Spring 2013
Industry Study

Final Report
Robotics and Autonomous Systems Industry

The Dwight D. Eisenhower School for National Security and Resource Strategy
National Defense University
Fort McNair, Washington, D.C. 20319-5062

ROBOTICS AND AUTONOMOUS SYSTEMS 2013

ABSTRACT: A decade-long increase in the funding and subsequent technological development of robotics and autonomous systems has resulted in a surge of commercial and military applications not imaginable just a few years ago. Significant advances in robotics and autonomous systems abound, but apart from industrial robots, this is still a fledgling, segmented, and immature industry. Focused government support and continued industry innovation are needed to sustain and capitalize on the momentum achieved in the last 10-15 years. The current state of the robotics industry has been compared to the IT industry circa 1970s. Robotics is poised to grow immensely over the next 10 – 15 years, and is regarded by some as the next big American industry. Though tremendous innovation has occurred in both commercial and government sectors, significant technical, policy, standards, societal, and funding challenges remain to be solved in order for robotics and autonomous systems to cross the chasm and enter the mainstream market. The risk of losing already achieved technical advantages and foregoing just-over-the-horizon breakthroughs could be a severe blow to US national security.

CAPT Carlos Aceves-Jiminez, Mexican Navy
Mr. Thomas Bikowski, Department of the Navy
Lt Col E. Marcus Caughey, US Air Force
COL Christopher L. Day, US Army
Mr. Joseph Fulford, Department of the Air Force
Ms. Sara A. Higgins, Office of the Secretary of Defense
LTC Heidi J. Hoyle, US Army
Mr. Laurent Jaffart, Cassidian - EADS
Mr. Michael Perozziello, Defense Logistics Agency
Col Francesco Presicci, Italian Air Force
Lt Col John S. Trube, US Air Force
LTC Bruce Walton, US Army National Guard
Lt Col Kenneth D. Warcholik, US Air Force
Ms. Linda L. Williams, Defense Logistics Agency
Lt Col Pamela L. Woolley, US Air Force

Mr. Ted Mann, Department of State, Faculty
Col David Gerber, US Air Force, Faculty
Col Roger D. Thrasher, US Air Force, Faculty

PLACES VISITED

Domestic:

AAI Textron Systems (Hunt Valley, MD)
AeroVironment (Simi Valley, CA)
Aethon Inc. (Pittsburgh, PA)
Air Force Aeronautical Systems Center Detachment 3, Gray Butte (Palmdale, CA)
Applied Minds (Glendale, CA)
Aurora Flight Sciences (Manassas, VA)
Bluefin Robotics (Quincy, MA)
Bosch Autonomous Technologies and Robotics (Palo Alto, CA)
Bossa Nova Robotics (Pittsburgh, PA)
Boston Dynamics (Waltham, MA)
Carnegie Mellon University Robotics Institute (Pittsburgh, PA)
Carnegie Mellon University Robotics Institute, National Robotics Engineering Center (Pittsburgh, PA)
Carnegie Science Center (Pittsburgh, PA)
Google Pittsburgh (Pittsburgh, PA)
GT Aeronautics, LLC (Simi Valley, CA)
Harley Davidson Vehicle Operations (York, PA)
Intuitive Surgical, Inc. (Sunnyvale, CA)
iRobot (Bedford, MA)
Jet Propulsion Laboratory (Pasadena, CA)
Johns Hopkins University, Applied Physics Laboratory (Laurel, MD)
Kiva Systems (North Reading, MA)
Massachusetts Institute of Technology, Humans and Automation Laboratory (Cambridge, MA)
Naval Explosive Ordnance Disposal Technology Division (Indian Head, MD)
Naval Research Laboratory for Autonomous Systems Research (Washington, DC)
Near Earth Autonomy (Pittsburgh, PA)
Northrop Grumman Corporation (Palmdale, CA)
NuVision Engineering (Pittsburgh, PA)
Quality Life Technology Center (Pittsburgh, PA)
RedZone Robotics (Pittsburgh, PA)
RE2, Inc. (Pittsburgh, PA)
Seegrid Corporation (Pittsburgh, PA)
SRI International (Menlo Park, CA)
Universal Technology, Inc. (Pittsburgh, PA)
Willow Garage (Menlo Park, CA)

International:

None

INTRODUCTION

Significant advances in robotics and autonomous systems abound, but apart from industrial robots, this fledgling, segmented, and immature industry requires focused government support and continued industry innovation to sustain and capitalize on the momentum achieved in the last 10-15 years. The industry has capitalized on technological advances and Department of Defense (DoD) investments in autonomous computational capabilities, multi-spectral sensing of the environment, and remote manipulation technologies facilitating development of new robotic applications for manufacturing, logistics, and health care. Military conflicts in Iraq and Afghanistan have acted as a catalyst for the DoD and the larger robotics community to adapt, develop, and field thousands of robotics systems across the domains of air, ground, sea, and space. A decade-long increase in the funding and subsequent technological development of robotics and autonomous systems has resulted in a surge of commercial and military applications not imaginable just a few years ago.

It is challenging to generalize about the future of the robotics sector due to the multifaceted nature of the robotics industry and the many niche uses where robotic technology has been employed. The industrial robotic sector has "crossed the chasm" from an immature market to widespread use in many manufacturing applications. "The chasm" represents the gulf between two distinct marketplaces for technology products—the first, an early market dominated by early adopters who are quick to appreciate the nature and benefits of the new development and are willing to pay a premium to get it, and the second a mainstream market representing "the rest of us," people who want the benefits of new technology at a reasonable price point, but who do not want to "experience" it in all its gory details.[1] The less mature robotics sectors are working through technological complexity issues, cultural concerns, governing policies, and/or financial barriers. As this paper will show, government funding and support has been largely responsible for the promising growth and implementation of robotic technology. Without continued US Government support, there is a strong likelihood segments of the robotics industry will flounder and the market will be lost to other international players, as has been the case with the industrial robotics sector.

This paper will analyze the current robotics and autonomous systems (RAS) industry, its outlook over the next five years, along with the respective challenges and will offer recommendations for government and industry to address those challenges. The 2013 RAS industry study concentrated on market segments with particular strategic interest to the Department of Defense, while performing a general analysis of the numerous segments where robotics and autonomous systems are being employed. The report concludes with four essays exploring the following topics in detail:

Culture, Trust, and Liability
The Coming Crisis in STEM Education
Innovation and R&D Funding
Open Architecture and Security

INDUSTRY DEFINED

Robots come in all shapes and sizes, from small robotic insects to huge ground and air systems. Robots are often used in dull, dangerous, dirty, or difficult jobs. With such wide diversity of type and mission, how is a robot defined? For the purposes of this paper, a robot is defined as a mechanical device that senses the environment, executes defined programs and moves or manipulates. The robot may have many different levels of autonomy or highly advanced levels of automation requiring little or no human intervention or control.

