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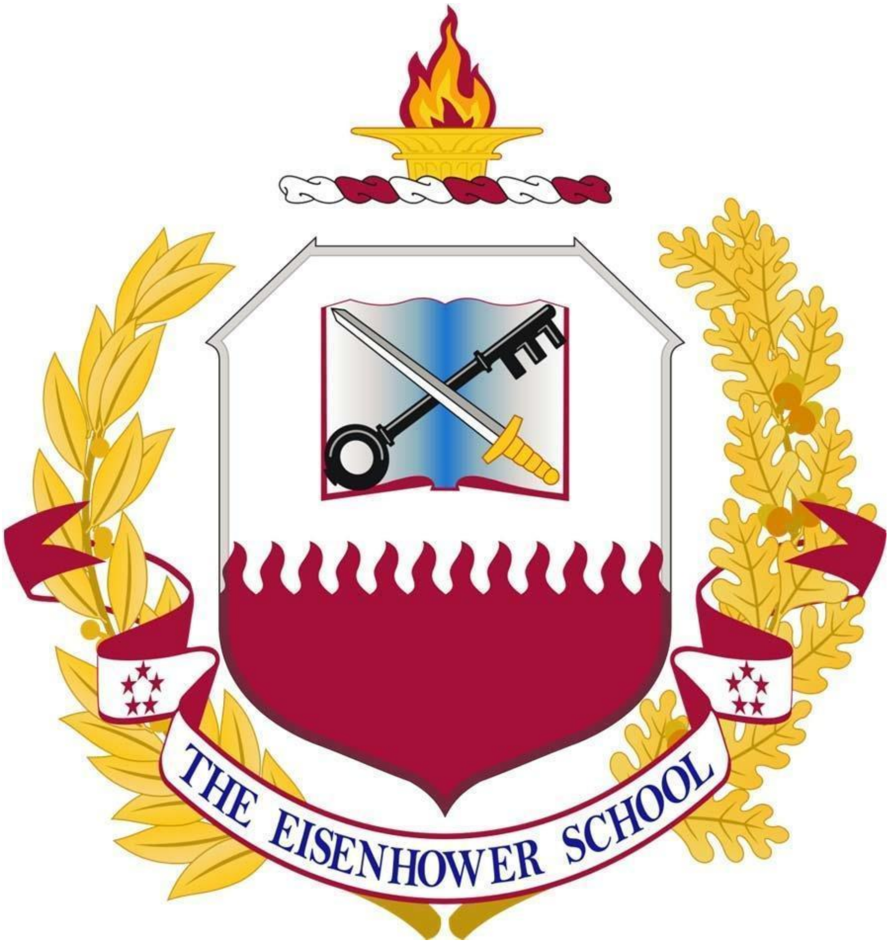
Industry Study

Final Report
Robotics & Autonomous Systems Industry



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ABSTRACT: A nation is compelled towards Robotics and Autonomous systems (RAS) when their use increases the effectiveness, efficiency, or safety of the mission. Beyond material RAS solutions, prospective gains are dependent on corresponding concepts of operation (CONOPS) to affect changes in the conduct and character of warfare. We believe the use of RAS can result in a significant comparative advantage in military capabilities and that the potential exists for a revolution in military affairs (RMA). This RMA potential directly impacts the defense industrial base (DIB) as that industrial base seeks to provide material solutions for the warfighter.

The 2014 RAS Industry Study group assessed industry's potential to support future security demands by analyzing the development of the technology, the current and future market forces, and the opportunities for these systems to generate a revolutionary change in the conduct and character of warfare. Our methods included questioning and challenging the designers, builders, and users of robotics. We employed a data collection methodology based on archival research, site visits, and interviews with individuals from government, academia, and private industry. The interviews occurred at the Eisenhower School campus and at several host sites in the United States and Japan. These engagements defined the current limits of technology, as well as the potential future for robotics and its application.

Given the rapid proliferation of RAS in recent conflicts, the U.S. currently possesses "first mover advantage." However, the nation must make the appropriate whole of government choices to maintain this lead. The results of our study show that the fulfillment of an RMA relies on strengths and opportunities in three areas of RAS development. First, industry has demonstrated that it can field systems that, to a degree, have already changed the conduct and character of warfare. Second, the states of the technology and the industry are sufficient to alter how an RAS-equipped nation might pursue security objectives. Finally, the drivers pushing innovation are accelerating, which can lead to a virtuous cycle of even more rapid development. We believe these trends will continue. We also identified three areas of industry weakness or external threats that could lead to evolution rather than revolution. First, much of the RAS industry is very small, with significant barriers to growth. Secondly, the complexity of the environment and difficulty in dealing with a thinking adversary require complex autonomy algorithms and culturally acceptable solutions. Lastly, the military services – in most instances - are not providing clear demand signals due to poor organization and a lack of innovative concepts of operation in which RAS use provides a decisive advantage. We conclude that the weaknesses and opportunities are not insoluble, and provide specific recommendations for their resolution.

The broader robotics industry is in the midst of an inflection point in which robotic service applications – to include robots that move among us – are beginning to change society. This societal change will provide great opportunities in the development and use of RAS in military affairs. The DIB, when infused with appropriate investments by government and commercial ventures, is ready to provide the requisite capacity and capability for the warfighter to meet a national security requirement. When combined with innovative CONOPS in which RAS use is critical to increasing the effectiveness, efficiency, or safety of a particular mission area, the nation will more clearly recognize that an RMA is underway.

ACKNOWLEDGEMENT

Our industry study group met with senior leaders from companies, research institutions, industry associations, and government and military organizations in the United States and Japan. We are deeply grateful to all those who shared their insights, perspectives, and valuable time with us. We also wish to thank the Eisenhower School faculty – CAPT Matthew Pregmon, COL David Shugart, CAPT Robert Wagner – for their hard work organizing the broad array of interactions with the robotics industry and their expert guidance and advice. We would also like to acknowledge Dr. Sorin Lungu and concepts derived from the Long Term Strategy elective for assisting in developing several ideas for this paper's focus of study.

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Nagoya Science Park, RIKEN
National Institute of Advanced Industrial Science and Technology, Robot Safety Center
Tokyo Institute of Technology and HiBot Robotics Company
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Association for Unmanned Vehicle Systems International (AUVSI)
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Office of Under Secretary of Defense (Acquisitions, Technology, & Logistics)/Strategic & Tactical Systems-Unmanned Warfare & Intelligence, Surveillance, and Reconnaissance

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Department of the Army, Program Resourcing (G8)
Department of Homeland Defense Coast Guard Liaison to Customs and Border Protection Air and Marine

Unmanned Maritime Systems (UMS) Panel
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Naval Sea Systems Command, Unmanned Maritime Systems (PMS-406)
Office of the Secretary of Defense for Test Resource Management Center (TRMC)

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LIST OF ACRONYMS

A2/AD	Anti Access Area Denial
AEODRS	Advanced Explosive Ordnance Disposal Robot
AF/A2	US Air Force Air Staff, Intelligence, Surveillance and Reconnaissance
AUV	Autonomous Undersea Vehicles
AUVSI	Association for Unmanned Vehicle Systems International
CAP	Combat Air Patrol
CBO	Congressional Budget Office
CCL	Commerce Control List
COLREGS	Preventing Collisions at Sea
CONOP	Concept of Operations
CONOPS	Concepts of Operation
DARPA	Defense Advanced Research Projects Agency
DIB	Defense Industrial Base
DoC	US Department of Commerce
DOD	Department of Defense
DoS	Department of State
DOT	Department of Transportation
EOD	Explosive Ordnance Disposal
FAA	Federal Aviation Administration
FCS	Future Combat Systems
GPS	Global Positioning System
HALE	High Altitude Long Endurance
IS	Industry Study
ISR	Intelligence, Surveillance, and Reconnaissance
LPI/LPD	Low Probability of Intercept and Low Probability of Detection
LRSB	Long Range Strike Bomber
METI	Ministry of Economy, Trade, and Industry
MTCR	Missile Technology Control Regime
MUMT	Manned-Unmanned team
N2/N6	Office of the Chief of Naval Operations for Information Dominance
NIS	National Innovation System
O&M	Operations and Maintenance
OCO	Overseas Contingency Operations
PMS 406	United States Navy Unmanned Maritime Systems Program Office
PPBE	Planning, Programming, Budgeting and Execution
R&D	Research and Development
RAS	Robotics and Autonomous Systems
RDT&E	Research, Development Test and Evaluation
RMA	Revolution in Military Affairs
ROV	Remotely Operated Vehicles
RPA	Remotely Piloted Aircraft
SATCOM	Satellite Communication
SDA	Sense-Decide-Act
T&E	Test and Evaluation

U.S.	United States
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Air Vehicle
UCLASS	Unmanned Carrier-Launched Airborne Surveillance and Strike
UGS	Unmanned Ground System
UMS	Unmanned Maritime Systems
UMV	Unmanned Marine Vehicles
UON	Urgent Operational Need
USAF	United States Air Force
USML	United States Munitions List
USRM	Unmanned Systems Roadmap
USV	Unmanned Surface Vehicles
UUS	Unmanned Underwater Systems

1 - INTRODUCTION

"What occurs when the application of new technologies into a significant number of military systems combines with innovative operational concepts and organizational adaptation in a way that fundamentally alters the character and conduct of conflict … by producing a dramatic increase - often an order of magnitude or greater - in the combat potential and military effectiveness of armed forces."

