-operated targeting just as they complicate operations for manned systems. The Army should continue research developing software and improving the ability of sensors to overcome deception and deceptive techniques against its systems, and apply to

improvements to both manned and unmanned systems.

Adversaries may employ various barriers and other physical techniques to counter the employment of unmanned systems. In response, the Army should develop improved vision systems and sensors that enable awareness of the environment around the vehicle while operating in remote-control mode. In the manned system equivalent, tanks operate in very difficult environments, maneuvering around, through, or over a wide range of obstacles, because the crew and commander have very good SA and are able to communicate to resolve obstacles and hazards. For the RAS, there are many sensors on the market that can provide enough details to maneuver a vehicle through most terrain. Continued development and improvement in sensor technology will make the SA better and enable the system to be more autonomous in maneuver.

An advantage of a manned system is self-awareness of the crew. While many adversary threats are common to manned and unmanned systems, the former have a crew that can quickly assess the effect of the threat and devise a solution to counter. The need for a continuous self-diagnostics and awareness of the environment around the system is unique to the unmanned system and will require significant work. An unmanned system will need to diagnose problems, develop solutions by repairing, re-routing, or overcoming the issue, and have an operating concept for how to act when it cannot self-repair (shut down, return to sanctuary, etc.).

The Army will need to ensure RAS are robust and can handle several different types of attack. Ongoing research will be necessary to develop solutions against current threats and those that evolve over time, as adversaries will continue to try new methods of attack against the systems. By building the RAS with open architectures, the systems should have the ability to adapt new solutions, material and non-material, to any number of adversary threats.

Finally, adversaries may use the media and appeals to social or cultural mores to prevent the use of unmanned systems on the battlefield. This type of campaign was successfully undertaken in Afghanistan, when the Active Denial System deployed but was never used.[20] The enemy used human shields, propaganda reports of unmanned systems indiscriminately killing, and accusations that U.S. forces were no longer ‘manly’ enough to fight, so they had to use robots. To counter this type of misinformation, the Army needs to focus part of the recommended campaign of learning on building and assuring public trust in the utilization of RAS. In addition, the Army should be prepared for information attacks against the use of unmanned systems by having an active information campaign of its own. This should include publicly describing rules of engagement (ROE) for RAS, even if that means allowing the enemy to exploit the seams or limits of the ROE to their advantage. The goal of the RAS information campaign should be to have ready, fact-based counters to false claims about how the systems are employed. The Army should also be as transparent as possible with the facts of any engagement involving RAS, especially as the systems are introduced to the battlefield for the first time.

[20] "US withdraws 'pain ray' from Afghan war zone." Daily Mail. London. January 25, 2010. Archived from the original on July 27, 2010. Retrieved July 27, 2010.

8 THE WAY AHEAD

Despite the clear operational benefits of RAS and the strength of R&D activity in autonomy and collaboration that will enable continuous improvement of RAS' operational benefits, the Army is not aggressively transitioning RAS from S&T to PORs, and little funding has been allocated to new Army RAS PORs that develop greater autonomy. This situation is particularly vexing given the rate at which adversaries are deploying RAS and using them in current conflicts. RAS offers solutions to the warfighting challenges the Army faces against near peer threats.

Therefore, in addition to answering the question "why RAS?" the study team addressed the equally important question of why the Army is not more aggressively transitioning autonomous system technologies into PORs. The principal factor appears to be a lack of advocacy for RAS by Army leadership, with an attendant lack of funding. There are 3 factors underlying the lack of advocacy and funding. First, authority and responsibility for RAS in the Army is fragmented. Second, fiscal reality; the Army Total Obligation Authority (TOA) is unlikely to increase to provide funding for new RAS PORs, and there's always organizational resistance to reallocating funds away from current PORs to new ones. The third factor is a lack of trust that the promise of RAS will be fully realized. The bottom line is that these issues are causing the Army to find itself at an impasse on RAS at the very same time that it's becoming globally ubiquitous and adversaries are developing and deploying them.

The study team also addressed another potential barrier to development and deployment of RAS in the future, the Verification and Validation (V&V) and Test & Evaluation (T&E) of RAS that is required before a new RAS is approved for operational use.

8.1 ADVOCACY

One of the principal factors causing a fundamental lack of institutional advocacy within the Army is the fragmentation of the authority and responsibility for RAS. Autonomy and robotics can improve effectiveness in many areas; however, none of the centers of excellence (which are focused on the six Army warfighting functions) has actively embraced RAS technology because it represents a new and different way of completing traditional missions. To make matters worse, there is no resource advocate for robotics and autonomy. While many RAS systems are likely to be relatively inexpensive and will extend capability in a cost-effective manner, the current budget climate makes it difficult for any new system to attract support when existing programs of record are struggling to make their milestones.

The Navy recently made a significant organizational change to improve its advocacy for unmanned systems by creating both a Deputy Assistant Secretary of the Navy for Unmanned (DASN (Unmanned)). This entity is specifically focused on guiding the development of future unmanned systems in the air and on and under the sea. While this might not be the best approach for the Army, it's imperative that an appropriate solution to the advocacy problem be instituted. The operational advocate should most likely be with the Army Capabilities Integration Center (ARCIC). If ARCIC is assigned this role, the challenge will be to develop

appropriate support within the ASA(ALT) program community so that validated concepts can be rapidly moved through development and acquisition to deployment.

8.2 TRUST

Trust is one of the broadest objections raised by skeptics to RAS, and thus stands as one of the key issues that must be addressed to expand the use of RAS. It's important to recognize that the trust issue is articulated variously depending on the level in the government, so each will need to be addressed on its own terms.

At government policy levels, the issue resides as concern over unleashing unbounded AI, particularly for lethal RAS. There's much concern expressed in the press and within the policy community about "killer robots." In addressing this concern, policy makers must understand that all autonomy, including AI enabled autonomy, can and should be supervised at some level, and can be constrained by human imposed limitations. There's very clear DOD policy guidance (DODD 3000.0, 2012) requiring "appropriate levels of human judgment over the use of force." Also, over the next decade or two, AI enabled autonomy will first be employed in the electro-magnetic and digital processing domains long before we are ready to employ them in the lethal kinetic domain, providing time for R&D and experimentation to explore and set acceptable design, development and operational guidelines for AI enabled lethal applications.

At senior DOD and Army leadership levels, the trust issue is expressed as concern that the promised RAS capabilities are grossly exaggerated in glossy brochures and Power Point presentations. Campaigns of learning like those outlined above for the two RAS concepts are essential for dealing with this trust issue. It's critical that CONOPS be validated and refined through operational experiments and exercises that demonstrate the military value of RAS and allow operators to develop confidence in the effects that RAS can be expected to produce.

Finally, at the Soldier level, the trust issue is concern over whether RAS will behave in predictable ways and not harm friendly forces. To address this issue, RAS architecture must include human-robot interfaces to facilitate transparency and enhance the operator's understanding of the robot's state and view of its environment (see Section 6.1). Development of the architecture and the required interfaces should be supported with model-based design principles leveraging a simulation environment that's refined throughout the development phase. Both during and following development, it's important to include Soldiers as operators of the RAS. The simulation environment can be used to support V&V and T&E, as well as the training of the operational force after the system is deployed.

8.3 VERIFICATION AND VALIDATION (V&V), TEST AND EVALUATION (T&E)

The V&V and T&E of autonomous systems is essential for building trust and for certifying that RAS is suitable for operational use. However, the V&V and T&E of RAS represent a significant challenge as cognitive functionality continues to evolve toward non-deterministic AI and as RAS is utilized in more complex, dynamic environments, particularly when operating near Soldiers.