Fully autonomous machines, capable of making of decisions completely independent of human supervision, do not exist today and are not likely in the foreseeable future, nor are Hollywood-style “terminators.” For the foreseeable future, sentience and self-awareness form the boundaries of truly autonomous behavior, belong exclusively in the realm of human intelligence. In robotics today, discussion of autonomy in the machine realm is one of highly advanced automation through complex deterministic and algorithm-driven computer processing, especially since machine autonomy is starting to resemble some aspects of human autonomous behavior. Rather than fixate on the nuances between automation and autonomy, this report uses the term “autonomy” to describe highly advanced machine automation and accompanying human interaction.

The robotics and autonomous systems industry is not a monolithic market or simply a collection of facilitating technologies for other industries. The industry as shown in Figure 1 is divided into two primary segments: industrial and interactive. The interactive robotic segment can be divided into government, commercial, and household sectors.

The industrial robotics segment is a mature market characterized by heavy machinery to accomplish repetitive manufacturing assembly line tasks and sophisticated materiel handling systems. These robots are generally located in cages with simple safety mechanisms to protect the humans who must work around them. They are designed to accomplish programmed routines to accomplish specialized tasks.

The interactive robot segment is the focus of this paper. Interactive robots are designed to work in and around humans on a daily basis or interact with humans in or on the loop. The term "interactive" robots replaces the more commonly used term: "service" robots. The industry study determined all robots provide some type of service, including industrial robots. Industrial robots are designed to be independent and forgotten once programmed with limited to no human interface The term interactive better characterizes the level human machine interface compared to industrial robots. Interactive robots either require regular human interaction through controls or the ability to deal with the dynamic environment working around or with humans. Working around or with humans safely requires a sophisticated level of awareness, the ability to orient, and act on that orientation not found in industrial robots.

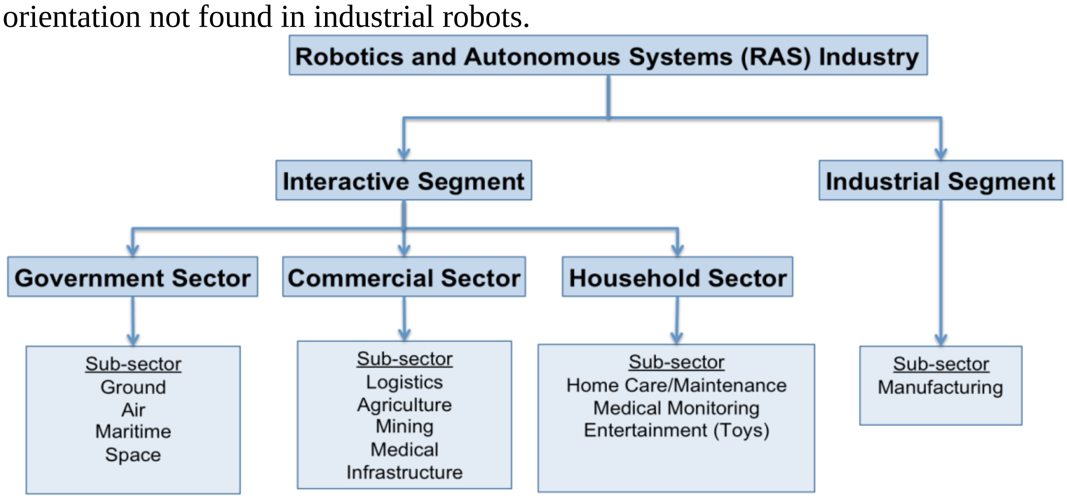


Figure 1. Robotics and Autonomous Systems (RAS) Industry

The interactive robots segment is divided into three sectors: government, household and commercial. Household robots use basic sensing and automated decision-making to accomplish tasks such as cleaning, cutting, monitoring, and entertaining. Examples of prevalent household sector applications include robotic vacuums, pool cleaners, and toys. However, technical advances are also making lawn mowing and remote medical monitoring possible. These robots are generally smaller and, while expensive compared to a non-robotic counterpart, they are generally significantly cheaper and less complex than the robots used in commercial or government applications.

Commercial robots generally employ much of the same technology, but on a much larger and complex scale. Robotic solutions have been successfully implemented in mining, agriculture, warehousing, and medical logistics applications. In these applications, it is not uncommon to have multiple robots working together to solve a particular problem such as moving medications in a hospital environment or transporting warehouse products.

Government robots include unmanned ground systems (UGS), unmanned aircraft systems (UAS), unmanned maritime systems (UMS), and unmanned space systems (USS). These vehicles are often accompanied by control stations/systems/devices which can be as complex as the vehicle itself. The functions performed by these different platforms include intelligence, surveillance and reconnaissance (ISR), weapons delivery, and other dangerous jobs such as explosive ordnance disposal (EOD). These robotic and autonomous capabilities have applications in multiple sectors of the government, such as law enforcement and search and rescue, and are not limited to military uses.

CURRENT INDUSTRY CONDITIONS

Assessing current conditions of this industry has been difficult if for no other reason than trying to look at the widely disjointed elements of the robotics “industry” with attempts to develop a single depiction. Past reports on this industry have highlighted the seemingly endless array of applications, cost, performance, actors, environments, and attributes associated with the robotics and autonomous systems market, defying one’s ability to perform a singular analysis of the structure, conduct and performance as a unitary market. Consequently, the question arises whether robotics is a distinct industry or simply a tool or technology supporting many other established industries and markets. Nevertheless, we believe a useful analysis can be made of several of the specific segments. The following sections further describe the interactive sectors of the RAS industry: Government, Commercial, and Household.

Robotic and autonomous systems today are produced by a wide range of companies, from mature industrial companies venturing into automated systems, to specialized robotic companies and start-ups specifically geared toward a small robot market niche. Over the last decade, the US market for robotics has largely been driven by the need to respond to combat operations overseas. The current state of the robotics industry has been compared to the IT industry circa 1970s.[2] The interactive robot market is poised to grow immensely over the next 10 – 15 years and is regarded by some as the next big American industries provided the government assists in efforts necessary from crossing the chasm. While some segments such as industrial robotics have experienced growth for many decades, other segments or sectors are only now emerging. The reduction in price of microprocessors and some sensors have permitted the introduction of some isolated commercial successes such as vacuum cleaning and entertainment robots. While early adopters have embraced advanced robotic applications, the robotics field as a whole has not ‘crossed the chasm’. “Robotics companies, especially consumer robotics companies, are identified as highly innovative companies focused on R&D, hardware design and manufacturing, but very few have "crossed the chasm" (Geoffrey A. Moore) between the early adopters of the product (the technology enthusiasts and visionaries) and the early majority (the pragmatists)."[3] Aside from industrial robotics, the robotics industry primarily resides in the early market segment, with a limited number of products having moved into the mainstream market. Figure 2 represents Moore's chasm.