Andrew Krepinevich

The robotic and autonomous system (RAS) industry has grown in importance over the last decade, particularly in systems with military applications. A Department of Commerce report on the Robotics Defense Industrial Base (DIB) revealed, "Aggressive development and application of machine intelligence and robotics technologies are needed for the U.S. to remain competitive on the battlefield as well as in manufacturing."[1] Written over twenty years ago in 1990, this quote still holds true today. Many believe that RAS technology, combined with the right organizational adaptation and concepts of operations, will not only allow the U.S. to remain competitive, but will create an order of magnitude increase in combat potential and military effectiveness for U.S. forces. In a limited sense, it has done that in certain mission areas, such as explosive ordnance disposal (EOD), Intelligence, Surveillance, and Reconnaissance (ISR), and Precision Strike. However, these mission areas alone, singularly or collectively, do not constitute an RMA. The line at which an RMA is realized is not clearly defined, but one can assume that an RMA will make a dominant force even more dominant, or in some cases, lead to an outcome that was previously unachievable. Regardless of whether RAS results in an RMA, our research showed that there is great opportunity in its development, and like all military endeavors, the defense industrial base (DIB) plays a critical role.

Although the study of an industry through the lens of its potential to create an RMA is not a traditional analytical method, the recent history and developing state of the RAS industry lent itself to this approach. To leverage this technology, one must consider whether the DIB will lead military implementation or if the DIB production will lag military needs. The U.S. must recognize the potential and position itself through the development of technology, organizational structures, and concepts of operations (CONOPS). Doing so would strengthen the DIB as it leads global development, and allow U.S. forces to benefit from a potential RMA. Under this construct, the 2014 RAS Industry Study (IS) team investigated the RAS industry by assessing how the interactions between technology, organizational structures, and CONOPS posture the DIB for the creation of a RMA. Specifically, this analysis led the team to a series of findings, listed in no particular order, across five areas:

1. Research and development (R&D) funding. The ability to posture the DIB to lead the development of RAS and realize a potential RMA is heavily dependent on research and development. Projected declines in both commercial and government funding in this area will challenge the growth of the industry.

2. Government rules and regulations. Restrictive export controls and inadequate air, maritime, and ground regulations are hampering the DIB's global competitiveness and necessary development to support the realization of a potential RMA. These, in turn, are suppressing RAS development.

3. Strategic guidance. DoD lacks a clear and comprehensive procurement strategy that articulates its goals and future plans for RAS. Areas of deficiency include CONOPS, autonomy requirements, and stable and predictable budgets. These impair industry's ability to create long-term plans and establish a foundation for industry's long-term business strategies.

4. Leadership and organization. There is a lack of RAS experience among senior military leaders, who, by their leadership positions, must make informed decisions and act as influential RAS champions. Additionally, oversight of UASs resides primarily in stove piped entities that are not well equipped to deal with missions beyond ISR. Combined, these are negatively affecting the development of technology, concepts of operation, and the RAS industrial base.

5. Culture. There are military and civilian cultural biases towards robotics and, perhaps even more intensely, systems acting autonomously that contribute to a lack of trust in RAS. This lack of trust leads to a reluctance to invest the time and energy in the development of RAS solutions.

2 - DEFINITIONS / MODEL

For the purpose of this investigation, the IS team defines a *robotic system* **as any electro-mechanical system that relies on varying levels of computer-aided autonomy to complete its design-task**. While the roles of robotic systems can range from human replacement, to entertainment, to even emotional companionship, the primary virtue on which our analysis focused was the use of robotic systems to augment and enhance America's national security apparatus.

To better understand the challenges and opportunities within the RAS industry, the IS team used the following model to functionally describe a robotic system.

Figure 1. Sense-Decide-Act Model of Robotic Systems

The Sense-Decide-Act (SDA) model illustrates a robotic system's three primary functions, which are to sense its environment, decide how it should interact with or manipulate its environment, and then perform an action to achieve its desired result. The greatest advantage of using this model is that it allowed the team to compartmentalize the RAS industry's ability to provide *sensory*, *autonomy* (decision-making) and *vehicular technologies*; either as independent technologies or as an integrated system. The term *robotic technology* refers to the sub-level technologies that perform one or more of the functions of the SDA model.

While sensory and vehicular technologies have relatively clear connotations, autonomy (computer based decision making) requires clarification. To the operational user, autonomy is the ability of the RAS to make decisions without user input and ranges from a step above completely human controlled to fully independent. A more technical definition of autonomy is **any algorithm that attempts to solve for unknown environmental variables to derive an optimal, action-driven outcome for the system.** Additionally, the term *automated/automation* is distinguished throughout this analysis from systems that are *autonomous* by an autonomous system's ability to decide based on environmental state variables versus an automated system that simply follows a pre-determined process flow.

Autonomy is also divided into two categories: *vehicular* and *mission*. This helps to distinguish the autonomy required to operate an individual vehicle from the autonomy required to meet mission goals. While vehicular-based autonomy is specific to the vehicle, mission based autonomy integrates a multitude of unique robotic systems into a shared task and is not unique to any platform. Additionally, mission autonomy algorithms are shared across multiple platforms and should follow their own development cycles that are independent of any platform development cycles.

3 - MOTIVATION - WHY AND HOW TO LOOK AT RAS DIFFERENTLY

The predominant and ubiquitous justification for when to apply RAS in the service of human endeavors is frequently narrowly scoped to those tasks that are *dull, dangerous or dirty.* In reality, these are descriptive characteristics of environments where RAS-based technologies thrive, but *do not provide a compelling reason* as to why a company or organization such as the U.S. Department of Defense (DoD) should choose RAS to meet its operational requirements over an existing capability. A company or nation is compelled towards RAS when its use increases the *effectiveness, efficiency, or safety* of the mission. Beyond material RAS solutions, prospective gains are dependent on corresponding concepts of operations (CONOPS) to affect changes in the conduct of warfare. For DoD, if the broad use of RAS results in a significant comparative advantage in military capabilities, then the potential exists for an RMA.

Determining where RAS platforms can increase mission *effectiveness* is the foundational challenge to enable an RMA and is broken into two broad categories: (1) increased effectiveness by performing tasks that humans physically cannot do and (2) freeing up humans to perform new tasks that add more value to the overall mission. An example of the first category is autonomous undersea vehicles (AUVs) that are able to operate for longer durations or in environments inaccessible to humans. Beyond the typical *dull* characterization, AUVs that remain at great depth provide operational opportunities that simply do not exist with a manned vehicle. When programmed to act autonomously and collectively, these AUVs could dramatically change how the U.S. Navy conducts antisubmarine warfare. At question, however, is whether the Navy bureaucracy would risk jeopardizing existing antisubmarine operational concepts to invest in a revolutionary – yet currently unproven – unmanned-centric CONOPS. The Navy is not unique in this regard. Indeed, every military service possesses constituencies concerned about the institutional and financial risk associated with emerging unmanned technologies that threaten to upend the current methods of warfighting.

If the implementation of RAS gains *efficiencies* by reducing human errors, overcoming human limitations in speed and persistence, or by simply producing the same output but at a cheaper long-term cost than a human operator, then there is a compelling case to implement RAS. As an example, General Robert Cone, the 2011 to 2014 Commander of the U.S. Army's Training and Doctrine Command, stated that DoD budget and manpower cuts have driven the U.S. Army to consider "reducing the size of a Brigade Combat Team from 4,000 soldiers to 3,000 with robots and drones making up for the lost firepower[2]." Gen Cone's goal for the Army is to mimic the savings in manpower the Navy has experienced by bringing automation and autonomy to their fleet of ships[3]. Using contemporary Congressional Budget Office (CBO) estimates, DoD spends roughly $100K per service member per year in pay and benefits alone[4]. Additionally, comparing the costs of training personnel versus the cost of software and hardware upgrades will further refine the cost-to-value ratio of migrating to a RAS solution. If DoD has any chance of achieving manpower savings, the cost of the RAS must at least meet this threshold to make the case of compelling efficiency.