The fundamental problem is that it's infeasible to test adaptive RAS behavior under all possible combinations of environmental conditions, dynamically changing battlefield situations, and failure modes and contingencies. A recent ASD(R&E) study conducted by the Autonomy Community of Interest TEVV Working Group concluded that:

> The notion that autonomous systems can be fully tested is becoming increasingly infeasible as higher levels of self-governing systems become a reality. As these systems react to more environmental stimuli and have larger decision spaces, the standard practice of testing all possible states and all ranges of inputs to the system becomes an unachievable goal.[21]

Considerable study and research of the issue is underway. Rather than summarizing that body of work in this report, the study team chose to propose a method based on the approach that's been used successfully for "clearing the flight envelope" during T&E of new combat aircraft. The idea is to determine whether an analogous approach might be useful for "clearing the trust envelope" for new RAS.

The approach used to clear the flight envelope on a developmental combat aircraft is an incremental, simulate-test-analyze-fix-simulate approach (Fig. 8.1). High fidelity simulation of aircraft "behavior" (e.g., flight characteristics, response to pilot inputs, etc.) is a critical first step in the process. The test pilots train with this simulation and develop certain expectations of how the aircraft will behave under various environmental conditions, flight parameters and failure modes and contingencies. The first test flights are always simple straight and level flights in which reams of data are gathered. Through analysis of flight instrumented data and pilot feedback, the fidelity of the simulation is improved, fixes to the aircraft are made (usually to flight software), and next flights with slightly reduced flight restrictions are approved. Through multiple iterations of this process, the flight envelope is gradually opened to more complex capabilities and conditions. Since it's infeasible to test the aircraft under all possible conditions, a test matrix is defined that provides validation of aircraft performance and behavior under a set of "stressful" conditions. At the end of the flight test program, the aircraft is certified for operational use and, just as importantly, the flight simulation is validated, which allows performance and behavior to be projected with high confidence to all other combinations of conditions that were not directly flight tested. The resulting validated simulation is then used for multiple other purposes, including pilot training and definition of product upgrades.

[21] Autonomy Community of Interest (COI) Test and Evaluation, Verification and Validation (TEVV) Working Group, Technology Investment Strategy, 2015-2018, ASD(R&E), May 2015

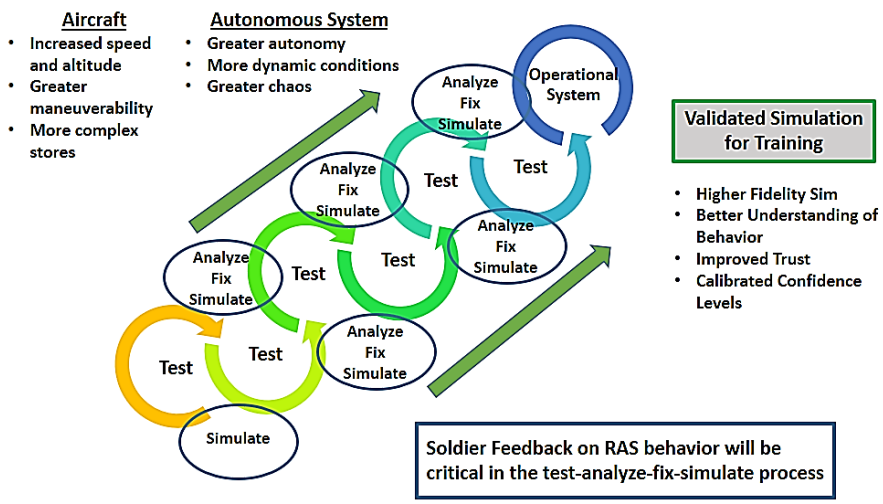


Figure 8.1 T&E to Build Trust in RAS

A similar simulate-test-analyze-fix-simulate approach could work for "clearing the trust envelope" during V&V and T&E of a new RAS. RAS functionality would be restricted initially and incrementally opened as behavior becomes better understood and simulation fidelity is improved. The resulting validated simulation can be used to extrapolate the limited test conditions to other environments and conditions, to calibrate levels of trust, and to conduct operator training. It could also be used during actual operations as a means for Soldiers to dynamically adjust autonomous functions granted to the RAS as a function of operational conditions, levels of risk, and ROEs.

The high-fidelity simulation of RAS operating in its SoS environment is the foundation of this approach. Likely, a simulation toolset, consisting of various constructive, virtual and live components will be required to model RAS at various levels of fidelity: from detailed physics-based and cognitive-theory-based models, to higher level "engagement" models that use abstraction from the more detailed, lower level models. Operator-in-the-loop and software-in-the-loop capabilities will be important to capture human-RAS collaboration effects and feedback. An agent-based simulation approach would seem ideal, in which the RAS is modeled as an independent agent interacting with the external environment and all the other agents in the SoS architecture (see Fig. 6.1 in Section 6.3).

9 FINDINGS AND RECOMMENDATIONS

RAS offers numerous operational advantages to Army formations across all six Army warfighting functions. The two concepts developed by the study team provide insight on how RAS can provide significant operational value in solving some tough warfighting challenges by utilizing the more open design space and by providing the JFC with the flexibility to employ his manned-unmanned forces in innovative ways that aren't available through conventional, manned forces.

9.1 FINDINGS

The study team believes we've reached a "tipping point" in the application of autonomous technologies in both the commercial and military sectors, which will drive a dramatic increase in demand. The Army has benefitted from the introduction of RAS on the battlefield, but with limited autonomy. Adversaries have also deployed RAS and appear intent on taking advantage of ubiquitous RAS technology to counter U.S. capabilities. The initial, but limited use of RAS has already started to change the character of warfare. Greater changes seem inevitable. Regardless of how the Army decides to take advantage of this inexorable march toward greater autonomy on the battlefield, other friendly and adversarial nations will continue developing and adopting new uses for battlefield autonomy.

> **Finding #1: Regardless of how Army proceeds, the application of ubiquitous RAS technology on the battlefield is inexorable and will change the character of warfare; adversaries are aggressively pursuing**

The underlying technologies for RAS are ubiquitous and global. Private sector investment in autonomous and collaborative technologies is growing and will likely far exceed military spending in the future. The U.S. does not necessarily have an asymmetric advantage in these technologies, nor is it likely to gain a disruptive advantage as the trends toward globalization and commercialization continue. As such, it's unlikely that U.S. Joint Forces will develop an asymmetric RAS capability based on technology alone. Disruptive capability will rely on both technology and how the technology is employed as part of innovative CONOPS.

> **Finding #2: Technology alone will not provide an asymmetric advantage; CONOPS also need to be innovative and disruptive**

The study team endeavored to understand the operational benefits of RAS to the Army, and the underlying attributes of RAS contributing to these benefits. The team determined there are two fundamental factors that allow RAS to provide better solutions to difficult warfighting challenges than manned systems and/or more standard solutions. The first is that RAS opens the design space for material solutions, allowing for smaller, lighter and more affordable solutions with equivalent or greater effectiveness than manned system. The second factor is the ability for Joint Force Commanders to innovate with CONOPS and TTPs that aren't viable with manned systems.

Finding #3: RAS offers solutions to difficult warfighting challenges because it opens the design space and enables innovative CONOPS

The study postulated two advanced RAS capability concepts and defined a point design instantiation of each to better understand how the RAS factors (opening the design space and enabling innovative CONOPS) contribute to operational effectiveness in the context of tough warfighting challenges that can't be solved effectively by conventional approaches. One concept examined adding a remote controlled, counter armor UGV (i.e. robotic tank) to an SBCT to enable the SBCT to defeat enemy armor formations without compromising deployability or maneuverability. The second concept evaluated using a UAS to conduct localized SEAD against capable threat IADS.

These two RAS concepts, instantiations and CONOPS were selected as representative of the wide spectrum of ways RAS can address Army warfighting challenges. Both the UGV counter armor and UAS counter IAD concepts were based on mature RAS technologies for near term initial operational capability, but with growth paths for continuous capability improvement through insertion of advanced autonomous functionality as it becomes available. While representative only, these concepts are excellent points of departure for further investigation of RAS operational utility that can be achieved by integrating mature technologies.