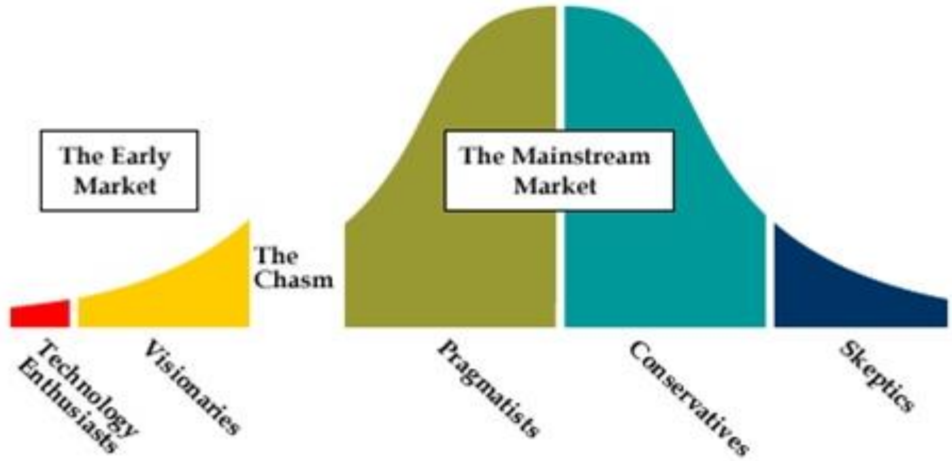


Figure 2. Crossing the Chasm (Geoffrey Moore)[4]

Government: Unmanned Aircraft Systems (UAS)

The UAS industry is the most robust of any subsector of the interactive robot segment, with US manufacturers holding a 70% share of the world market for unmanned air vehicles. [5] The reported number of UAS programs worldwide is approximately 680, greater than a three-fold increase from 2005.[6] This subsector has benefitted from more than a decade of DoD funding to support the wars in Afghanistan and Iraq.

While UAS funding has been robust in the past, the recently released 2014 Presidential budget shows a decline in UAS spending of approximately $1.3 billion from the prior year, with a planned expenditure of $2.5 billion in 2014. This budget includes funding for a number of mature programs and new development efforts. There are more than 7,000 UASs in the DoD inventory, supplied by over a dozen companies ranging from traditional prime aircraft manufacturers to those specializing only in UASs. Several of these companies are delivering UASs which have secured program-of-record status. Other 'up and coming' companies, such as Aurora and GT Aeronautics, are attempting to enter the market with various niche systems in support of DoD. While DoD UAS procurement is expected to dip until 2017, overall UAS market growth is expected to be level or slightly positive through 2020 and beyond.[7]

Several companies are anticipating smaller, less costly UASs to drive increased procurement interest in that subsector of the market. Many of these companies are working to position themselves to leverage directives to the Federal Aviation Administration's (FAA) to open the National Airspace System (NAS) for civil and commercial UAS use. Expanding UAS operations within the United States to other government agencies such as the Department of Homeland Security or state and local law enforcement, and possible uses in agriculture (crop dusting), fighting forest fires, and searching for lost souls during disaster recovery operations depend on the FAA opening the NAS to unmanned aircraft.

The barriers to entry into the UAS market are relatively high. Contractors must have the capability to design, build and test (or contract some of those services out) an aerospace vehicle, while incorporating some of the most advanced sensors in the world and the associated ground control system. In addition, interested competitors need experience working with the DoD procurement system, require a place to test their designs, and need to find a niche for their products. This niche must consider endurance, sensor payload, range, or other performance characteristics that displace current offerings from mature aerospace companies, established UAS producers and other potential niche new market entrants. With the end to Overseas Contingency Operations (OCO) funding, price may become a noteworthy differentiator in a market typically accustomed to providing top performance at a premium price, potentially opening the market to additional suppliers.

Government: Unmanned Ground Systems (UGS)

Although DoD acquisition budgets are shrinking, it is likely unmanned ground system technological development will continue, largely due to the force multiplier function it provides. According to the Association for Unmanned Vehicle Systems International (AUVSI) in their most recent Defense Forecast, unmanned ground systems will continue to account for about five percent of defense spending on RAS.[14] These specialty ground systems mainly support EOD and remote ISR activities—work that is typically dirty, dangerous, and dull. Although EOD and ISR robots represent only a small portion of DoD's unmanned resource outlay, these robots significantly increase the effectiveness of ground forces—a force multiplier capability the Defense Secretary requires to help DoD cope with future budget and force reductions.

Two firms, iRobot and QinetiQ, primarily constitute the small unmanned ground vehicle industrial base. There are well over 6,000 ground systems "on hand" today the DoD can rely on for mobile assessment and response capability when dealing with improvised explosives and other security concerns.[8] However, there are fewer than 100 new systems funded for near term procurement—a steep post-war decline impacting UGV production numbers. In addition, the Army recently announced it plans to divest itself of 2,469 of the older robots, which it plans to give to other government agencies.[9] With the downturn in DoD orders, market leader iRobot expects to turn its attention to the commercial side of its business.[10] On the other hand, QinetiQ has recently won contracts to provide Talons to the Czech Republic and Poland.[11]

The advent of driverless cars and other vehicles promises to revolutionize the way the world transports itself and its goods every day. Google and other carmakers around the world are racing to develop technologies applied to currently "manned" vehicles to permit drivers to take their hands off the wheel and focus on other tasks. Some states are permitting test vehicles to operate on their roads with additional proper precautions, opening growth opportunity for makers of devices supporting "optionally manned vehicles." It is still too early to discuss what form this market may take, but it is sure to contain a mix of mature companies in automotive and sensor production as well as new entrants. There are a number of DoD applications for intelligent vehicles to include logistics, convoy operations, and other transport functions that could benefit from these commercial advancements.

Government: Unmanned Maritime Systems (UMS)

Today, there are approximately 450 unmanned maritime vehicles in the DoD inventory. UMSs have several challenges to overcome to operate in the nautical environment. Obstacle avoidance, autonomous navigation in a GPS limited environment, communication, and data transmission must improve before generalized adoption. The commercial market may end up leading the defense market given the growing demand in mining and underwater energy exploration and its commensurate successful employment of UMSs.

The US Navy has plans for both unmanned underwater and surface vehicles to conduct mine hunting and countermeasures, inspection, oceanography, and sustained surveillance. Endurance, safe power generation and supply, obstacle sense and avoidance, communications, fault detection, and reliability represent some of the key challenges. It remains to be seen whether the course the Navy has charted for UMSs, in a roadmap published in 2004, remains sufficient to incubate a nascent industrial base in the United States to support defense needs or whether the US may find itself heavily reliant on overseas producers. It is evident that an uncertain future has limited US manufacturer interest to existing robotic land vehicle producers or relatively embryonic startup companies.

The current UMS sub-sector is diverse and not dominated by any particular company. International competition is expected to be aggressive, and to date there is no clear market leader. Several non-US based companies are successfully supporting the oil and gas exploration and extraction industry with UMS products. Depending on tradeoffs made in future budget requests, it is expected that US use of UMSs will continue to expand, albeit at a slower rate than what once was anticipated.[12]

Household: Home Care & Entertainment

Currently, household robots perform domestic chores (home care/maintenance) or provide entertainment. Domestic robots perform tasks such as cleaning of various surfaces (carpets and floors, garage floors, pools, windows, gutters, etc.), and mowing lawns. Entertainment and leisure robots are aimed at youth in the hopes of boosting their interest in robotics and other technical fields. In recent years there have been about 900,000 entertainment and leisure robots sold with a value of $166 million.[13] The home care/maintenance and entertainment robotics market is currently worth $1.6 billion worldwide but this is expected to grow rapidly, trebling to over $6.5 billion, over the next several years.[14]

While the household robotics sector is not the focus of this report, it is useful to examine this sector as an area where DoD may leverage commercial technology developments as defense budgets decline. There are also a number of robotics companies primarily serving the government sector that intend to pursue commercial products as a way to offset expected defense budget reductions.