Finally, the most frequently used reason to implement RAS is *safety*; in particular, using RAS platforms as surrogates for humans in environments that are too hazardous for humans. Current environments and activities include, but are not exclusive to, nuclear reactors, high-threat combat zones and explosive ordnance disposal scenarios. Again, this is not simply eliminating the danger to humans, but rather creating opportunities in unsafe environments. The 2011 Fukushima nuclear reactor disaster provides an excellent example of this situation. The close proximity of the population and the ocean, and the reactor's location atop a known fault line drove a sense of urgency to contain the fallout. Although not impervious to radiation, robots can operate longer, and in certain cases, more effectively in this environment than humans can. Discussions with engineers and government officials in Japan confirmed their desire to improve the mobility and sensors for operations in these arenas. In the end, the opportunity to satisfy a critical objective in a hazardous operating environment compels the use of RAS and requires new CONOPS.

The qualities of effectiveness, efficiency, and safety, coupled with a valid and compelling need, are the foundational criteria required for when and where to use RAS. The development of CONOPS dictates *how* to apply these concepts. A nation's potential to create a RAS RMA depends on how well its industry can design and build systems to enable these qualities for new operational implementations. For the purpose of this industry analysis, the concept of new possibilities for application provides a foundation to understand what is driving demand, innovation, and suppliers in this fast-growing field.

4 - METHODOLOGY

The IS team gained a thorough understanding of this broad topic by questioning and challenging the designers, builders, and users of robotics. The team employed a data collection methodology based on archival research, site visits, and interviews with individuals from government, academia, and private industry. The interviews occurred at the Eisenhower School campus and at several host sites in the United States and Japan. The engagements defined the current limits of technology, as well as the potential future for robotics and its application. The team would like to acknowledge the time, experience, and wisdom the guest speakers and industry hosts shared to help us develop our analysis and this report.

Using the knowledge gained, the team considered the past, present, and future RAS industry, including how the technology and suppliers have grown in the context of two wars in Afghanistan and Iraq. The study offered valuable insight into how wartime funding and operational necessity have both helped and hindered the industry. Given the announced Asia-Pacific rebalance, the group looked at the potential future of robotic systems in this area of operations, including differences in the geographic environment and potential combat scenarios. These historical and future situations provided a context to view the current RAS market, including its suppliers, purchasers, and development mechanisms in both the U.S. and abroad. In particular, the team leveraged its extensive knowledge of the Japan industry gained during site visits, and research on Israel, South Korea, and China, because of their impacts on the global market and Asia-Pacific region.

The dynamics of an RMA and the knowledge gained through this investigation led the team to develop the model in Figure 2. This systems model expands on Krepinevich's elements of technology, organizational structures, and CONOPS, by describing how these elements interact to create dramatically more effective, more efficient, or safer systems. Within the model, industry produces both RAS platforms and technology innovations. The governmental structures define operational regulations and trade mechanisms to enable the flow of commerce between industry and the consumer. The users generate CONOPS for implementation of current and future systems. The *RAS Market* box defines how the industry interacts with consumers. For example, when the industry creates technology, it introduces possibilities. Users take these possibilities and create new CONOPS, which lead to new requirements. Government structures filter these requirements based on culture and policy, resulting in funding to industry to produce new systems. These same cultural and policy-related influences also create limitations on systems utilization, which subsequently validates both operators' priorities and platform implementation for industry. Finally, industry responds with infrastructure to support the validated technology.

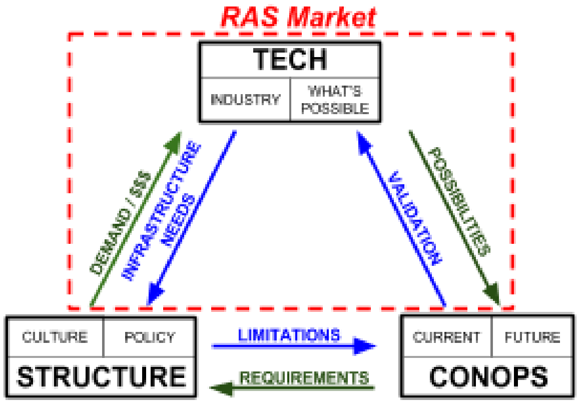

Figure 2. Systems model of RAS Market and Industry

5 - MILITARY IMPLICATIONS OF RAS CAPABILITIES

Although the U.S. has substantial experience from fielding RAS systems during the last 20 years, DoD has focused primarily on systems that sense and act, keeping a human in the loop for most operations and avoiding true autonomy. This section addresses the current state and future concepts that utilize autonomy and human interface to improve effectiveness and DoD acceptance of RAS.

5.1 Current State of Military RAS

The DoD achieved significant increases in the use of autonomous systems. The US Air Force (USAF) has arguably the most mature handling of autonomous systems, significantly expanding the roles of the medium altitude UAVs in the theater of operations. Between 2004 and 2009, warfighter demand for these Combat Air Patrols (CAPs) increased by more than 600 percent, leading to today's capacity to maintain 62 simultaneous CAPs[5]. Nevertheless, DoD's investment in this technology is declining due to the reduction in combat operations and shrinking defense budgets. Additionally, the U.S. Army is shelving over 10,000 small and medium sized systems as units return from theatre[6]. Many of these small systems, which the Army rapidly deployed and never designated as programs of record, lack the funding stream for sustainment. While UAS sensors, kinetic capabilities, communications infrastructures, and automated launch and recovery systems have advanced significantly, the USAF has not made much effort toward developing and implementing the autonomous "decide" capability. If implemented, this capability could improve efficiency, augment pilot safety, and most importantly, boost effectiveness through better decision making.

Similarly, the land domain has experienced progress with EOD systems, yet DoD appears to have a conservative approach to its investment in unmanned ground systems (UGS) technology. Currently, the Army is investing $11 million in a driverless vehicle that can perform the relatively simple tasks of negotiating an intersection, a traffic circle, and oncoming traffic. Although estimates are that this program could reduce the required number of convoy drivers by one third, the program goals appear modest compared to current commercial ventures[7]. In terms of logistics, the team's visit to Kiva Systems, a leading producer of commercial warehousing and supply chain automation, demonstrated an untapped opportunity for DoD to significantly improve logistics.

In coming years, DoD plans include moving away from proprietary solutions for autonomous systems by encouraging the use of open architecture. The Advanced Explosive Ordnance Disposal Robot System (AEODRS) is an open architecture robot that leverages vendor competition to build one or more of the robot's components. Ultimately, it will assign a separate systems integrator to assemble each platform, avoiding dependence on proprietary software or hardware[8]. According to one government official, however, "the program garnered criticism from industry executives who warned that an open architecture process could lead to higher costs, a distressed supply chain and schedule delays[9]." This statement aligns with our observations and discussions with industry leaders, who expressed similar concerns. Throughout the industry research and engagements, several leaders noted concern that the open architecture approach is not consistent with existing business models and could create an unpredictable and potentially unprofitable situation if the company does not own and license intellectual property and software.

5.2 Future Implications for Military RAS

Despite the challenges of integrating unmanned platforms over the last 20 years, DoD has a great opportunity to implement RAS capabilities in a revolutionary manner going forward. To do so, planners, operators, and acquisition professionals must address all aspects of the operational process, to include requirements definition, cultural acceptance, and even foreign industry involvement. Unlike operations in Afghanistan and Iraq, where the U.S. maintained air and space supremacy, other rising militaries may soon have the capability to challenge U.S. dominance in all domains. Furthermore, it is likely that future conflicts in the Asia Pacific theater will involve anti-access/area denial (A2/AD) environments. These environments will contest the traditional satellite communications (SATCOM) and Global Positioning System (GPS) augmentation for unmanned platforms, hence, new research is focusing on completing unmanned missions without the use of a continuous communications signal. The new concept requires a low probability of intercept and low probability of detection (LPI/LPD) communication option, or even complete platform autonomy, for operation in the A2/AD environment[10].

Current USAF plans call for a family of systems, which includes the new Next Generation Remotely Piloted Aircraft (RPA), to handle A2/AD[11]. The concept provides ISR and combat capability that is more operationally effective, minimizes risk to aviators, and reduces overall cost. Today, many platforms have sensors that can characterize images and statistically predict an object based on preprogrammed characteristics. In these cases, the operator uses the results to direct kinetic activities. The idea of allowing an autonomous system to make subjective targeting decisions may be controversial, but the programming of most subjective decisions will occur prior to launching the platform[12]. Decisions, such as where an autonomous system can look for a target, how long it can look, programmed "no-fire" areas, and sensor confidence of target recognition, are all made subjectively before system autonomy is activated. The scrutiny will focus on the decision makers who place the restrictions and algorithms into the programming as more autonomous systems appear on the battlefield[13].