Finding # 4: Counter-Armor RAS and Counter-IAD RAS are excellent points of departure for understanding RAS operational utility by integrating mature technology

By means of its evaluation of the counter armor and counter IAD concepts, the study confirmed that RAS can help the Army solve some major warfighting challenges. Moreover, these benefits are available with current technology but, if architected correctly from the beginning, can easily capitalize on new autonomous technology developed by private industry or the government in the coming years. Therefore, in addition to answering the question "why RAS?" the study addressed the equally important question of why the Army is not more aggressively transitioning autonomous system technologies into PORs. The principal factor appears to be a lack of advocacy for RAS by Army leadership, with an attendant lack of funding.

Finding # 5: Three factors limit advocacy and funding for RAS with greater autonomy:

- **Fragmented authority and responsibility for RAS**
- **Organizational resistance to reallocation of funds from current PORs**
- **Lack of trust**

To address these underlying factors for developing advocacy, Army leadership must be convinced that the promise of RAS can indeed be realized. Doubts about the value of RAS are based on the limited capabilities of current UAS and UGVs, for which the term "unmanned" seems to be a misnomer due to the high ratio of operators and maintainers to RAS vehicles. It's

well understood that this ratio is driven principally by the limited autonomy of the current systems, which were not designed to take advantage of rapidly advancing autonomous functionality. Nevertheless, a compelling case must be made that more advanced RAS can mitigate the man to unmanned system ratio and other lingering issues as well. A campaign of learning is required to build this compelling case.

Finding # 6: An integrated campaign of learning is needed to:

- **Evaluate innovative CONOPS**
- **Validate operational value**
- **Develop next generation autonomy**
- **Inform capability needs for future AROC**
- **Build trust**

An autonomous system will operate as one system within a SoS environment. The RAS itself will continuously evolve within this SoS environment, but so will all the other SoS entities. While the RAS POR program manager will have control of the RAS, he/she will generally not have control of the other entities. Therefore, it will be important for the RAS architecture to ensure interoperability of the interfaces and interactions with the other entities as they continuously evolve. Efforts are underway to define the open system standards and protocols for these interfaces and interactions, but it will be important for a single multi-service set of open system standards to emerge from these efforts.[22]

Any new platform-based RAS POR will be subject to the rules and regulations of DOD 5000 major acquisition programs. In such programs, the technology base used for the RAS design and development is necessarily frozen early in the program, at Milestone A or B. It's not unusual for design, development, DT&E, initial production, and OT&E to take 10-15 years from MS A/B to Initial Operating Capability (IOC) of the system.[23] For systems that are heavily dependent on electronics hardware/firmware and platform/sensor/processing software, this long, time delay between technology freeze at MS A/B and product fielding at IOC presents two dilemmas. The first is that the technology maturation cycle for electronics components is much more rapid than for other platform technologies (e.g., structure, propulsion). Therefore, by the time the system is finally fielded, the embedded electronics can already be obsolete. The second issue is the software that controls all system functions is generally written by the system prime contractor and typically highly coupled to platform unique dynamics (e.g., inner control loops) and other platform specific design attributes (e.g., signatures, failure modes). Also, typically, there's no requirement for the software architecture to be functionally partitioned to separate and isolate platform unique functions from mission functions. Finally, software often contains

[22] Examples of these efforts include the Scalable Controller Interface (SCI), Future Airborne Capability Environment (FACE), Software Communications Architecture (SCA), Vehicle Integration for C4ISF/EW Interoperability (VICTORY), and many other efforts.

[23] An argument could be made that the acquisition timeline for some new RAS systems might be compressed by exploiting NDI/COTS solutions that will be generated through commercial investment in autonomous systems. This study did not evaluate this possibility. Regardless, the need remains for continuous electronics and software insertion over the full life cycle of and RAS POR.

proprietary code. These factors make it difficult to upgrade software or add new capabilities on a cycle commensurate with electronics maturation cycles without expensive coding, V&V and regression testing by the prime contractor.

This is a particularly thorny problem for RAS systems because RAS is software intensive and cognitive functionality is expected to advance rapidly, on a global scale, and won't be constrained to the limited experiential base of a single prime contractor or contractor team. To fully exploit advances in autonomy and human-RAS collaboration, it's essential for the RAS software to have a modular, functionally partitioned, open systems architecture, that enables a continuous insertion of "best of breed" cognitive software modules from independent developers. Also, returning to the first dilemma (rapid electronics maturity cycle), it's important to recognize that some of the cognitive functionality will be resident in electronics hardware/firmware (e.g., DRFM board), as well as software. Thus, the architecture must support the modularity of electronics as well, to allow for continuous insertion of new modules as well as best of breed software over the extended life cycle of a platform-based RAS.

Finding # 7: RAS architecture is important to:

- **Ensure the interoperability of RAS in a continuously evolving Systems-of-Systems environment; many open architecture systems in development**
- **Allow for independent development of high order cognition S/W applications and facilitate insertion of "best of breed" applications into current and future RAS**

9.2 RECOMMENDATIONS

Based on these findings, the study team developed two recommendations. The first addresses those findings associated with lack of Army leadership advocacy for new RAS with greater autonomy and collaboration. Advocacy must start from the top and build on convincing evidence that RAS can deliver as promised. Among the actions that must be taken to build the evidence are a RAS-focused campaign of learning and advanced concept design. Given the operational benefits inherent in the two concepts studied, it's recommended that the Counter Armor and Counter IAD concepts be used as the advanced concept design activity. As they become available, results from these efforts, which should be conducted in parallel, should be consolidated and synthesized into a set of initial capability requirements for future RAS.

Recommendation # 1: CSA – Issue an EXORD that:

- **Establishes a RAS focused Army Campaign of Learning for evaluating operational utility of RAS and developing RAS CONOPS and TTPs. The campaign should include simulation, prototyping, limited fielding, experiments & warfighting assessments**
- **Initiates the advanced concept design of a) an attritable robotic counter-armor capability and b) an attritable, autonomous loitering UAS with a modular payload design that provides a counter IAD**

capability

- **Establishes an AROC committee to develop requirements based on inputs from the campaign of learning and the concept design**
- **Designates a central RAS advocate**

The second recommendation is to provide the essential building blocks for future RAS development. These building blocks include an inter-service, modular, open system architecture that enables RAS interoperability within a SoS environment and that facilitates continuous insertion of independently developed autonomous software over the life cycle of the RAS. The other essential element is a high-fidelity simulation toolset for RAS, which is critical for all life cycle phases of future RAS, from initial design and development, through V&V and T&E, and for operator or collaborator training. Simulation will be particularly important for understanding RAS behavior and calibrating trust in RAS behavior in complex environments.

Recommendation # 2: ASA(ALT)

- **Working with Joint Services, define a modular open system architecture that allows for independent development of high order cognition S/W applications and that facilitates insertion of "best of breed" applications into current and future RAS**
- **Develop a high-fidelity simulation toolset for understanding RAS behavior in complex environments; for calibrating trust confidence levels of RAS under dynamic conditions; and for design, development, V&V, T&E, training and life cycle management**

APPENDIX A – TERMS OF REFERENCE

SECRETARY OF THE ARMY
WASHINGTON
JAN 0 4 2016

Dr. James Tegnelia
Chairman, Army Science Board
101 Army Pentagon
Washington, DC 20310

Dear Dr. Tegnelia:

I request the Army Science Board (ASB) conduct a study entitled "Robotic and Autonomous Systems-of-Systems Architecture."

While the Army has made significant research investments in robotics and autonomous systems (RAS), the primary operational employment of RAS technology has been in unmanned aerial systems (UASs) operated as single vehicles in the battle space with dedicated operators. The Army accomplished the last expansive architecture study directed at integrating RAS technology into Army formations during the Future Combat System program.