Commercial: Medical

The aging world population coupled with rising health care and assisted living care costs are driving the market for cost effective solutions that extend a patient's ability to stay in the home versus a hospital or assisted care facility. The IBIS World Report for 2011 states that the robotics surgery equipment market generated 2.1 billion dollars in revenue. Medical robotics include: surgical robots (used in the operating room to treat patients); non-clinical hospital logistics robots (medicine delivery systems); tele-presence patient care robots; and prosthetics. Surgical robots have been demonstrated to offer high precision, tele-presence surgical procedures that are minimally invasive and provide for shorter hospital stays. These systems have been the beneficiaries of government interest and funding (with help from the National Institute of Health and DARPA). Many of these advances are only at the early stages of adoption with rapid growth potential ahead. An aging demographic in many countries, combined with a need to improve care, and lower health care costs are potentially creating a perfect environment for growth of this industry. Future uses of robotics in medicine include: robotic scrub nurses, triage assistants, drug delivery, and nano-robotic surgeries.[15]

Industrial: Manufacturing

Sales of industrial robots continue to be strong with 2011 sales increasing a significant 38% to over 160,000 robots--a record for industrial robotics producers. The installed base for industrial robots worldwide is estimated at 2.3 million units l.[16] The estimated value of the global industrial robotics markets is $8.5 billion[17] rising to an estimated $33 billion by 2017. [18] While Japan and the Republic of Korea represent half of the installed base for industrial robots, China, the United States, and Germany represent the countries with the highest growth in industrial robot purchases in 2011. But the US lags countries like Japan and Germany with an installed operations industrial robot base representing about 14% of the world total (Japan is 42%, Germany is 14% on a per capita basis robot usage is much higher in those countries than in the US.).[19] Robots offer a variety of applications in the industrial environment, but the most prevalent uses remain assembly, material handling, welding, and painting.

Some new entrants into the material handling world are attracting attention and offering new solutions to the problem of storing and retrieving warehoused goods. Companies like Kiva offer the capability of bringing the inventory to the human packer by moving shelves to the packing station. Others, such as Seegrid, are leveraging improved sensor technology to enable the movement of robotic pallet trucks. Both systems rely on sensors instead of costly infrastructure installations to guide pallet trucks around the warehouse. There may be the potential to leverage this technology in and between DoD warehouses in the future.

The bright line between industrial and interactive robots is blurring. There is a new breed of industrial robot emerging combining the repetition and precision of current industrial robots with increased interaction with humans. These robots can be used for a variety of tasked and easily reprogrammed with specialized computer skills or training. This drives down the unit cost. ReThink Robotics is marketing a trainable robot called "Baxter" at an expected unit cost of $20,000. This price point makes robots available to small and mid-size companies thus expanding the available market.

INDUSTRY OUTLOOK

While some robotics companies have “crossed the chasm” with solid markets in industrial manufacturing, material handling, medical surgery, and pharmaceuticals distribution, there are a number of firms whose early market position is less robust and dependent on research and development (R&D) grants and private investment. Whether US companies cross the chasm, maintain technical leadership, and achieve market success depends as much on market direction, government funding stability, and demonstrated utility as it does on continued technological innovation. Faced with tightening government budgets and a recent economic downturn, this industry is working to overcome technological challenges, cultural resistance, looming talent shortfalls, and regulatory issues.

Each sector or subsector deals with a unique set of regulatory issues managed by a different federal entity. The FAA is currently working through what will be necessary to admit UASs to the NAS; the Department of Transportation and each state government will regulate the introduction of intelligent vehicles; the Coast Guard will regulate the introduction of UMSs; and the Departments of State and Commerce will regulate what technologies may be sold internationally. Devices such as the daVinci® surgical robot represent one example of success in obtaining Food and Drug Administration (FDA) approval for the device.

For those firms in the government sector for unmanned systems, most have been working largely in a near-monopsonistic environment for the last decade. A few exceptions include iRobot with its household robot line and the UMS companies providing systems for the mining and petroleum exploration industry. Those companies dependent wholly or in large part on the US government face a struggle as government budgets are reduced. Unmanned air and ground system makers are seeking to develop additional customers now that they are faced with the inevitable downturn in the US defense budget. They have been seeking municipal, state and other government agency customers with limited success.

Several UAS manufacturers are developing lower cost tactical UASs to offer local surveillance at a lower price point in the hopes of selling to DoD, civil agency, municipal, and state customers. But nearly all producers are eagerly preparing for the opening of the National Air Space by the FAA with the eventual hope that this will pave the way for broader governmental and commercial usage of their products. The commercial, home and industrial robotics markets all have a wide range of domestic and international customers.

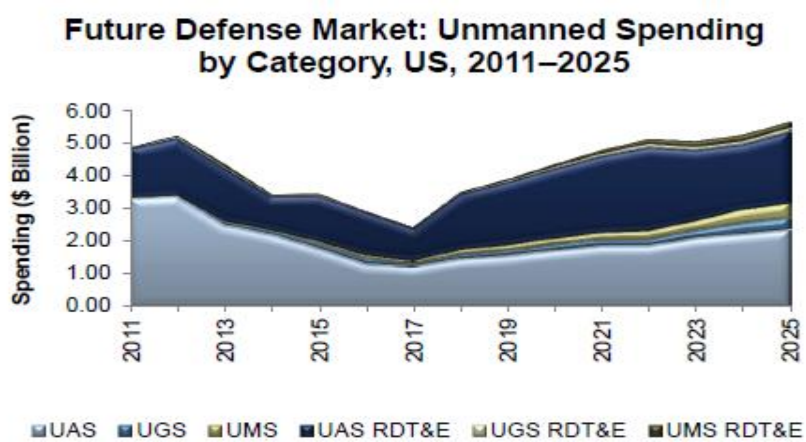


Figure 3– Source: Frost & Sullivan – Future Defense Market 2011-2025

Figure 3 indicates the level of investment in unmanned systems is low in comparison with overall DoD spending and is slated to decrease further over the short term. The funding for procurement and operations is planned to drop dramatically while research, development, test and evaluation funding will be more constant.

This means less money for new systems but adequate money to continue to work technological issues with respect to robotic and autonomous systems. The impact of sequestration or further budget reductions will drive prioritization and hard decisions on where to spend limited funds.

The UAS sector is currently dominated by US players, with Israeli firms also playing a prominent role. According to discussions with experts in the industry, future trends in the UAS market include: 1) a push for manned-unmanned systems; 2) systems that involve the distributed control of multiple UASs; and 3) the increased integration of commercial off the shelf (COTS) equipment into platforms and ground control stations.