In the maritime market, the U.S. Navy has increased its demand signal, better reflecting its updated requirements and priorities. While the growth of Naval systems in the past decade has not been as dramatic as the other military services, the Unmanned Maritime Systems Program Office (PMS 406) and other Navy program offices are actively pursuing a variety of capabilities with acquisition program stages ranging from analysis of alternatives through low rate production. One senior defense official acknowledged the predominance of experimental systems within the Navy, but indicated a move toward establishing formal programs of record. Prominent Navy programs, in various stages of development, include the AN/BLQ-11 Autonomous Unmanned Undersea Vehicle, the MQ-8C Fire Scout unmanned aerial helicopter, and the Unmanned Combat Air System X-47B demonstrator.

On land, unmanned logistical support capabilities could provide long-term economic benefits and limit risk in hostile environments, but the current approaches, including the Army's current investment of $11 million in unmanned ground vehicles, are not strategically game-changing. Although technology has already overcome the basic requirements for driverless vehicles, the dynamic wartime environment in a restricted access area will cause significant navigation issues. DoD should leverage existing commercial logistical systems, such as Kiva's automated supply system or Google's driverless car, to accommodate the unexpected dynamics of an unfamiliar environment and dramatically change supply chain management. Thus, in certain mission areas, DoD can capitalize on commercial investments that are already occurring rather than absorbing the research and development costs for an autonomous or semi-autonomous systems that possesses a dual-use capability.

Communication technology, particularly as it applies to networked unmanned systems, is growing in importance. According to Marius Vassiliou, an analyst at the Institute for Defense Analyses, "Commercial wireless services depend on a well-maintained and reliable infrastructure, whereas military operations may require communications between mobile [unmanned] platforms and command posts in areas without such an infrastructure[14]." The Defense Advanced Research Projects Agency (DARPA) is investing R&D money into emerging communication technologies to help build the required multifarious communication architectures. During one site visit, an industry leader advocated providing incentives to the military industrial complex for new technologies, such as mesh networking to accommodate the vast distances of the Pacific and establish a reliable communications foundation for manned to unmanned teaming (MUM-T) activities[15]. The Air Force RPA Vector provides a vision of how UASs can contribute to an aerial layer communications network, without the assistance of space based assets in the A2/AD environment[16]. The vision of the layered network uses a variety of nodes (manned or unmanned platforms) to transfer data. DARPA research into optical communication shows potential for high data rate transmissions that may be useful in solving this problem[17]. Therefore, in addition to leveraging commercial ventures, DoD should also continue to invest in the DIB development efforts.

Lastly, as identified in finding five, the internal organization of each service's office for unmanned platform requirements creates challenges for integration of development and procurement actions. Even though the role of UASs expanded to include precision strike, the generation of requirements for UAS still resides within AF/A2 (ISR). The AF/A2 (ISR) primarily focuses on intelligence collection requirements for both manned and unmanned aerial platforms and often lacks the expertise to generate requirements for autonomous combat operations or MUM-T. A similar situation exists with the Navy's N2/N6. For both services, requirements generation for UASs resides in stove-piped organizations that are not well-equipped to deal with missions beyond ISR. The military services must either expand the expertise of their UAS directorates, work more closely with those that have the expertise, or create new organizations with expertise across all applicable mission areas.

5.2.1 Anti-Access/Area Denial CONOPS

The concept of performing unmanned operations in an A2/AD environment requires investment in software systems, communications networking, and cultural acceptance as future unmanned platforms drive the need for CONOPS development. These platforms include, but are not limited to the Unmanned Carrier-Launched Airborne Surveillance and Strike (UCLASS) system and optionally manned vehicles like the Long Range Strike Bomber (LRSB). If an unmanned system can carry modular payloads with a stealthy A2/AD penetrating capability, it is feasible that a manned platform could manage the mission from a safe distance while tasking several unmanned platforms during the mission[18]. Without the cultural acceptance or software development to provide an unmanned system with inductive reasoning, the military services will have to script missions to bound the actions during the operation. The following example considers both man in the loop and autonomous operations.

In a MUM-T approach, a swarm of unmanned ISR and strike platforms, with high-fidelity sensors, enters an A2/AD environment to identify and strike mobile ballistic missile launchers. This approach uses a collection of small UASs, working together as an individual system. The UASs collectively optimize a search pattern within a pre-designated area, and using pre-programmed sensor characteristics, patrol until a finding or until the mission time is exhausted. Once a suspected target meets the prerequisite matching characteristics, the UASs transmit their findings to a manned platform or ground station acting as the mission commander. The mission commander, in turn, uses the information to authorize the team to strike. As unforeseen circumstances arise, the mission commander dynamically re-tasks, using programmed autonomous tactics. If a completely autonomous mode is authorized, the systems automatically engage when the pre-specified level of target identification is obtained and basic rules of engagement are met.

Manned platforms could execute the mission described above, but the strategic risk of losing aircrew might prevent the mission altogether, and if not, would require the acceptance of a high level of risk. In this case, a bridge to full autonomy would involve teaming manned aircraft with unmanned platforms.

The vastness of the operational spaces and the growing regional investments in military development and procurement will threaten freedom of maneuver for U.S. assets. Consequently, an expanded operational picture must include the integration of unmanned ground and maritime vehicles into the network architecture. In the Pacific, unmanned underwater vehicles can provide a critical layer of protection by detecting and possibly defeating underwater threats, without risking human life. However, transmitting usable data through the water is very unreliable, so the unmanned underwater systems require full autonomy for very long periods.

Even though technology is improving across the air, ground, and sea domains, there remains concern – both internal and external to DoD – about the use of unmanned systems operating in complex environments. Many observers point to the potential for these weapons systems to autonomously operate in a manner antithetical to the rules of war. Much of this concern is perhaps cultural, as these observers would be less concerned with a manned platform conducting the same mission. In the observer's mind, there is a human in the machine to both make a decision and be accountable for a hostile act. There is often a lack of understanding that rather than being "unmanned", these systems possess a "man in the loop" completing the decision cycle and thus being held accountable for the results. The unmanned vehicle is, in reality, a part of a larger manned-unmanned system or MUM-T CONOPs. In order to overcome the current cultural resistance to unmanned systems, *it is recommended that DoD emphasize MUM-T in CONOPS development.*

6 - MARKET AND INDUSTRY ANALYSIS

To understand the robotics and autonomous systems industry, one must consider the market characteristics, drivers, and data for both today and the future. This analysis, consisting of a mix of quantitative and qualitative factors, helps to focus discussion and prevent exaggerating or underestimating the potential development of these systems. The group closely examined U.S. and Japanese markets because of extensive travels in these regions, followed by considerations from other influential countries in the global market. This section investigates the following characteristics: market structure including aggregate size and firm types; growth projections; major defense related projects; import and export market dynamics; government and industry relationships; and innovation structures.

6.1 U.S. RAS Industry

Aside from industrial robotics, the U.S. is the largest player in the global RAS market. U.S. companies lead the world with fielded military systems, initiatives for homeland security, and a number of firms ready to support domestic applications. Adapting to the non-monolithic nature of the market, group divided the description into the air, land, and sea (including surface and subsurface) domains. Following the domain and context specific details, the analysis will consider innovation structures and government and industry interactions in the United States.

6.1.1 Markets by Domain

Unmanned air systems are the largest and fastest growing field of robotics in the U.S. market. This large relative growth is likely due to a number of factors, including relative ease of navigation, the ability to project power with air vehicles, or viability in the recent conflicts. A $4.8 billion industry, the market developed rapidly with 4.8 percent sales growth and 13.2 percent revenue growth in 2012. When viewed broadly, the U.S. UAV market has a variety of sellers offering a range of products. However, Bloomberg's analysis of 2013 government contract obligations shows Northrup Grumman, General Atomics, and Textron dominating the market with an oligopolistic tendency. Because of budget constraints and contracts focused primarily on military products, this tendency will likely not lead to significant seller pricing power; however, that dynamic could encourage developers to leverage their advantages during negotiations, including a resistance to the release of data rights. Maintaining control of software and hardware details will likely enable these manufacturers to negotiate future maintenance and development contracts for both the vehicles and ground segments. Furthermore, the fees that sellers can command for maintenance of a fielded system will increase, as there will be few options for the buyer if others do not have access to system data. Unfortunately, this current reality is at odds with the government push for open architecture and common standards.