Across all the Services, RAS investments have tended to focus on platform development, not on the autonomy software or integration of these systems into effective manned or unmanned teams. This study should identify the Army formations with the greatest potential to benefit from adoption of RAS technology in both the near term (7-10 years) and the long term (10-25 years). For each selected application, the study team should define the benefits of RAS, considering such factors as cost, manpower reduction, survivability, and mission effectiveness. To the extent possible, the team should make maximum use of existing platforms available in the Army, other Services, or commercially. The study team's tasks shall include, but not be limited to, the following:

a. For each of the most promising applications, investigate the operational and systems integration or architecture that will provide disruptive and innovative capability. Identify the issues to address across the full spectrum of Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities (DOTMLPF) to ensure achievement of this capability. Suggest top-level architectures that facilitate manned and unmanned teaming.

b. Identify approaches to human-system collaboration demonstrated in the research community to facilitate near-term inclusion of RAS technology into Army formations. Specific issues to address include experiments to validate concept of operations, building trust, and approaches to testing and evaluation. Such experimentation may require new forms of instrumentation and training to assure achievement of optimal performance.

-2-

c. Recommend further research required to (1) dramatically expand RAS capabilities in the long term, (2) provide the Army with significant overmatch, and (3) expand beneficial applications of the technology to maximize its effective use.

d. Anticipate enemy countermeasures to RAS capabilities and recommend how future Army forces should counter enemy RAS.

The study should provide an independent report of its deliberations, findings, and recommendations, as well as cooperate with and provide its results to the parent ASB study on "Disruptive Innovative Concepts for the Future Army."

The Commanding General, U.S. Army Training and Doctrine Command is the sponsor of this effort. The G-3/5/7 will assist the study team in accessing classified information up to Top Secret and including Sensitive Compartmented Information and Special Access Programs. The Board will provide a briefing and report with findings and recommendations by September 30, 2016 to me and the Chief of Staff, Army.

The study will operate in accordance with the Federal Advisory Committee Act and DoD Directive 5105.4, "DoD Federal Advisory Committee Management Program." I do not anticipate that this study will need to go into any "particular matters" within the meaning of Title 18 United States Code Section 208, nor will it cause any member to be placed in the position of acting as a procurement official.

Sincerely,

Eric K. Fanning

Eric K. Fanning
Acting

APPENDIX B – STUDY TEAM MEMBERS

Mr. Mike Heinz (Chair)

Dr. Mike Macedonia (Co-Chair)

Dr. Bob Atkins

Ms. Vivian Baylor

Dr. Vanu Bose

RADM (Ret) Grant Hollett

Dr. Sung Lee

Mr. Michael Molino

Mr. Jim Shields (Co-Chair, Red Team Advisor)

Dr. Bob Sadowski (Advisor)

BG (Ret) Bob Wynn (Analytic Team Liaison)

LTC Ben Fernandes (Study Manager)

MAJ Craig Martin (Study Manager)

Mark S. Swiatek (Tech Writer/Editor)

APPENDIX C – ASB APPROVED BRIEFING, FINDINGS & RECOMMENDATIONS

The following briefing was delivered to the Army Science Board membership in a public session at the Beckman Center of the National Academies of Sciences & Engineering on July 28, 2016. Board members adopted the findings and recommendations as briefed by unanimous vote.

Robotic and Autonomous Systems (RAS) Study

Version Final

07/28/16 (Cosmetic Updates 9 Sep 2017; updated concept vehicle 9 Nov 2017)

Army Science Board 1

Outline

- Introduction
- Robotic Armor Concept
- Counter-Integrated Air Defense (IAD) Concept
- RAS Way Ahead
- Findings and Recommendations

Army Science Board 2

Team Members and Visits

Team	Visits and Briefings
Dr. Bob Atkins (Member) Ms. Vivian Baylor (Member) Dr. Vanu Bose (Member) LTC Ben Fernandes (Study Manager) Mr. Mike Heinz (Chair) RADM (Ret) Grant Hollett (Member) Dr. Sung Lee (Member) Dr. Mike Macedonia (Co-Chair) MAJ Craig Martin (Study Manager) Mr. Michael Molino (Member) Dr. Bob Sadowski (Advisor) Mr. Jim Shields (Co-Chair, Red Team Advisor) BG (Ret) Bob Wynn (Analytic Team Liaison)	Army - DASA(R&T), G3/5/7 - TRADOC ARCIC, G2, G9, TRAC - PM-Force Projection, PEO-STRI - AMRDEC, CERDEC, TARDEC, ARL - AVNCOE, FCOE, MCOE Other Services - Air Force Research Lab (AFRL), A3 - Office of Naval Research (ONR), Naval Air Warfare Center (NAWC) Joint - Joint Staff, J8 - OSD PD ASD(R&E), CAPE, DARPA Other - Software Engineering Institute (SEI) - Industry RFI - Studies, Roadmaps, and Strategy Docs

Why Robotic and Autonomous Systems (RAS)?

- Intractable warfighting challenges vs. near-peer adversaries stress conventional approaches
  - Inhibited ABCT deployability and maneuverability
  - Limited firepower in IBCTs/SBCTs
  - Loss of air superiority against IADS
- RAS opens the design space
  - "Attritable" assets with equivalent or better effectiveness
  - Improved deployability/maneuverability over manned systems
- RAS enables innovative CONOPS that change the character of warfare and present multiple dilemmas to the adversary

Outline

- Introduction
- Robotic Armor Concept
- Counter-IAD Concept
- RAS Way Ahead
- Findings and Recommendations

Army Science Board

5

Challenge: Engagement of Threat Massed Armor

- Potential future near-peer conflicts challenge deployment timelines and quantity of Army heavy lethality units (e.g., ABCT units)
  - Weight and logistics footprint of M1A2 system severely limits deployment options and maneuver corridors
  - Present ABCT force structure insufficient to counter potential massed armor of near peer armor forces
- Need exists to augment the lethality of lighter SBCT units
  - Solution needs to be equally deployable as current SBCT force structure, but with equivalent ABCT lethality
  - Affordability of solution critical

Russian Armata-14

Army Science Board

6

Manned vs. Unmanned High Lethality Vehicle

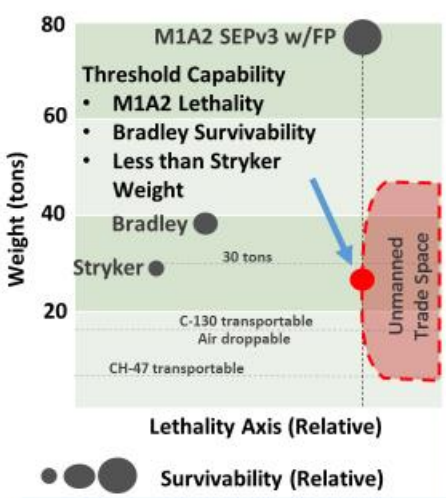
	Manned Solution	Unmanned Solution
Survivability	• High survivability required to protect crew in armor vs. armor fight; increasingly difficult to achieve	• Survivability tradeable for other capabilities (cost/lethality/weight); fewer requirements (NBC, 6W ride)
Lethality	• Shock from gun limited due to crew presence	• Higher local shock from gun permitted but constrained by weight
Volume	• Hull volume needed to accommodate crew; adds weight and size	• Smaller hull volume possible; greater magazine depth possible as trade
Logistics	• Above factors lead to heavy solution increasing vehicle wearing, maintenance, and fuel needs	• Smaller & lighter vehicle more deployable; less vehicle wearing, maintenance, and fuel needs
Training	• Heavy expensive vehicle represents substantial asset; greater training needed to "qualify" crew	• Less expensive vehicle potentially allows lighter training to "qualify" crew; more natural interface possible

Unmanning of tank opens design space & offers potential for lighter, less expensive, lower logistic footprint vehicle with lethality matching or exceeding M1A2