Commercial UAS market development is largely on hold, pending rule changes and government review of privacy laws. Therefore, the commercial market is not expected to take shape before 2015 at the earliest, thus, delaying DoD's ability to leverage commercial technological gains in the near term.

Despite facing similar issues within the ground and maritime sectors, the unmanned industry for those two sectors is far more fragmented, smaller, and, in the case of the maritime, not dominated by US industry.

Compound Annual Growth Rates (CAGR)

The CAGR is one way to gauge an industry's potential. It is often used in the business and investing world to look at growth industries by dampening the volatility of periodic returns and instead focusing on longer term expected annualized rates of growth. CAGR estimates is one indication of the sustainability of a given industry or sector. According to a major international research and consulting firm, the interactive robotic industry as a whole is expected to have a CAGR exceeding 17% over the next several years.[20] Estimated CAGR for the various sectors are shown in the table below. Major shifts by a single large customer, such as DoD, could, of course, dramatically affect these numbers.

RAS Sector	CAGR (2010-2015)
Unmanned Aircraft Systems	4.7%[21] - 12% (though 2018)[22]
Unmanned Ground Systems	Subsector specific
Unmanned Marine Systems	6.77%[23]
Household: Home Care & Entertainment	(optimistically) as high as 52%[24]
Commercial: Medical (Robot Surgery Only)	14.9% (through 2016)[25]
Industrial: Manufacturing	5.5%[26]

Table 1: RAS Compound Annual Growth Rates (CAGR)

The future of the UGS sector is less certain. If only Explosive Ordnance Disposal UGSs are considered, the CAGR is expected to be negative over the next several years. If appliqués and automated automobiles are taken into account, the CAGR may be positive. Remote control appliqués to existing manned vehicles, as well as, the emergence of automated automobiles, could significantly affect the annualized growth of UGV market and enhance the list of new entrants into the market.

The commercial interactive robotics sector is expected to do quite well. Overall, personal interactive robots are expected to grow from the current installed base of around 2 million units to 16 million units by 2015, with 11 million of those units being for the cleaning and mowing market, valued at $4.8 billion.[27] There is expected to be an emergent sub-sector for home assistance or tele-presence robots as many researchers and robot manufacturers aim to capitalize on the large, graying population worldwide. "Sales of robots for elderly and handicapped assistance will be about 4,600 units in the period of 2012-2015. This market will increase substantially within the next 20 years."[28]

Shaping the Outlook: Lessons for the Future

Somewhat surprisingly, it was US companies, not Japanese firms, positioned to offer disaster assistance to Japan following the Fukushima meltdown - a result of the DoD-driven development of EOD robots. The Japanese found themselves unprepared because their robot technology development aimed primarily at industrial manufacturing and elder care. Three lessons can be learned from this event. First, disjointed development of point-solution robots has been prohibitively costly. Second, denying there are conditions and environments where robots and autonomous systems offer a reliable, safe and cost effective alternative to a manned approach risks abandoning promising technologies that might prove invaluable later. Finally, industry without government participation may not realize opportunities are being missed until it is too late.

With DoD's help, U.S. firms are positioned to do better. The DoD operates in some of the most challenging operating environments in the world. This represents both a persistent challenge to robot developers as well as a "call to arms." The challenges provided by "DARPA-hard" contests and real-life advances necessary to support combat operations have served as the catalyst for robotic technology innovation in the U.S. . Collaborative approaches leveraging business and academic research and help bring down costs, however, continue to remain more the exception than the rule.

A majority of the robotics and autonomous systems industry have not crossed the chasm to the mainstream market. All the technology, policies and awareness of the industry is not fully developed to make the leap. The majority of the advances to date have depended on government R&D funding, requirements, and interaction. The United States could consider ignoring this responsibility moving forward, but it risks relinquishing its lead in several key areas such as UASs and UGSs to other countries, much the same way it did with industrial robots in the 1970s allowing other countries such as Japan and Germany to capitalize on their development.

CHALLENGES

Within the RAS industry, there are several challenges affecting health and growth, thereby limiting the ability of each sector to cross the chasm from early development to mainstream production. These challenges include reduced defense budgets, limiting government regulations, technological limitations, cultural resistance and the lack of investment in domestic education programs.

Challenge No. 1: Reduced Defense Budgets. Throughout its history, the US Government has been the conduit for innovation in many US industries; the robotics industry is no exception. There are still significant technological challenges in robotics yet to be solved requiring focused effort and funding to ensure they are solved in the US. During periods of fiscal constraints such as the one the US is currently experiencing, it is a challenge to allocate federal funding to perform general purpose innovation research. Within the DoD budget "most of its R&D is devoted to the development, testing, and evaluation of weapon systems, and only about 12 percent of its R&D has gone for actual research (both basic and applied) in recent years." The more recent impact is shown in the below table which illustrates a 7.4% reduction in projected S&T funding for DoD in FY 2013. Any downturn in federal R&D funding will have an impact on a rapidly evolving industry such as robotics. Most of the companies in the robotics market are young, have relatively small revenues, and currently dependent on government funding. With the size of spending cuts that are anticipated in federal R&D budgets, a significant portion of these companies may cease to exist without a concerted push to avoid such reductions.

Challenge No. 2: Industry Standards, Interoperability, and Security Considerations. The DoD Unmanned Systems Roadmap 2011-2036, identified interoperability as a major challenge.[29] This challenge specifies the requirement to "operate seamlessly across all domains of air, ground, and maritime and also operate seamlessly with manned systems."[30] Closed architectures are generally not intended to be upgraded or changed by the end-user or other vendors which can lead to vendor-lock in.[31] Vendor lock-in makes the DoD dependent on a specific vendor for products and services which can lead to higher costs and barriers to entry in the market.[32] Interoperability standards allow more participants in the robotics and robotics component market increasing competition resulting in increased innovation, reduced barriers to entry and reduced costs. From a security perspective, open standards may simplify rogue actors' ability to insert malicious hardware or software into a robotics system through various places in the supply chain. The security problem in the cyber environment is magnified in robotic application because they have the ability to do physical harm. Additionally, the security in the communications links must be a top priority. Without a secure robot and a trusted communications link, DoD's use of robotics could be abolished with a lone hacker taking control and potentially degrading the public's trust and acceptance of military unmanned systems.

Challenge No. 3: Restrictive Government Regulation. There are a variety of laws, regulations, policies and procedures inhibiting the expanded use of robotic and autonomous systems beyond the DoD and limited commercial applications. Currently, unmanned systems and associated technology are in a United States Munitions List (USML) category limiting industry growth potential through US manufacturers' participation in international markets. Additionally, expanding the UAS market within the United States to other government agencies, state and local governments and commercial uses depends on the FAA opening the NAS to unmanned aircraft systems, currently planned for no earlier than 2015. Furthermore, many state and local governments have ordinances restricting UAS and UGS use due to privacy and/or safety concerns. Finally, the lengthy process for FDA approval of robots for medical use, taxes on medical devices or limited reimbursement under Medicare/Medicaid is limiting to the commercial-medical subsector. The various levels of government regulation restrict the industry to expand beyond the DoD into the commercial or international market.