Section 5 describes a number of well-documented UAS military projects purchased or in development. The Triton, UCAS, as well as other classified systems represent potentially sizeable investments in the U.S. market. The DoD Unmanned Systems Roadmap (USRM) estimates that the military services will fund unmanned air systems at a peak of $4.8 billion in 2015 (RDT&E, procurement, and operations and maintenance (O&M)). Although RDT&E dollars are declining through 2018, procurement is roughly stable at approximately $2 billion, indicating that some current firms can expect a sizable budget for sales of new equipment. Qualitatively, many of the firms the team visited identified the general budget downturn as a large concern for their UAS strategy, but none had any plans to exit the military market based on the current situation. However, many speakers recognized the need to diversify their companies' portfolios to commercial applications, develop new technologies, or open foreign markets for UAS sales to continue to make this segment profitable.

Unmanned ground systems are a much smaller market than air systems. Nonetheless, first responders, border patrol, state and local police, and civilian bomb squads have similar needs for robotic equipment as the military, which represents growth possibilities for the industry. In spite of the relatively small size of this segment, the team uncovered several areas of interest. Of particular note was Google's acquisition of Boston Dynamics and the automation of heavy machinery at companies like Caterpillar. Although the terms of the Boston Dynamics acquisition remain undisclosed, Google's interest in the company's intellectual property and human capital demonstrates a clear interest in developing mobile robotic solutions in the commercial space. Research indicated that Caterpillar's automation of mining equipment also has the potential to grow into a significant market. Fortunately for industry, mining has significant access to capital and small increases in efficiency can generate large returns, thus incentivizing innovation.

The U.S. market is not as established in the sea domain, but development of unmanned surface and subsurface vessels is growing steadily. The Association for Unmanned Vehicle Systems International (AUVSI) 2013 report on Unmanned Marine Vehicles (UMVs) identified approximately 225 companies worldwide, with one third, or 85, located in the United States. This market is somewhat segmented between AUVs, remotely operated vehicles (ROVs), and unmanned surface vessels (USVs). This distinction is important, as the different vehicles rely on very different technologies for communication, navigation, power, and maneuverability. Notably, of the platforms considered in the report, ROVs made up 57 percent while AUVs and USVs comprised 28 percent and 10 percent, respectively. IBISWorld reported that the AUV market had revenues of $157 million in 2013, implying a rough overall UMS market of $560 million[19].

While the overall RDT&E and procurement dollars for unmanned maritime systems (UMS) are relatively small, DoD USR projects the industry to grow by 14 percent from $165 million in 2014 to $188 million 2018[20]. IHS Janes' forecast for the U.S. market concludes a similar figure of approximately $200 million during the same period with growth through the early 2020s[21]. With promising growth expectations, particularly given the expected broader defense funding downturn over the same period, DoD is sending a positive demand signal to the UMS industry. The team's visit to a leading UMS provider confirmed that industry is receiving this signal. The same firm also provided strong indications of a growing technological capability to meet DoD's operational requirements with RAS capabilities.

With DoD's budget shrinking, the unmanned maritime market in the commercial segment may have significant influence. One of the greatest application areas in the business-to-business space is for undersea management of oil and gas infrastructure maintenance. Companies like C&C Technologies are pushing the growth in power, navigation, automation, and sensors through partnerships with highly profitable energy companies. The Autonomous Undersea Vehicle Applications Center estimates there are 3,000 subsea wellheads and 180,000 kilometers of pipeline that need monitoring, and AUVs will likely provide a far more cost effective method[22].

6.1.2 Innovation Structure

Any consideration of the industry supporting the development and fielding of a RAS must examine the innovation framework necessary to conceive and construct revolutionary systems. Typically referred to as a National Innovation System (NIS), this framework supports the growth of a multitude of industries through research, funding, resource organization, and prioritization policies. While the robotics industry is more than 50 years old, it is currently experiencing a technological revolution with the possibility of significant future market growth. The U.S. NIS will directly affect the ability of U.S. firms to lead development of and compete in these new markets. As stated by the National Robotics Initiative:

> Over the past five years, tremendous advancements in robotics technology have enabled a new generation of products in industries as diverse as manufacturing, logistics, medicine, healthcare, military, agriculture, and consumer products. It is becoming increasingly evident that these early, next generation products are a harbinger of numerous, large scale, and global, robotics technology markets likely to develop in the coming decade[23].

Federal spending has advanced RAS technology and DoD supports a significant amount of R&D in the field. Defense-related research spending has transformed U.S. universities, which play a critical role in the NIS and advancement of RAS technology. Basic and applied research, system development and large-scale procurement supporting operations in Iraq and Afghanistan are examples of how recent DoD spending have served as both technology creator and lead purchaser. Challenge grants and competitions, such as DARPA's Robotics Challenge and Urban Challenge, have led to the current state of humanoid robots and autonomous vehicles, as well as serving as an opportunity for interaction amongst various robotics technology clusters. DARPA's director recently testified, "Challenges reach a broad range of performers by offering prizes to those who accomplish previously unattainable goals. They have proven to be an extraordinarily effective way to tap the creative ideas of an ever-wider community to help DARPA push the frontiers of technology forward" while also adding, "[the Robotics Challenge] is also demonstrating just how far these kinds of robots are from serious battlefield application[24]." Dr. David Mowery of the UC Berkeley School of Business highlights that the "willingness of at least some U.S. defense program managers to place substantial orders for new systems and components with young firms, as well as the prominent role of universities as performers of a considerable amount of [DoD]-funded research, also distinguish the U.S. programs from those of such nations as Japan[25]." These efforts contribute to the national innovation system interconnections as the "creation of an R&D infrastructure[26]." In order for the DIB to lead the implementation of RAS, DoD must supplement the projected decline in industry R&D investments through targeted funding of this nascent industry.

In addition to targeted funding, the concept of "clustering"[27] of innovation centers has positive impacts on RAS development. Michael Porter defines clusters as a "geographic concentrations of interconnected companies and institutions in a particular field."[28] These technology clusters are typically comprised of related and supporting industries (e.g. suppliers) as well as a conglomeration of production factors such as human, knowledge and capital resources. Four major technology clusters have emerged in Pittsburgh, Pennsylvania (Carnegie Mellon University and University of Pittsburgh Quality of Life Technology Center); Boston, Massachusetts (Massachusetts Institute of Technology, Worcester Polytechnic Institute); and Los Angeles (Caltech) and Palo Alto, California (Stanford University). Not surprisingly, these clusters are all near major universities and targets for venture capital to support start-up efforts. A review of the National Science Foundation's 88 awards as part of the National Robotics Initiative illustrates the effect of these clusters on their home states: out of 88 awards, California firms received 14, and Pennsylvania and Massachusetts each received 13. The state with the next highest total was Texas, which received six.

6.1.3 Government/Industry Interaction

The U.S. government rules, regulations, and acquisition process impacts the development, sale, and validation of RAS products. For systems to operate in the U.S., manufacturers must meet significant requirements, for example, the ability to "see and avoid". The uncertainty shaped by pending FAA regulations to govern the use of UAS in the national airspace dampens RAS development as the final requirements have yet to be determined. Similarities are found between international regulations for preventing collisions at sea and domestic regulations for the implementation of unmanned ground vehicles. Additionally, the U.S. also exerts a number of export controls in an attempt to reduce RAS technology proliferation. Because the U.S military is a dominant player in the RAS market, the DoD acquisition system, including contracting, requirements development, funding mechanisms, and testing and evaluation (T&E) all influence industry growth

Nearly every firm the team visited cited operational regulations as a barrier to growth and strategy development. In the air domain, the Federal Aviation Administration (FAA) has a congressional mandate to develop the CONOPS for integrating UASs across the national airspace by 30 September 2015[29]. Although some were hopeful, many firms expressed concern about the FAA's apparent lack of progress and expected this to continue to hamper commercial UAS development.

Like the regulatory struggles with the air domain, most sea-based systems must meet the International Maritime Organization (IMO) regulations for preventing collisions at sea. In coordination with PMS406 and the U.S. Coast Guard, industry leaders are already participating with regulatory committees to accommodate unmanned platforms in future versions of the international regulations. Early involvement by experts will help eliminate regulatory barriers for both the commercial and military sectors. Developmentally, engineers are already creating sensors to satisfy expected rules. Coordinating hardware solutions and regulatory policy will help ensure the fielding of compliant platforms.