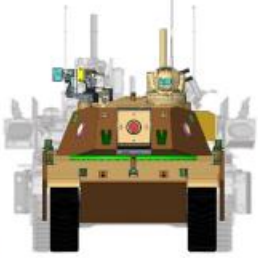
Army Science Board 7

Combat Vehicle Lethality & Laden Weight

Crew: 2-3 remote operators



M1A2 Abrams vs. ACT3205 Concept Size

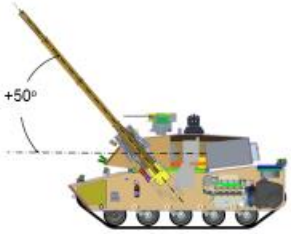


Remoted, unmanned systems enable a variety of lightweight, high-lethality vehicles with survivability, CONOPs and magazine depth as the tradespace

Army Science Board 8

Baseline Robotic Armor Concept

Robotic Counter Armor
(Remotely Piloted Ground Vehicle)



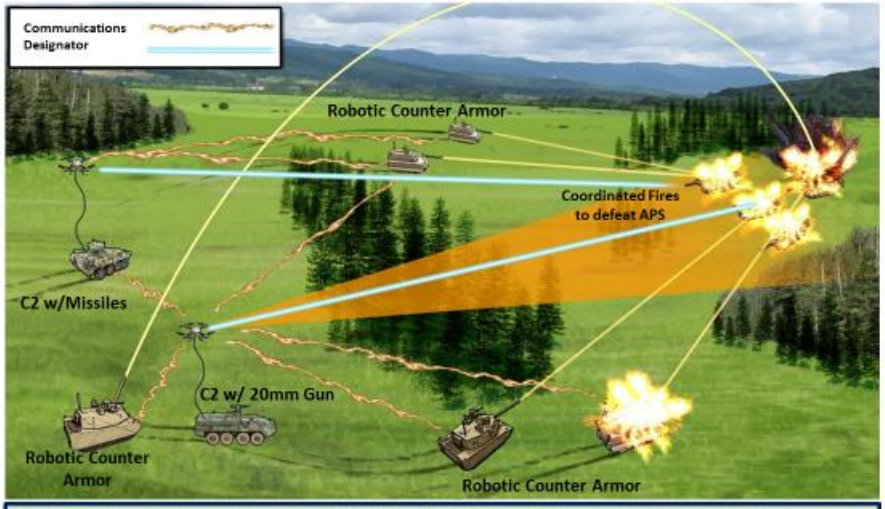
Control two robotic counter-armor vehicles
2 UGV drivers, 2 Gunners, & 2 TCs w/ shared SA

XM360 120 mm, M1A2 lethality with existing/future rounds
Elevation for Urban or **BLOS** engagements
(BLOS ammo *not* developed)
Cost Estimate: ~$2-3M / vehicle

Large Cal DF-Unmanned Objectives	
# Occupants	Unmanned
GVW	~ 27 tons
Survivability Estimate (Full)	HMG to Med Cannon, RPG/CE, EFP, up to 2x UB
Lethality Primary	120mm XM360 LOS & BLOS (8-12 km range) w/ 35 rounds
Lethality Secondary	.50 cal ARAS
Propulsion	Next Gen Combat Engine (650 HP)
Transmission	Series hybrid electric drive (2 sprocket traction drives)
Suspension	In-arm hydro with band track
Power/ Weight Ratio	~24 hp/ton

Army Science Board 9

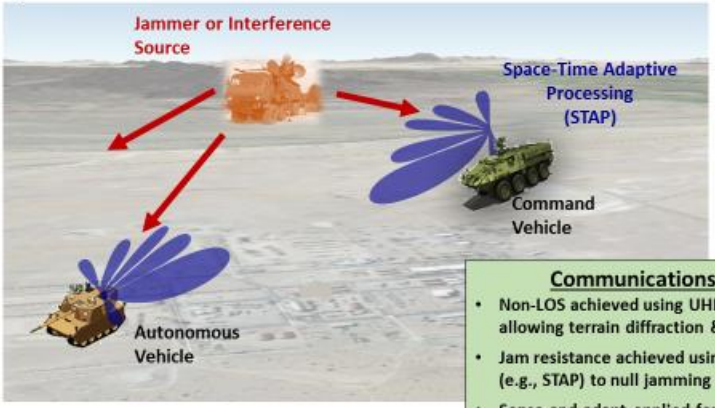
Robotic Vanguard CONOPS



UGVs require semi-autonomous movements/cueing to overcome cognitive load/latency challenges while maintaining DoDD 3000.09 lethality compliance

Army Science Board 10

Communications Concept



Communications Characteristics

- Non-LOS achieved using UHF/L-band frequencies allowing terrain diffraction & foliage penetration
- Jam resistance achieved using adaptive beamforming (e.g., STAP) to null jamming & interference
- Sense-and-adapt applied for data rate, anti-jam, or low probability of intercept enhancements

Communications concept exploits short separations, low frequency, adaptive beamforming, & sense-and-adapt for high rate (Mbps), secure, non-LOS communications

Army Science Board 11

Evolving Levels of Autonomy: Today to Future

	Timeframe	Maturity	Autonomy Offered
Baseline Concept	Now	Mature	• Remotely tele-operated vehicle & gun • Follow-me robotic drive for convoy to frontline • Semi-automated gun (e.g., automated slew to source of fire - adapted Boomerang equivalent)
	< 5 years	Maturing	• Supervised autonomy • Automated evasive maneuvering • Supervised coordinated fires to defeat APS
	5-10 years	R&D	• Voice command driving • Cross country, fully automated driving
	10+ years	R&D	• Intelligent autonomous maneuver

Strategy allows fielding of unmanned tank with currently mature technology; open architecture approach allows path to evolve level of autonomy in the future

Army Science Board 12

Campaign of Learning

Phase 0
Phase 1
Phase 2

Hardware & Software Development
CONOPS & TTP Development
Exercises & Operational Assessments

- **Phase 0 – Surrogates**
  - Concept exploration with surrogate vehicles (e.g., Stryker as unmanned vehicle)
  - Interfaces: Remote operation shown effective; initial development of man-machine interface; etc.
  - Table VI (in testing) to Table VIII operational capability
  - Initiate driver autonomy software development
  - Develop simulations

- **Phase 1 – Component Prototyping**
  - Systems integration lab
  - Early prototype (e.g., integrate reduced recoil XM360 120mm gun on Bradley chassis)
  - Weapon related prototyping and automation demonstrated (e.g., autoloader, remoted 50 cal, fire control system for 120mm gun)
  - Universal remote control demonstrated on vehicle similar to final capability
  - Engagement modelling and simulation development
  - Command and control software development

- **Phase 2 – System Prototyping**
  - Prototype purpose-built, robotic system
  - Platoon-size force-on-force exercises to show integrated end-to-end capability
  - Electromagnetic dense environment testing
  - CTC experimentation using OPFOR

Campaign of learning recommended to reduce overall concept risk, while progressively developing and hardening autonomy / man-machine interfaces

13

Outline

- Introduction
- Robotic Armor Concept
- Counter-IAD Concept
- RAS Way Ahead
- Findings and Recommendations