Challenge No. 4: Cultural Resistance. The continued acceptance and fielding of robotic and autonomous systems will involve overcoming technological limitations but will require overcoming resistance at the individual, organizational and societal level. Operators and consumers have a distrust of robotic systems particularly autonomous features if they experience a lack of reliability or robustness compared to the perceived and/or advertised capabilities. The lack of trust and confidence in robotic and autonomous systems, competing priorities in a resource-constrained environment results in an unwillingness to transfer mission sets to unmanned systems. When new technologies are introduced into a society, there is a natural resistance due to lack of knowledge or understanding. This fear of the unknown results in the evolution of legal, political, and cultural barriers.

Challenge No. 5: STEM. Our ability to "pioneer" in the field of robotics and autonomous systems as well as other technology sectors, relies on a strong scientific, technical, engineering, and math savvy community of experts—our "STEM" capital. Technology-heavy industry sectors rely on STEM graduates and their research. Unfortunately, funding for our STEM educational institutions, a key cog ensuring strong research and development (R&D) in leading-edge industries such as robotics, continues to decline. Not only are our universities struggling but also the number and quality of K-12 grade teachers and students pursuing STEM pathways are decreasing. We are a "laggard"[33] in K-12 STEM education producing *smaller cohorts* of significantly *lower quality* high school graduates as measured across [34] developed countries by the Organization for Economic Cooperation and Development (OECD). Furthermore, having a robust STEM education program will be required to train and educate workers displaced by robotic systems.

GOVERNMENT GOALS AND ROLE

There are actions the DoD and greater US government can take in order to address the challenges facing the robotics and autonomous systems industry. The goal of that action is not to make the industry more dependent on the US government for its success. The goal is to make the industry more competitive in the global market and less dependent on the US government. The current and future budget restrictions will preclude the large investments in robotics experienced over the last decade. New market, both foreign and domestic, must be developed to make the shrinking revenue from the US government. Furthermore, there are still "DARPA-hard" technology challenges to be solved in order for robotics to be more reliable and useful.

Addressing Industry Challenges: The challenge in these austere times is identifying the source of these necessary resources. Congress and DoD must look for non-traditional means of funding future innovation. **Amend the Bayh-Dole Act to allow the US government to obtain a small royalty from commercial industry for profitable patents derived from government-funded research.** The Bayh-Dole Act is the federal patent policy allowing recipients of federal funds who invented a product or process the opportunity to hold title to the item and realize gains from transferring it to commercial channels. The technology for Intuitive Surgical's minimally invasive da Vinci® surgical system originated with DARPA funding. It is now a profitable 25 billion dollar market capable of providing a small royalty back to the government. The royalties obtained by the government would be reinvested in future R&D grants thus, reducing the burden on the taxpayer to fund R&D that ultimately benefits industry.

Programmatically, the DoD should continue its discussion and engagement with industry and academia. **Although already occurring with varying degrees of intensity and priority, the Services, in collaboration with DARPA, Joint Staff and OSD, should maintain a constant dialogue with industry and academia.** This dialogue would ensure DoD agencies are cognizant of the latest technological development efforts. Industry and academia would gain increased and up to date understanding of DoD needs, priorities, and interests.

The improved mutual understanding will enable DoD to **focus government R&D funding to address gaps and opportunities among Service efforts.** These efforts should be focused on the "DARPA-hard" problems. Addressing the security vulnerabilities inherent with efforts towards standardization and open architecture in robotic systems is a good example of a "DARPA-hard" problem requiring focused funding. In addition to addressing the standardization challenge, there are governmental opportunities to address cultural resistance and the impacts of system 'trust,' reliability, and potential liability. DoD, in particular DARPA and other research agencies, should prioritize and resource efforts to address robotic/autonomous system liability and weaknesses in the information technology security and cyber domains to foster trust and demonstrate increasing levels of autonomy, reliability, and robustness. Besides enhancing the robotic industry, this same technology can be used in other military and civilian applications. The goal of government in this aspect is to provide an environment for domestic industrial innovation while protecting public networks and critical infrastructure.

In the context of government regulations, two efforts are of significance to the RAS industry--opening the NAS and reforming ITAR. The first effort has a direct impact on the UAS market. The FAA Modernization and Reform Act of 2012 (FMRA) directed the FAA to integrate UASs into the NAS by September 2015. The ability to exploit the integration of UASs into the NAS will assure US dominance in this sector. The government role, with the FAA as the lead, is to develop regulatory guidelines to integrate this emerging technology into contemporary society to protect citizens, yet acknowledge and facilitate emerging RAS technology exploitation and evolution into commercial applications. Based on recent combat use and experience the DoD is a direct stakeholder in this effort. With the impending loss of the combat theatre for experimentation, the DoD should be an advocate and technical expert helping the FAA address the issues connected with opening the NAS.

Second, the Departments of State and Commerce, in coordination with multiple other agencies are reassessing commercially produced US military products and systems that are currently restricted for international sale per the International Traffic in Arms Regulations (ITAR).

This effort is important to expanding foreign markets for the RAS industry. We are currently the technology leader in many robotics markets including UAS, UGS and medical systems. By reducing US government restrictions on foreign sales, our domestic defense industrial base partners can more easily compete in the global market. The revenues and growth from the expanded market will make up for the loss of US government revenue ensuring the industry's viability into the future. The DoD performs a supporting role in the ITAR review and modification process.

Finally, to mitigate K-12 STEM education shortfalls to support future development in the industry, **DoD should make a portion of its limited discretional funding available for priority STEM initiatives, to include robotics and autonomous systems.** Continued investments by DoD in R&D on the far left side of the "chasm" are imperative to improve our current and future innovative talent base. The DoD must focus on supporting efforts for improvement in the national STEM education pipeline to generate the innovators required to overcome future asymmetric and disruptive threats. The allure of robotics is a dual-use opportunity and potential catalyst (i.e., the new "Sputnik moment") to address this national challenge while helping maintain a US military and commercial technological edge.

CONCLUSION

The Robotics Industry, and the technological innovations and advances associated with autonomous systems, are at substantial risk in the current fiscal environment. As discussed above, this fragmented and diverse industry has primarily been fueled by Government investment and driven by DoD need. Primary breakthroughs in government as well as medical (Da Vinci) and commercial (Roomba) sectors have been the result of DARPA and DOD research facility investments.

Without continued US Federal involvement in RAS, only a small minority of robotics companies can be expected to survive, likely the larger ones that can weather the Government cutbacks and successfully cross their products into commercial applications. For UASs, "crossing the chasm" will rest heavily on FAA approval of airspace usage. For other Government unmanned systems, ITAR restrictions will need to be addressed to facilitate entry into the larger global market as the US domestic market shrinks.

With decreasing government budgets, there needs to be targeted government leadership and direction in autonomy and robotics. R&D funding needs to be not only maintained, but in some areas, redirected and increased. Open standards and interoperability need to be a primary theme in the next generation of robotics advancements. Security can no longer be an afterthought for this industry. Investment in human capital needs to become prevalent in STEM outreach, recruitment, and enhancement. Government and DoD need to be strong proponents and leaders in the Robotics and Autonomous Systems Industry. Otherwise, the US risks losing already achieved technical advantages and foregoing the just-over-the-horizon breakthroughs that could enhance US national security.