The major issue in the ground domain will likely be the integration of autonomous cars on public roads. Since the first DARPA Grand Challenge in 2004, several manufacturers have ventured into the autonomous vehicle market, and to date, four states in the U.S. have passed legislation that allows the testing of autonomous vehicles on public roads[30]. According to a December 2013 Motor Authority account, "Among the major automakers already testing self-driving cars are Ford, Nissan, Volvo, Toyota and Mercedes--all of which have shown off autonomous vehicle technology in the past few months[31]." As with the air domain, ground regulations are evolving but remain relatively undeveloped and provide a level of uncertainty for industry. It is likely that the Department of Transportation (DoT) will face a mandate, in the not too distant future, to integrate autonomous vehicles in the U.S. road system much like that for the FAA in the air. As the markets continue to grow, it becomes more important that industry experts work with partner organizations to influence government regulation of the air (FAA), maritime (IMO), and ground (DoT) domains.

Additionally, there is an extensive array of restrictive government export controls. As DoD begins to make tighter procurement decisions, many contractors are looking to other commercial and overseas markets to help offset the decrease in U.S. defense budgets. There are significant potential markets, but controls prevent the export of technology that may have military utility to foreign customers, even when similar capabilities are already available in those markets. In fact, U.S. government regulations meant to prevent proliferation impact the UAS market more than any other controls. Two major regulations are the International Trafficking in Arms Regulations (ITAR) and the Missile Technology Control Regime (MTCR).

The ITAR, maintained by the U.S. Department of State (DoS), is a set of regulations that control the export and import of defense products involving U.S. technology. Items included on the United States Munitions List (USML) fall under ITAR controls and any item on the USML requires that DoS issue an export license before selling to foreign markets. UASs are categorized as ITAR Category IV, which includes anything relating to launch vehicles, guided missiles, ballistic missiles, rockets, torpedoes, bombs and mines. Specifically, paragraph 121.5 of the ITAR states, "equipment in this category includes robots, robot controllers and robot end-effectors specially designed or modified for military applications[32]." Essentially, the language of the ITAR means that nearly every UAS related item is subject to strong export controls.

The MTCR is an informal, voluntary partnership between 34 countries that requires both the departments of State and Commerce license systems that can fly farther than 300 kilometers and carry more than 500 kilograms. Initially established in 1987, the agreement intended to reduce the proliferation of unmanned delivery systems, particularly for nuclear weapons. In July 1992, the MTCR grew to include the nonproliferation of UASs for delivery of all weapons of mass destruction. Because of their extended range and carrying capacity, UASs like Global Hawks and Predators fall under MTCR controls, the same controls that govern the international sale of cruise missiles.

According to Eric McClafferty, "in the race to capture a share of the $81 billion international UAS market through 2021, industry is being hobbled by restrictive export controls[33]." For the UAS industry to compete in the lucrative international market, the U.S. must reconsider export laws and agreements by conducting a thorough review and revision of ITAR paragraph 121.5, the MTCR, and other export controls. From a defense security cooperation perspective, DoD can only benefit from increased cooperation with allies that results in the procurement of U.S. RAS systems. As U.S. defense budgets decline, the need to further increase U.S. RAS sales to partner nations becomes even more compelling. *Thus, DoD should increase its advocacy for opening global markets to U.S. RAS systems.*

The monopsony of the government as the sole buyer of many RAS systems presents concerns for many RAS firms due to the complex and unpredictable acquisition and funding mechanisms. During interviews, several small companies cited the complexity of contracts and certification process for contractors as a barrier to entry. Although this reality tends to serve larger firms well, particularly those focused on highly complex systems, it simultaneously inhibits competition and innovation in the market and is causing some firms to consider alternatives outside DoD. Moreover, while Urgent Operational Needs (UON) statements of the recent past allowed DoD to field systems rapidly and industry to generate quick profits, this shortcut to normal acquisitions does not engender predictability and is unlikely to continue. On the funding side, the use of overseas contingency operations (OCO) funding facilitated RAS procurement, but this funding is now redirected to other missions or may disappear entirely. Compounding this problem, sequestration will constrain the overall DoD budget going forward. Expressing his frustration with the situation, one active duty acquisition professional stated, "As a result of sequestration in FY '13 we canceled or rescheduled over 100 contracts … ultimately delaying improved capabilities for the warfighter[34]." Besides delaying programs, sequestration has prevented the start of new programs that could directly support the RAS industry. In summary, the lack of clear and comprehensive acquisition strategies, supported by stable and predictable budgets, impairs industry's ability to create long-term plans. The study team recognizes that the rapid fielding of unmanned systems in the recent conflicts made a decisive impact in several mission areas. Moving forward post-conflict, however, there needs to be a more faithful adherence to the acquisition process, to include planning, programming, budgeting, and execution (PPBE) to support formal programs and establish a foundation for industry's long-term business strategies. Thus, it is recommended that *DoD transition mature technologies to programs of record to provide predictable procurement and life cycle sustainment plans*.

Even in the wake of the challenging acquisition structures and government export regulations, the IS team's visits to U.S. commercial, academic, and research institutions supported the conclusion that the U.S. RAS industry understands that autonomy is a critical enabler to the future success of RAS technology, and remains actively engaged. However, the team's investigation of foreign RAS industries and, most notably, the Japanese RAS industry, showed that Japan does not share the focus on software or autonomy. In particular, Japan institutionally and culturally chooses to focus on articulation and manipulation technologies (a subset of vehicular technologies). Based on that observed distinction, the team posits that autonomy, specifically mission autonomy, is where the U.S. has and can further its comparative advantage. However, current efforts focus on intra-vehicular interfaces rather than defining mission execution parameters that allow an autonomous system to, at some level, recognize and execute commander's intent. Additionally, mission autonomy embodies a set of recognized protocols that allow disparate systems to execute along the same mission thread with minimal operator input. To enable growth in the area of mission autonomy, DoD must emphasize it in the acquisitions process, incorporate it the CONOPS, and validate it by prioritizing funding and promulgation of requirements.

The complications of the acquisition process and funding mechanisms are two reasons industry is increasingly considering alternative customers outside DoD, but there are others as well. The recent reduction in U.S. government spending has increased the attractiveness of alternative revenue streams, resulting in the migration of high-caliber RAS firms from military to commercial markets. This makes it even more difficult for DoD to retain the expertise of industry leading firms. A contemporary example of how the industry is separating itself from pursuing DoD business is Google's acquisition of successful RAS-centric firms such as DARPA Challenge winner, Schaft, and a perennial DoD robotics heavyweight innovator, Boston Dynamics. Both Schaft and Boston Dynamics had strong and successful relationships with the DoD but as Michael Hoffman, editor of Defense Tech noted, "it appears [Google] would prefer to distance itself from the military in its initiative to develop next generation robots[35]." Without the support of these smaller firms, DoD is left with large defense conglomerates, which focus on providing value as system integrators rather than developing innovative software as a core competency. The team's interviews with the larger firms support this assessment. This absence illustrates a potential lack of access for DoD, or at least a reduction of DoD's power to influence the path of the industry towards delivering military-grade autonomy solutions.

Finally, the military has failed to fully account for RAS capabilities in its test and evaluation (T&E) process. If RAS is to proliferate within the U.S. military services and fulfill more efficient, effective and safe missions, the government will have to develop requirements to capture system accuracy, reliability, repeatability, and perhaps most important, predictability. Improvements to the T&E process are necessary to improve trust in these systems both in the military and for civilian decision makers. Specifically, this requires a robust plan that demonstrates predictable performance in all plausible scenarios within a dynamic operating environment. Physically demonstrating all these scenarios is impractical, and thus requires application of modeling and simulation. Because software testing will become a significantly greater portion of the T&E process, evaluators must coordinate with industry during development to create accurate test conditions and relevant performance metrics to measure performance. Further complicating the T&E problem, the nature of environment variables and validation requirements will vary by domain. For example, UUSs will have very limited communications, UGSs will have significant terrain obstacles, and UASs CONOPS may drive significant interaction between platforms for mission effect (e.g., swarming behavior). Furthermore, the level of autonomy and human interaction presents perhaps the greatest unknown, demanding predictability from RAS to be operationally successful. The complexity of the systems will drive the T&E community away from testing programmed tasks in known environments to utilizing techniques that demonstrate system behavior and predictable task completion in uncertain and dynamic environments. With the "newness" of these innovative systems, the warfighter may be concerned with the fielding of technologies that fall under a different T&E regimen compared to more traditional weapons systems. Thus, it is recommended that *DoD make technical development and testing transparent to include demonstrating the utility of promising capabilities to the warfighter early in the acquisition cycle.*

6.2 Japan's RAS Industry

Japanese culture and government polices drive Japan's RAS industry towards civilian applications in the ground domain. Its strengths are in the industrial robotics and hospice and service sectors, while it is severely limited in the military and security contexts. Japan's RAS industry follows a human-machine teaming ethos, known to Toyota as *Jidoka.* According to a Toyota representative, Jidoka is "automation with a human touch as opposed to a machine that simply moves under the monitoring and supervision of an operator[36]."