Army Science Board

14

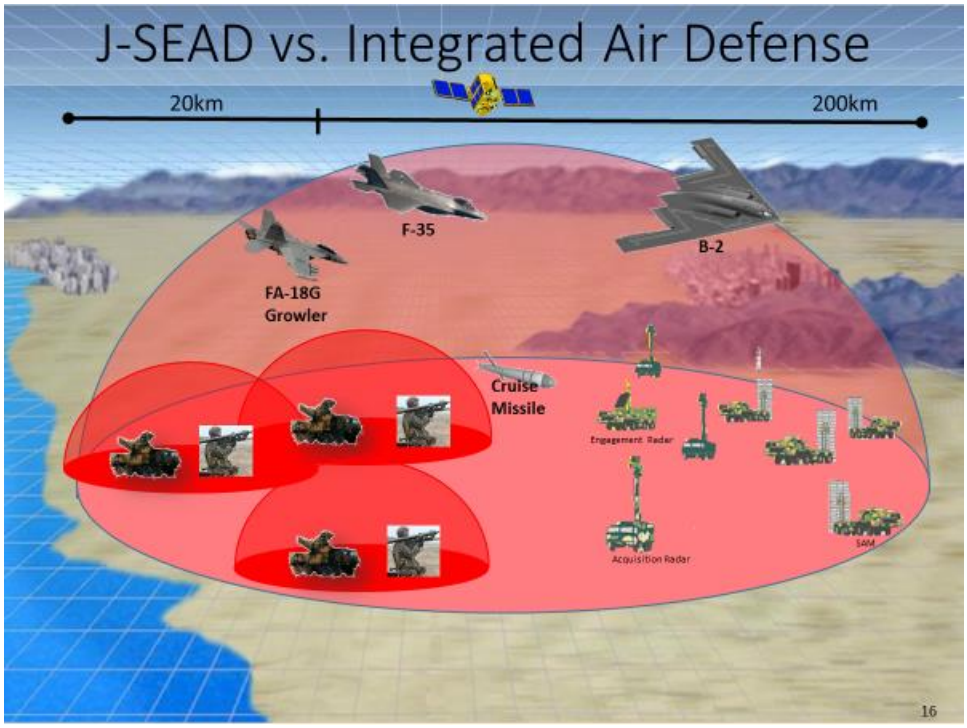
Loss of Air Superiority has Profound Implications for Army Maneuver Forces

- Past air superiority permitted Joint Forces to conduct Close Air Support (CAS) and deep shaping missions
  - However, air superiority is no longer ensured against near peer IADS
  - Army combat aviation assets are particularly vulnerable to mobile tactical elements of the IADS
- CAS is vital to enabling freedom of maneuver of ground forces
  - Army maneuver forces depend on deep shaping operations to counter massed indirect fires and armor formations
- Additional Joint SEAD capability needed to disrupt and degrade threat IADS to restore CAS operations
  - RAS provides Army capability to conduct localized J-SEAD against mobile tactical IADS components contributing to J-SEAD
  - Allows Army Combat Aviation to conduct deep shaping missions supporting maneuver forces

The Army will have to solve the IADs problem near the FLOT

Army Science Board

15



Mobile Air Defense Systems

Pantsir System	Parameter
Range Missile	20,000m
Altitude Missile	5-15,000m
Missile Load	8-12
Range Gun	4,000m
Altitude Gun	0-3,000m
Gun Load	1450
Multiple Targets	2

Verba System	Parameter
Range Missile	6,000m
Altitude Missile	3,500m

17

RAS Provides Convergence of J-SEAD Functionality in Small Attritable UAS

	Manned Aircraft		Unmanned Systems	
Collection ISR/SIGINT	RC-135 EP-3 Guard Rail	ARL-E	Global Hawk Predator/ Gray Eagle Shadow RQ-21	Small Attritable RAS
Electronic Attack	EF-111A EC-130H EA-6B	F/A-18G	MALD-J	
Kinetic Attack	F-4G F-117A F-16CJ F/A-18E/F	F-35	TLAM ALCM HARM Harpy Hellfire	

While survivable A/C are Drawing Down → UAS are Taking on Greater Role → Convergence of Autonomy and Miniaturization

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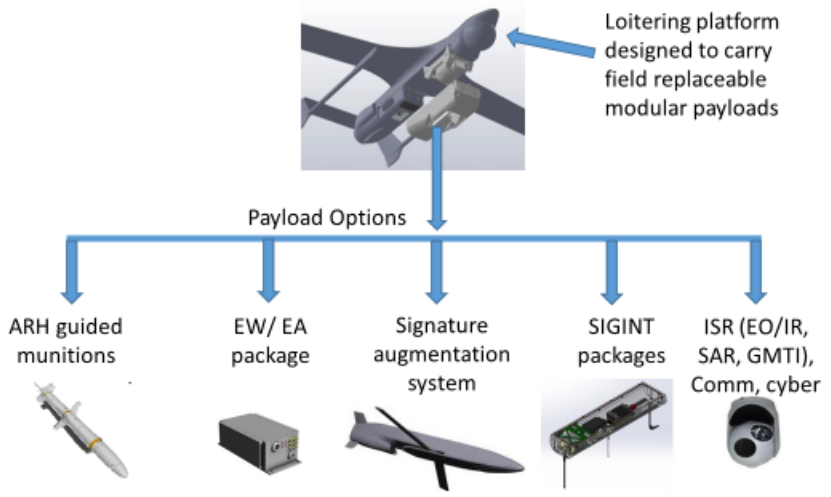
18

Potential RAS Solution: Counter IAD

- Central Idea- Unmanned Air System constellation deployed to create a temporary corridor against mobile IAD threats that:
  - Enhances the survivability of Army Combat Aviation to conduct deep shaping missions in support of joint maneuver forces
  - Allows USAF/USN J-SEAD aircraft to focus on strategic IADS suppression
- Capability Concept- A small low cost UAS that can carry a variety of field replaceable payloads that provide mix/match mission tailoring
  - Payloads include ISR, Signature Augmentation System (Spoofing), SIGINT, Electronic Warfare, lethal Anti-Radiation Homing or Home-on-JAM, communications and cyber
- Concept Technical Basis- The concept takes advantage of:
  - UAS platform maturity in the small size of interest
  - Payload technology maturity on deployed UAS or missile systems, such as the IDF Harpy/HAROP, the USAF MALD and MALD-J, the USN/USMC RQ-21A and the USA Shadow

Army Science Board 19

Low Cost Modular Payload UAS is the Core of the RAS C-IAD Concept



Army Science Board 20

Existing and Developmental Payloads with Small Size Weight & Power

Type	Exemplar	Capability	Approximate Weight – lb.
Signature Augmentation	MALD	Replicates the RF signatures of A/C, creating multiple "ghost" images	5 (electronics)
Electronic Attack	MALD-J	Radar jammer to degrade IAD emitters	5 (electronics)
SIGINT	Spectral Bat Cylon Smoke	RF/DF for localization of emitters Simultaneous collection of SOI	2 + Antenna 20
ISR & RSTA	Split Aces	Dual Band (UWB & Ku) for SAR/GMTI	20
Warhead	Hellfire Javelin MLRS APKWS/M247	HEAT HEAT DIPCM (compliance issue) HEAT/HEDP	20 20 <1 each 9