ESSAYS ON MAJOR ISSUES AND TOPICS

CULTURE TRUST AND LIABILITY

The continued acceptance and fielding of robotic and autonomous systems will involve overcoming technological limitations as well as resistance at the individual, organizational, and societal levels. Individual resistance to robotic and autonomous systems is typically based on a lack of trust and confidence and a perceived threat to individual utility and livelihood. At the organizational level, the new systems represent competition for finite resources and challenge concepts of organizational identity. Societal resistance stems from a fear of the unknown and results in the creation of legal, political, and cultural barriers.

Individual resistance is not consistent across all sectors of robotics but varies with the maturity and application of the technology. It has been most visible in the use of UGVs and industrial robots. When presented with systems with autonomous capabilities, operators expect 100% assurance the robotic system will do only the directed tasks and nothing more. Without that assurance, the operators do not want and will not trust the robotic capabilities of the system. At present, robotic systems are generally used in a tele-operated mode with a human operator providing direct commands to the system via a wired or wireless communications link. Difficulties in understanding how autonomous systems work, in trusting robots to do what they are designed for (and nothing more), and in learning how to interact with robots are some of the obstacles that need to be overcome in order to cross the chasm from early market adopters to mainstream employment. As RAS proliferates, the user will be an average person, not a robotics specialist, trying to accomplish tasks at home and work. Therefore, interfaces between humans and robots should be easy to use, familiar, and intuitive.[34]

Individuals also fear losing their jobs to robots. This perception has been fueled by recent media coverage and misinformation from organizations whose purposes are aligned with the status quo. While robotic and autonomous systems have replaced some low skill labor and are expanding into skilled labor fields such as education and healthcare, it has not resulted in a comparable increase in overall unemployment. Conversely, increased opportunities in technical fields supporting the expansion of robotics including programming, microelectronics, and specialized manufacturing have emerged.[35] According to most companies the RAS Industry Study met with, the incorporation of robotic systems typically supports business expansion and results in fewer new hires, and does not necessarily result in the replacement of existing workers.

Organizations have to determine the best way to integrate robotic and autonomous capabilities to preserve organizational identity and to ensure efficient resourcing. This has been particularly true with respect to UASs in the US Air Force. In 1985, after the Air Force negatively reacted to the apparent capability of QF-4 Phantom unmanned target drones to fight back and occasionally win in air-to-air combat training, the system's maker, Robert Finkelstein of Robotic Technology Incorporated, observed, “The Air Force was terrified of unmanned planes. You know, the whole silk scarf mentality. Pilots are what become generals, not anyone else....”[36] While UASs have been wildly successful in supporting operations in Iraq, Afghanistan, and other operating areas during the war on terrorism, some senior military leadership argue UASs are not good for anything else and thus unsuitable for near-peer combat operations in the future.[37] The organizational resistance to UASs is evident in the fifteen percent lower promotion rate for UAS pilots compared to other career fields despite clear contributions to wartime success.[38]

In addition to challenging what an organization stands for or holds important, robotic and autonomous systems provide direct competition for scarce resources. While UASs have been incredibly effective in combat over the last decade, they are not inexpensive. At $25,000 to $100 million a copy, depending on the UAS system, effective systems like Reaper and Global Hawk funnel resources away from manned programs like the F-35 and KC-46. Without continued funding for operations or R&D, the current systems will decline in capability and reduce their effectiveness in the future. The competition from UASs for resources is not just an Air Force issue. "In the Navy, funding is scarce for UAS R&D, which is often shortchanged in favor of flashy physics-based systems like the magnetic rail gun or laser programs. Of six innovative naval prototype projects at ONR, only one is focused on autonomy and robotics.

As robotic and autonomous systems overcome resistance at the individual and organizational levels, they still face wider societal barriers. When new technologies are introduced into society, there is a natural resistance due to lack of knowledge or understanding. This fear of the unknown results in the creation of legal, political, and cultural barriers. The President of the Association for Unmanned Vehicle Systems International recently stated, "While unmanned aircraft have been hugely successful in the military market, they have had a tougher time expanding their domestic applications in areas such as law enforcement. The barriers are not technological but regulatory."[39] Furthermore, there are still pending issues regarding product liability for commercial applications of unmanned and autonomous systems. A comprehensive legal framework is necessary to include regulatory, statutory, and company-driven changes, which will not only encourage manufacturers to take safety precautions with the machines and systems they are developing, but also protect consumers and promote innovation.

Beyond explicit safety-related laws and regulations regarding the commercial use of robotic and autonomous systems, there are political debates about the impact of such systems on ethics and personal rights. The increased use of unmanned systems in warfare has sparked a political debate about the ethics of such use. Will the increased use of robots make it easier and cheaper to wage war and thus make war more likely? Within the current laws of armed conflict, where does responsibility fall if unmanned or autonomous systems seriously malfunction? Additionally, there are political and value concerns with the employment of certain robotic technology. Recently, the US Senate held a hearing to discuss privacy concerns. During the hearings, the Senators seemed unaware of the current state of unmanned technology.[40] It will take time for the politicians to determine how unmanned systems differ from similarly employed manned systems, what new rules or laws are required and which entity (federal or state) should make the rules. With the reduction of DoD budgets, some companies may struggle to survive while these political and ethical questions are addressed.

THE COMING CRISIS IN STEM EDUCATION

Our ability to "pioneer" in the field of robotics and autonomous systems as well as other technology sectors, relies on a strong scientific, technical, engineering, and math savvy community of experts—our "STEM" capital. Technology-heavy industry sectors rely on STEM graduates and their research. Unfortunately, funding for our STEM educational institutions, a key cog ensuring strong R&D in leading-edge industries such as robotics, continues to decline. According to the Association of American Universities, public university funding has dropped hundreds of millions of dollars to help offset state fiscal liabilities estimated as high as three trillion dollars.[41] According to Norman Augustine, Chairman of the National Academy of Science's "Rising Above the Gathering Storm" Committee, federal R&D funding in the STEM arena has dropped 60% over the last four decades due to similar budgetary pressures.[42] In his 2006 State of the Union address, President George W. Bush declared the availability of our cadre of scientists, engineers, and mathematicians, key to our nation's capacity to innovate.[43] Unfortunately, not only are our universities continuing to struggle but also the number and quality of K-12 grade teachers and students pursuing STEM pathways are decreasing. We are a "laggard" in K-12 STEM education producing smaller numbers of significantly lower quality high school graduates as measured across 34 developed countries by the Organization for Economic Cooperation and Development (OECD).[44] Despite widespread agreement within government that STEM education is vital to our nation's economic health, budgetary pressures on R&D and a weak supply of STEM students threatens our nation's strength.[45]

For our nation to remain secure, we must invest in a diverse STEM workforce that can innovate and rapidly develop solutions to asymmetric threats. As Defense Secretary Hagel mentioned in his first public speech at National Defense University on 4 April 2013, DoD must let go of Cold War structures and weapons so it can be prepared for very different conflicts. Yes, the United States has a shortfall in STEM education writ large, but GAO's recommendations in a 2012 paper[46] advocating aligning programs and working to a strategic plan are achievable. Basic R&D is a public good in which the government has historically been the leader. It is imperative that R&D investments improve to maintain our innovative talent base.