While the U.S. RAS industry values autonomy, the *decide* portion of the RAS model, the Japanese market is primarily interested in improving the *act* portion, with the majority of its innovation structures focused on advancing mechanical articulation and precision. The Japanese government has further solidified this with the Ministry of Economy, Trade and Industry's (METI) four concentration areas for its RAS industry: manufacturing, hospice and elderly care, infrastructure, and disaster relief[37]. Noticeably absent from this list are any military applications. Japan, with the world's third largest economy, budgets only approximately one percent of its gross domestic product on defense, amounting to $66 billion projected for fiscal year 15[38] [39]. Of that, Japan plans for only $3 million to go to research on surveillance drones. [40] There are several reasons for this lack of defense focus in annual budgets, including the historical relationship in which the U.S. has provided a security umbrella; however, this analysis will focus on two specific reasons. First, Article 9 of the Japanese Constitution limits Japan from pursuing overtly offensive weapon systems. Second, in 1949, Japan adopted the three principles of armed exports, commonly known as the 3-Ps of defense export control, which prevented Japanese industries from selling weapons technology to nations that meet any one of the following criteria:

1) Communist Nations
2) Countries Subject to a UN resolution or embargo
3) Countries involved in armed conflict or in the process of entering armed conflict

In 1976, Japan further clarified the third P to include any foreign country, thereby bringing to a halt any opportunity for Japan's RAS industry to reach external defense markets. Therefore, regardless of the domain, Japan's military context has been noticeably vacuous due to both a lack of domestic demand and the inability to compete in foreign markets. Of note, in April 2014, Japanese Prime Minister Shinzo Abe "decided to allow arms exports and participation in joint weapons development and production when they serve international peace and Japan's security[41]." While the goal of loosening the 3P restrictions is closely tied to an effort to "fortify ties with allies and bolster the domestic defense industry[42]", the current Japanese defense industry is heavily vested in the civilian context and is not currently structured to support near-term defense needs. What this move does provide, however, is an opportunity for foreign entities, such as the U.S., to invest in Japan's tech-heavy industry and possibly shape the growth of their military and security related technology. Leveraging Japan's significant lead in articulation, as shown by its contributions to the International Space Station and recent success in the DARPA challenge, will highly complement the U.S.' current efforts in robotic autonomy[43].

The one area where Japan sees great potential in spurring new and innovative technologies comes from a construct called an 'innovation arena'. The first of such arenas is the Tsukuba Innovation Arena for Nanotechnology. While not currently tied to robotics, the idea behind an innovation arena is to concentrate government, academia, and industry into a geographic region where resources and manpower can move more easily between these institutions, as well as establish a place where technology startups can grow[44]. Started in 2009, the arena is a purposeful arrangement that resembles the U.S. innovation clusters previously discussed.

From a national defense standpoint, Japan has not had a compelling reason to pursue a RAS solution to its national defense needs. However, rising tensions over territorial disputes appear to be causing Japan to reevaluate its policies. Japan is taking small, incremental strides to loosen the reins and provide the structures for its RAS industry to grow. Moreover, as with the

U.S., domestic demand, the ability to compete in foreign markets, and governmental strategic guidance and policy play major roles. Prime Minister Abe's economic reforms and innovation structures may very well create a new market for the U.S. DIB. Accordingly, the U.S. should build relationships within the Japanese market to shape future opportunities in RAS development and leverage Japanese expertise.

6.3 Global Industry

The U.S. and Japan are not alone in the global market for RAS, with global influences of supply and demand. As these systems become more effective and efficient, more countries will look to augment or replace traditional security capabilities with these systems. The team considered the RAS markets in South Korea, China, and Israel, as these three countries offer a unique collection of characteristics in their development, demand, and production.

The South Korean RAS industry shares several characteristics with the U.S. and Japan, and the overlap of these similarities has an effect on global market. Like the U.S., South Korea focuses on military and defense-related production, and actively pursues export relationships. Like Japan, South Korea has large conglomerates that dominate its industry and reinforce a conservative business attitude. The South Korean government has three strategic objectives for its national defense market, including self-reliance, the generation of national revenues, and maintaining a military-technological edge over North Korea[45]. As South Korea works toward domestic production, they have increased exports to provide enough demand for their industrial base[46]. Within the RAS-specific market, the South Koreans are among the top-tier developers and users in the field. The South Korean government has determined the industrial robotics market is saturated and is moving towards the personal robotics market with a goal to have a robot in every Korean household by 2020[47].

The growth of the South Korean robotic market and desire to create an indigenous market has led to the development of its military RAS industry. Its aerospace industry, including KAI and Korean Air Lines Aerospace Division, has developed four UAS designs for their domestic market[48]. There is speculation that South Korea has a number of micro UASs in development, as well as the Korean Aerospace Research Institute's tilt-rotor Smart UAV, designed for speeds up to 300 mph[49]. Although planned for 2011, the South Koreans delayed their planned purchase of Northrop Grumman's Global Hawk, with a restart of this deal pending in April 2014[50]. Although they cited price as the reason for the delay, it is equally plausible they were simply protecting the domestic industrial base by "trying to develop [their] own Medium Altitude, Long Endurance UAV[51]." The South Korean government has not limited itself to UAS development, with demonstrated capabilities to produce deep water (>6000m) unmanned submersibles for study of the ocean floor[52]. Although the available test results describe the ISiMI6000 as a research vessel, many have characterized this line of vehicles as dual civilian and military systems[53]. Lastly, South Korea has developed unmanned ground systems primarily to perform duties along the demilitarized zone. With an estimated $32 million planned investment in surveillance and combat UGS programs through 2011, reports surfaced in 2010 of the deployment of a $330,000 vehicle with plans for additional vehicles already in place[54].

Similar to South Korea, Israel has a requirement for defense and strong interest in indigenous production. However, because of the relatively small size of their domestic forces, Israel has looked to the export market to sustain their industrial base. Within Israel, two agencies control the approval decision process and oversight of UAS sales to foreign customers.

Compared to the cumbersome process in the U.S. involving 11 different agencies, the Israeli firms have a huge advantage in sales efficiencies. According to the Drone Wars UK paper, 40 out of 70 countries utilizing UASs received either the platform, technology, or both from Israel[55]. Per shared government agreements, Israeli and U.S. administrations are required to manage the export of any technology to other nations. Through significant government investments in their industrial base, particularly their aerospace sector, Israel has become one of the world's top exporters of unmanned aerial systems, exporting 75 percent of its entire defense production[56]. These efforts resulted in exports of over 41 percent of all UASs worldwide (24 countries) from 2001 through 2011. This is an average of approximately $578 million per year from sales of these vehicles and presents challenges to the U.S. industrial base[57].

China's economic growth and potential role as a military competitor influences many considerations for RAS technology development. The International Federation of Robotics expects China to more than double their number of industrial robots from 2012 to 2016, placing them behind only Japan and all of North American in overall number of industrial robots. In addition to Russian equipment, the Chinese procured equipment from Israel, including the Harpy UAS in the 1990s. More recently, "a U.S. investigation concluded that technology, including a miniature refrigeration system manufactured by Ricor and used for missiles and in electro-optic equipment, was sent to China [from Israel][58]." China has also developed its own indigenous UAS program, reportedly copying the Russian Mikoyan Skat in their "Sharp Sword" Unmanned Combat Aerial Vehicle (UCAV) program, as well as copying a number of other UAS initiatives. The 1996 Taiwan Strait Crisis and 2001 U.S. P-3 collision with a Chinese J-8 are two of many incidents the Chinese study when determining how to counter U.S. influence in the South China Sea. Recognizing the need for ISR capabilities, China is actively developing both unmanned air and underwater vehicles to enable their A2/AD CONOP[59]. Specifically, the U8 unmanned helicopter, previously mentioned "Sharp Sword" UCAV, HQ-4 Soar Dragon HALE, and Qianlong-1 Unmanned submersible are all in testing or production.

7 – SWOT Analysis

The belief that a technology could fundamentally alter the character and conduct of conflict implies one of two mandates. If a nation's security apparatus believes an achievable technological leap could change warfare, it must pursue this technology, including development, adoption, and operationalization to provide for the security of its citizens. The second is that a nation must pursue a defense against this technology, as an adversary may accomplish these tasks and present a significantly greater threat. Coupled with the analysis model introduced in the methodology section, Krepinevich's RMA definition provided a context to consider the state of the RAS industry. Specifically, it illuminated how industry responded with products in recent conflicts, drivers affecting industry's development, and industry's potential to support future security demands. We have discussed industry strengths and market opportunities that the U.S. must leverage to realize a RAS RMA, as well as weaknesses and threats that may hold the industry back. In the context of the U.S. industrial base's ability to support an RMA, our conclusions follow.