20-30 lb. Weight is a reasonable Modular Payload Design Target

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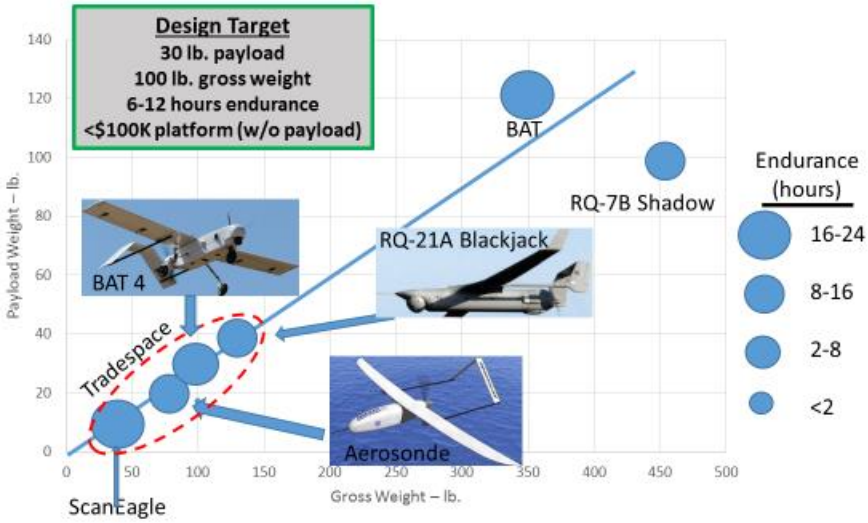
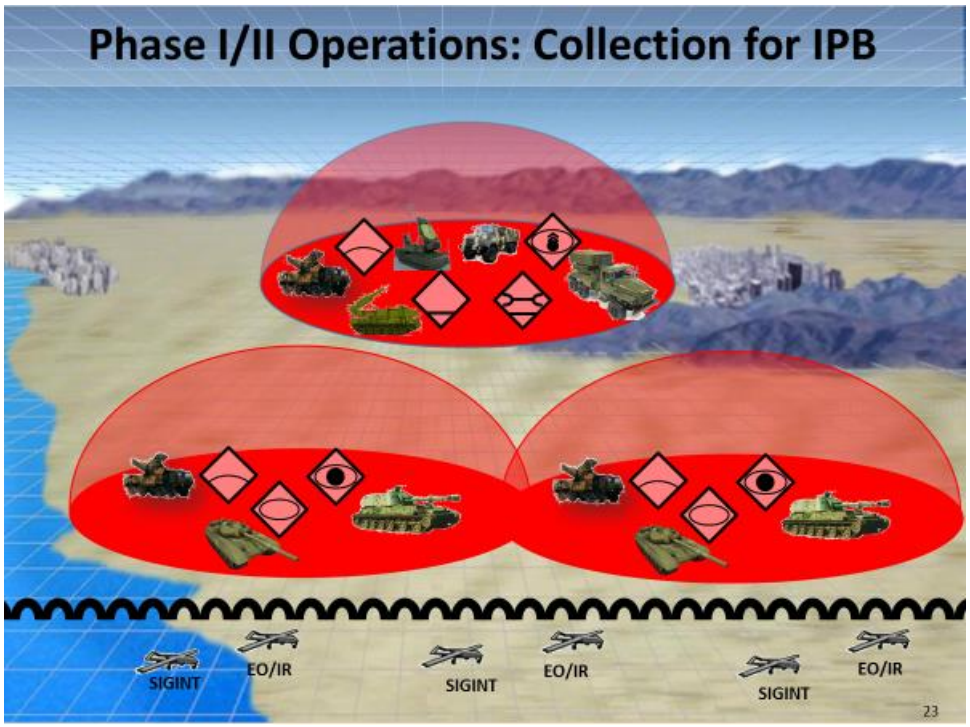
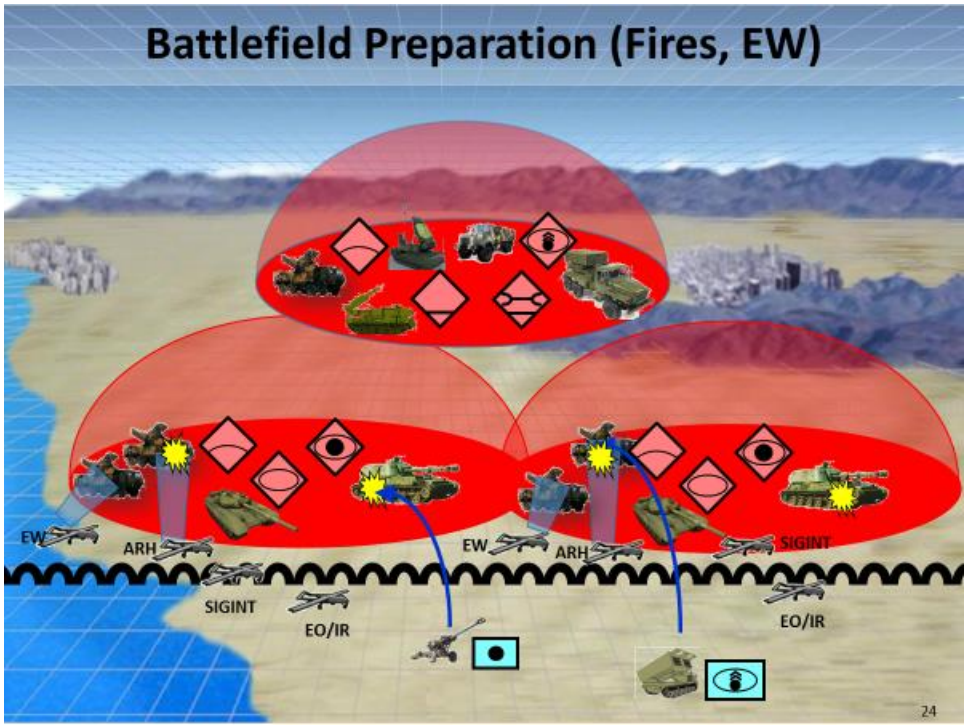
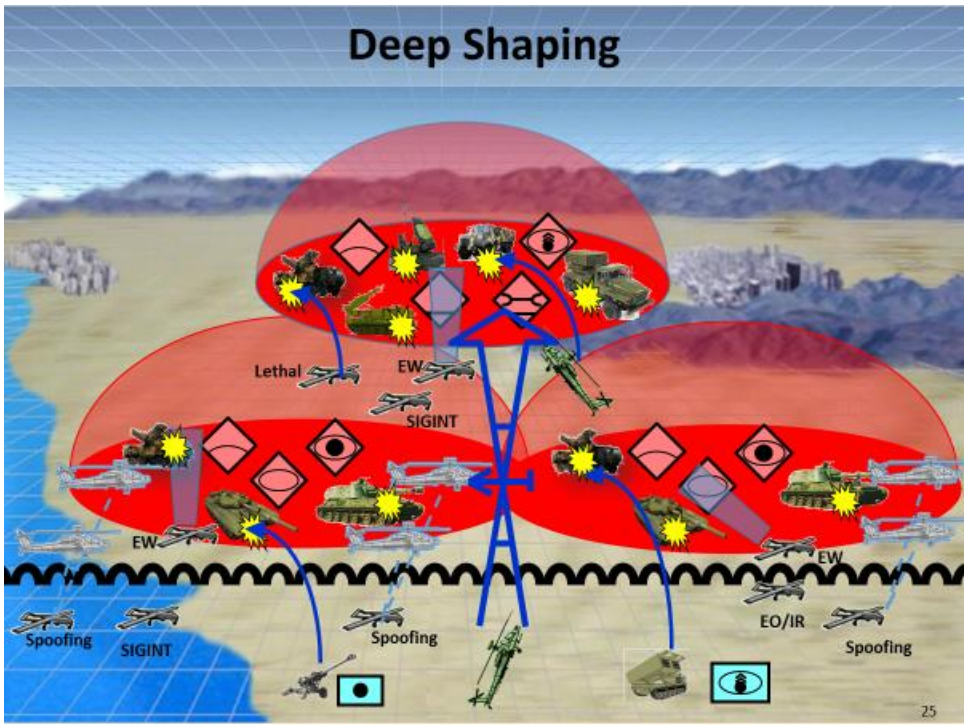
Design Space for Low Cost Loitering UAS



Army Science Board 22


Phase I/II Operations: Collection for IPB
SIGINT
EO/IR
SIGINT
EO/IR
SIGINT
EO/IR
23


Battlefield Preparation (Fires, EW)
EW
ARH
SIGINT
EO/IR
EW
ARH
SIGINT
EO/IR
24



RAS C-IAD Concept Features That Contribute to J-SEAD Effectiveness

- **Small Size**
  - ***Lower RCS*** **allows operations in closer** ***proximity*** **of threat IAD nodes**
  - ***Runway independent*** **launch and recovery operations from austere areas provided surprise and concealment**
- **Low Cost**
  - **Platform may be considered as** ***"attritable" (<$100k),*** **providing JFC flexibility to utilize it in sacrificial roles or provide a positive cost exchange ratio**
- **Modular Field Replaceable Payloads**
  - ***Mix-match operational flexibility*** **to tailor the mission package to specific tasks in response to changing battlefield situations**
  - **Coordinated multiple-RAS constellation operates simultaneously in several EM spectrum bands, resulting in** ***real time data fusion*** **options for enriched targeting**

Army Science Board 26

Evolving Levels of Autonomy: Today to Future

	Timeframe	Maturity	Autonomy Offered
Baseline Concept	Now	Mature	• Flight Guidance, Navigation and Control (take-off, ascent, waypoint navigation, loiter & search patterns) • Emitting target ID via library • Non-emitting target image recognition • Automated launch and recovery
	< 5 years	Maturing	• Mission contingency management • Cognitive EW, cyber protection, adaptive SOI ID • False target rejection • Enhanced ATR for targets in camouflage/deception environments • Automated evasive maneuvering
	5-10 years	R&D	• Swarming, multi-agent collaboration • Coordinated fires • Wireless distributed beamforming arrays for high resolution SAR and jamming

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27

Campaign of Learning

Phase 0
Phase 1
Phase 2

Hardware & Software Development
CONOPS & TTP Development
Exercises & Operational Assessments

- Phase 0 – Surrogates
  - Concept exploration with surrogate vehicles (e.g., Shadow, RQ-21)
  - Interfaces: Universal controller; modular payload architecture
  - Test payload utility on alternate platforms (e.g., King Air)
  - Initiate autonomy software for non-lethal actions (e.g., EW, target identification)
  - Validate high fidelity RAS simulation tool set
- Phase 1 – Component Prototyping
  - Conduct rapid prototyping and SIL testing of key modular payloads
  - Demonstrate effectiveness of spoofing payload for Army combat aviation rotorcraft
  - Movement and universal remote control demonstrated on similar UAS
  - Engagement modelling and simulation development
  - Reprogrammable autonomous software development
- Phase 2 – System Prototyping
  - Prototype purpose-built multi-agent system with lethal capability
  - Cross-domain force-on-force exercise with manned aviation and ground units showing integrated end-to-end capability
  - Electromagnetic dense environment testing
  - CTC experimentation using OPFOR

Campaign of learning recommended to reduce overall concept risk, while progressively developing and hardening autonomy / man-machine interfaces

Army Science Board

28

Outline

- Introduction
- Robotic Armor Concept
- Counter-IAD Concept
- RAS Way Ahead
- Findings and Recommendations

The RAS Environment

- Much S&T activity within Army, throughout DoD and in the private sector
- But, few Army Programs of Record have been fielded
  - Mostly single mission with limited autonomy and collaboration
- No institutional advocacy for RAS concepts within Army
- Advocacy and funding for RAS with greater autonomy are inhibited by several factors:
  - Fragmented authority and responsibility for RAS
  - Organizational resistance to reallocating funding from current PORs
  - Lack of trust

Army is at an *impasse* on RAS - while it is becoming globally ubiquitous and adversaries are developing and deploying them

What is Required to Break the Impasse?

- Building trust
- Architecture
- Test and evaluation

Building Trust

- At Government Policy Level, the trust issue is primarily associated with lethal autonomy and public concerns of uncontrolled robots
  - Recognize that all autonomous systems are supervised at some level and that AI-enabled actions are constrained by human imposed limitations
  - DoD has a very clear and explicit policy (DODD 3000.09, 2012) requiring "appropriate levels of human judgment over the use of force"
  - AI-enabled functionality will continuously evolve, with near-mid term applications more likely in the EM/digital domain
- At the DoD and Army leadership level, the trust issue is that the "promise" of autonomy can actually be realized
  - Campaign of learning that validates operational utility in relevant environments
- At operational level, the trust issue is that the RAS will do no harm and behave as predicted and desired
  - Architecture that facilitates transparency (operator understanding of the computer's state of knowledge and basis for delegated decisions)
  - High fidelity RAS simulation validated through T&E with operator involvement and feedback

Architecture Considerations

- RAS architecture is important to:
  - Ensure the interoperability of any RAS with external entities in a continuously evolving Systems-of-Systems environment
  - Facilitate incremental insertion of rapidly advancing cognitive functionality and human-RAS collaboration technology
- RAS architecture should:
  - Allocate cognitive functions between human operator and computer during design recognizing that human-system collaboration is key to effective performance
  - Allow for dynamic reallocation of cognitive functions allocation during mission in response to changes in external conditions
  - Require open system, government owned software to facilitate future growth in capability
  - Separate software from the platform during acquisition to enable multi-platform applications

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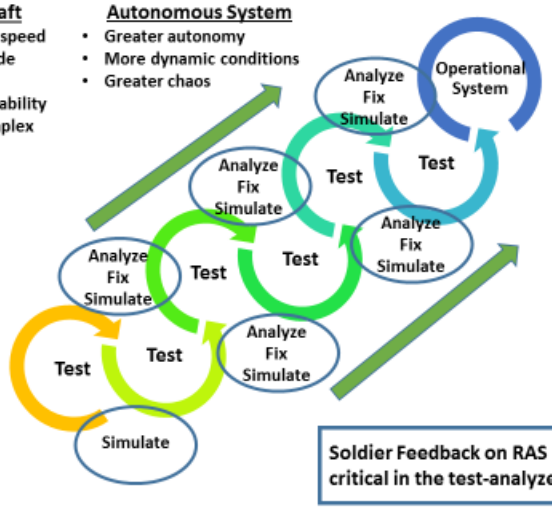
33

Test and Evaluation to Build Trust in Autonomous Systems

Aircraft
- Increased speed and altitude
- Greater maneuverability
- More complex stores

Autonomous System
- Greater autonomy
- More dynamic conditions
- Greater chaos



Validated Simulation for Training
- Higher Fidelity Sim
- Better Understanding of Behavior
- Improved Trust
- Calibrated Confidence Levels

Soldier Feedback on RAS behavior will be critical in the test-analyze-fix-simulate process

Analogous to Expanding the Flight Envelope for a New Aircraft

Army Science Board

34

Outline

- Introduction
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Findings

- Regardless of how Army proceeds, the application of ubiquitous RAS technology on the battlefield is inexorable and will change the character of warfare; Adversaries aggressively pursuing

- Technology alone will not provide an asymmetric advantage; CONOPS also need to be innovative and disruptive
- RAS offers solutions to difficult warfighting challenges because it opens the design space and enables innovative CONOPS
- Counter-Armor RAS and Counter-IAD RAS are excellent points of departure for understanding RAS operational utility by integrating mature technology
- Three factors limit advocacy and funding for RAS with greater autonomy
  - Fragmented authority and responsibility for RAS
  - Organizational resistance to reallocation of funds from current PORs
  - Lack of trust

Findings - Continued

- An integrated campaign of learning is needed to:
  - Evaluate innovative CONOPS
  - Validate operational value
  - Develop next generation autonomy
  - Inform capability needs for future AROC
  - Build trust
- RAS architecture is important to:
  - Ensure the interoperability of RAS in a continuously evolving Systems-of-Systems environment; many open architecture systems in development
  - Allow for independent development of high order cognition S/W applications and facilitate insertion of "best of breed" applications into current and future RAS

Recommendations

CSA – Issue an EXORD that:

- Establishes a RAS focused Army *Campaign of Learning* for evaluating operational utility of RAS and developing RAS CONOPS and TTPs. The campaign should include simulation, prototyping, limited fielding, experiments & warfighting assessments
- Initiates *the advanced concept design* of a) an attritable robotic counter-armor capability and b) an attritable, autonomous loitering UAS with a modular payload design that provides a counter IAD capability
- Establishes an *AROC committee* to develop requirements based on inputs from the campaign of learning and the concept design
- Designates a central RAS advocate

ASA(ALT)

- Working with Joint Services, *define a modular open system architecture* that allows for independent development of high order cognition S/W applications and that facilitates insertion of "best of breed" applications into current and future RAS
- *Develop a high fidelity simulation toolset* for understanding RAS behavior in complex environments; for calibrating trust confidence levels of RAS under dynamic conditions; and for design, development, V&V, T&E, training and life cycle management