7.1 Strengths and Opportunities

The fulfillment of an RMA relies on strengths and opportunities in three areas of RAS development. First, the industry has demonstrated an ability to produce systems that, to a lesser degree, have already changed the conduct and character of warfare. We believe this trend will continue. Second, the states of the technology and the industry are sufficient to alter how a RAS equipped nation might pursue security objectives. Finally, the drivers pushing innovation and the industry are accelerating, which should lead to a virtuous cycle of development. The team's study of the industry indicates that all of these factors could lead to an RMA.

As described in section 5.1 (Current State of Military RAS), the industry produced a significant number of systems in response to military demands during the last decade. The fielding of EOD robots and UASs, at a rate beyond consideration prior to recent conflicts, demonstrates the RAS industry has the capacity to deliver products. In uncontested environments, RAS capabilities changed the way leadership considered ISR, casualties, or opportunities to target key personnel in terror networks. This success, and more importantly, the post-war drawdown illustrate the importance of strategic guidance from the government to retain this strength of industry capacity for future security requirements. While our analysis suggests current systems may struggle against an A2/AD defense, industry now has both the opportunity and incentives to design and build systems for this challenging new environment.

According to Krepinevich, a RMA requires both new technology and sufficient systems. Although the team determined that a significant leap in the current state of autonomy is necessary for unmanned systems to be effective in the most complex scenarios, we believe that the U.S. RAS market is dynamic enough such that overcoming this challenge of producing systems with greater levels of autonomy is attainable. As discussed in section 5.2.1, (Anti Access/Area Denial CONOPS), there are opportunities to bridge the gap between today's remotely operated systems and the future's fully autonomous capabilities. Teaming manned and unmanned systems is a reachable goal that could significantly enhance combat capabilities while keeping human subjective decision-making "in the loop". This path to game-changing capabilities requires that the military reconsider how it should integrate these systems. The growth in UAS employment, recognition by the Navy of the importance of AUVs to retain undersea dominance, and attempts to start the Army's FCS program all show willingness, across domains, to acquire sufficient RAS systems to change the conduct and character of warfare.

Finally, the availability of innovation and accelerating growth demonstrate a critical strength in the potential for continued development of this capability. If one accepts that autonomy, and more specifically software, represents the key to changing conflict with RAS, the U.S. has a demonstrated capability to innovate and produce results in this field. However, maintaining "first mover advantage" in autonomy is not preordained. Thus, with the downturn in DoD resources moving forward, *DoD should target research and development funding to protect technological edge in autonomy.*

The clustering of robotics in regions of strong software capabilities, targeted research funding from DARPA, and a focus on bridging the "valley of death" between technology development and production have consistently shown results, and suggest RAS will follow a similar path as previous IT-based revolutions. The RAS industry, when faced with national security requirements and infused with new investments by government and commercial ventures, is ready to provide enough capacity to support military systems. With each innovation, cultural acceptance will grow within the military through operational effectiveness, and outside the military through a demonstrated improvement in security.

7.2 Weaknesses and Threats

Opponents believe that RAS will only lead to evolutionary changes and thus will not create a dramatic increase in military capacity, suggesting that if development is sufficiently slow, then no nation will be able to develop a relative benefit from the capability. The team's research and analysis identified three areas of industry weakness or external threats that could lead to evolution rather than revolution. First, the RAS industry is very small, with significant barriers to growth. Second, the military services are not providing clear demand signals due to poor organizational structures and a lack of new concepts of operation. Lastly, the complexity of the environment and difficulty in dealing with a thinking adversary require unobtainable autonomy algorithms and culturally acceptable solutions.

As the identified in section 6 (Market Analysis), the much of the RAS industry is still in its infancy based on financial size. Many of the smaller firms, who our research showed are critical to the development of new technology, have muted influence with congressional decision makers, as compared to larger defense conglomerates. This lack of leverage affects a smaller firm's ability to draw financial and human capital to facilitate future growth. Higher return on investment in other industries and outsized salaries from firms in other industries for engineers, threaten funding and siphon talent from hardware and software design needed for RAS development. Export controls and restrictions on domestic operations further complicate growth potential of both RAS technology and firms. To address the weakness of size and the threat of over-regulation, the government must revise regulations for RAS as well as exports to enable the growth of vital domestic and foreign markets. None of these issues are unsurmountable.

Leaders in both the military and business confirmed that having the technology is only the start of effective change. As Dima Adamsky argues in *The Culture of Military Innovation*, RMAs, "depend as much upon gaining access to the requisite technologies as on restructuring concepts and organizations[60]." This weakness, characterized by a lack of leadership with RAS acquisition or employment experience, leads to a dearth of advocacy for building this capacity. Without visionary guidance from the top, military structures will likely continue to slowly integrate these capabilities as replacements for the legacy platforms rather than consider completely innovative approaches to employment. Organizationally, the services' isolation of RAS acquisitions and operations within ill-equipped ISR organizations will further inhibit opportunities to develop manned-unmanned approaches and likely delay fully autonomous solutions. These structures will create limitations for CONOPS development and inconsistent demand signals to industry. Unless DoD addresses these issues, RAS development will stagnate. Furthermore, DoD will be less likely to overcome the existing cultural biases. To overcome these threats, it is imperative that DoD focus its efforts to improve cultural acceptance of RAS capabilities by increasing communication and advocacy at all levels. Additionally, it must enhance leadership's knowledge and understanding to enable informed decisions and develop influential RAS champions. *Thus, it is recommended that senior RAS advocates are designated at OSD, Joint Staff and the military services accountable for the development and fielding of RAS technologies that clearly increase the effectiveness, efficiency, or safety of a particular mission area.*

The key to a RAS RMA is in creating systems that can operate autonomously. Many argue that doing so is beyond our software development capability. Currently, the development of autonomy software represents the greatest challenge in realizing an RMA - the ability to choose the most strategically beneficial course of action, in any situation, involving a large number of unknowns. The dynamic nature of the intended RAS environments further complicates the issue. Software developers must maintain a level of responsiveness and flexibility in their designs to respond to changing environments. If not, their systems may very well be irrelevant when finally called upon. Our research showed a definite competitive advantage for the U.S. in software development, which, if properly acted upon, will enable the technology to deal with these challenges. In the interim, RAS operations may have to depend on vulnerable communication links and rely on human operators, which could degrade the ability to coordinate actions for rapid mission effects. However, our research shows considerable progress in this area, as DARPA is investing R&D money into emerging communication technologies to help build the required multifarious communication architectures. The Air Force RPA Vector program provides another vision, including technology and CONOPS, of how to deal with potential communication problems. Lastly, RAS producers currently have access to software developers, but the attractiveness of commercial ventures, with limited military application, threatens access to this critical human capital in the future. Furthermore, because DoD does not clearly articulate autonomy requirements, industry may continue to struggle with the issue of when and where to invest critical research and development dollars. DoD must clearly emphasize autonomy – to include targeted R&D investments in autonomy technology - if it expects the development of autonomous solutions, and the government must test and validate these algorithms to develop trust, confidence, and cultural acceptance. Combined, these will lead to industry growth and help attract critical human capital.

8. Conclusion and Recommendations

The broader robotics industry is in the midst of an inflection point in which robotic service applications – to include robots that move among us – are beginning to change society. This societal change will provide great opportunities in the development and use of RAS in military affairs. The DIB, when infused with appropriate investments by government and commercial ventures, is ready to provide the requisite capacity and capability for the warfighter to meet a national security requirement. When combined with innovative CONOPS in which RAS use is critical to increasing the effectiveness, efficiency, or safety of a particular mission area, the nation will more clearly recognize that an RMA is underway

Based on our research, interaction with industry stakeholders, and overall analysis, the (RAS) Industry Study provides the following specific recommendations for DoD.

1. Emphasize Manned Unmanned Teaming (MUM-T) in CONOPS development in order to influence cultural resistance to unmanned systems. (5.2.1)

2. Increase advocacy for opening global markets. (6.1.3)

3. Make technical development and testing transparent to include demonstrating the military utility of promising capabilities to the warfighter early in the acquisition cycle. (6.1.3)

4. Transition mature RAS technologies to programs of record to provide predictable procurement and life cycle sustainment plans. (6.1.3)

5. Target research and development funding to protect technological edge in autonomy. (7.1, 7.2)

6. Designate senior advocates at OSD, Joint Staff and the military services that are accountable for developing and fielding RAS technologies that clearly increase the effectiveness, efficiency, or safety of a particular mission area. (7.2)

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