Robotics and autonomous systems provide a compelling STEM catalyst to motivate our youth as they choose career paths in industry, academia, or government. Hummingbird-size air vehicles, autonomous cars, undersea mappers, and interplanetary space rovers should inspire and captivate technological talent. The President's National Robotics Initiative to develop robots that assist and interact with humans excite seasoned scientists as well as aspiring young scientists—manned-unmanned teaming is the kind of STEM challenge that generates student interest. Robotics generates a high curiosity factor.

Our nation's security depends on its ability to lead the world in innovative technology R&D. Robotics R&D feeds our economic engine bringing jobs, prosperity, and world standing. But, robots that inspire students to pursue STEM related fields bring much more than technical prowess and the cool factor to our shores. The same STEM experts that pioneer the hard problems of autonomous robotics are the same experts that will move our technological frontiers forward and build our "bank" of innovation required to preserve national security.

INNOVATION AND R&D FUNDING

Throughout its history, the Government has been the conduit for innovation in many US industries, supporting most of the nation's fundamental research focused on gaining knowledge irrespective of a specific application. The robotics industry is no exception to this rule. During the course of the RAS Industry Study Program, one theme that has been prevalent in visits with companies in the robotics market is the impact government has played in initiating innovation, particularly DoD. In the case of DoD, R&D spending for basic and applied research is typically associated with furthering advancements in weapons system technology, allowing the US military to maintain its advantage as a premier power. Such funding sometimes spurs technology advancements that are of significant commercial benefit. In many of these cases the transfer of DoD-funded technology to the commercial sector has resulted in industry's proliferation and financial profit of the technology. This is best exemplified in the information technology sector with the advent of the internet, the start of which began with DARPA funding and ended in what we now know as a global network. This case underscores the benefit that the commercial sector derives from government "seed" investments.

Despite such successes, during periods of fiscal drawdown including the current sequestration, it becomes challenging to identify federal funds to perform general purpose innovation research. Within the DoD budget "most of its R&D is devoted to the development, testing, and evaluation of weapon systems, and only about 12 percent of its R&D has gone for actual research (both basic and applied) in recent years".[47] Because such fundamental research is not supported by significant private sector investments due to the anticipated lack of sufficient financial returns, federal support of basic research is vital to long-term national interests.[48]

While the US was the leading innovator in the industrial robotics field at its onset, a lack of continued government support to push the industrial robotics sector past the "chasm" led to low profits and limited industry investment. Consequently, the market share for US industrial robotics manufacturers was driven down to the point that, by 1990, over 80% of robotics orders were filled by imports.[49] Today, the US manufacturing sector, including the defense industry, the automotive industry, and assorted other manufacturing industries, have come to rely on imported industrial robotic technology primarily from Japan, Europe and Korea in order to stay viable. "While the European Union, Japan, Korea, and the rest of the world have made significant R&D investments in robotics technology, the US investment, outside unmanned systems for defense purposes, remains practically non-existent".[50] While there are pockets of federal funding such as the National Robotics Initiative (NRI), there is a lack of a cohesive US robotics strategy to help bring focus to the industry. Many of the companies in the robotics market are young, have relatively small revenues, employ a limited number of technically advanced STEM employees, and rely, in part, on federal funding to perform innovation research. These factors make them highly vulnerable to revenue reductions. With federal spending cuts on the horizon, including federal R&D budgets, a significant portion of these companies may cease to exist without a concerted push to avoid such reductions. Not only will such cuts result in the robotics industry being placed further at risk of becoming irrelevant, it could result in a major lost opportunity for the US economy as it gives up its standing in the robotics market to other nations committed to the industry. This is an unacceptable outcome for an industry, which in many subsectors has yet to "cross the chasm," particularly given that robotics has been identified as critical to US national security by the current administration.

US industry leads the rest of the world in air and ground robotics largely due to the influx of funding into development during the Iraq and Afghanistan wars. However, as those wars have begun to wind down, so too is the funding that has helped develop robotics technology. It would be a major error on the part of Congress and the US Government, particularly DoD, to fail to sufficiently fund R&D for robotic innovations going forward. The challenge in these fiscally constrained times is identifying the source of these funds. Congress and DoD must look for non-traditional means of funding future innovation. There should be an established means by which the government can replenish its basic and applied research funds. One such method of recouping funds would be to obtain royalty-like payments from industry when it commercializes and profits from government funded innovation. While the government is a non-profit entity, small royalty revenues from government-funded patents could be obtained for the exclusive purpose of re-investing in innovative research.

Such a proposition would require an amendment to the Bayh-Dole Act, which revised federal patent policy to allow recipients of federal funds who invented a product or process the opportunity to hold title to the item and realize gains from transferring it to commercial channels. The change would merely be that the US government would be entitled to a small royalty from these patented products to be used exclusively for innovation research; thus, reducing the burden on the taxpayer to fund R&D that ultimately benefits industry. This solution would serve to stimulate fragile US industries, such as the robotics industry which are primarily performing in a high risk basic research environment, helping it to effectively "cross the chasm" in those subsectors still constrained by technological challenges. "Given that the world is moving to more sophisticated and more complex products, wages and growth go to the people who master that…and ultimately you have two choices: You can basically decide that you're going to invest in the way that we're describing, and build these industries in America, or you can permanently give them up to somebody else".[51]

OPEN ARCHITECTURE AND SECURITY

Many believe the robotics is a "gold mine" poised to explode by 2025 where "the robotics industry might rival the automobile and computer industries in both dollars and jobs."[52] The Department of Defense could facilitate making robotics the next big industry. The DoD's influence on robotics is similar to its influence on the computer industry in the 1970s. For example, The DoD, in concert with industry, led the invention of a standard computer language called "COBOL" enabling computer programming by people other than just computer scientists.53 The DoD also enabled the development of the Transmission Control Protocol/Internet Protocol (TCP/IP) protocols, which became the standard for communications between computers as well the internet.[54] This essay will discuss the benefits of open architecture, key information technology (IT) and emerging robotic standards, and the DoD's role in future developments.

Open architecture is a type of hardware and software framework designed to make adding, upgrading, and swapping components easy.[55] Across all the sectors of the robotics industry, there are proprietary hardware and software systems that bind consumers to a specific vendor, leading to higher costs for the customer and barriers to entry in the market.[56] A balance needs to be achieved between improving the technology, removing barriers while allowing innovative companies to be competitive, and reducing the overall cost to the DoD. A computer is a good example of a modular system because the individual parts inside the system such as the hard drive, memory, DVD drive, and even software, can be upgraded with relative ease. The external components (keyboard, mouse, printer, and monitor) can be changed even easier. Continued US Government (USG) investment and guidance to utilize open standards will drive development of modular robotic hardware.

Three key benefits of an open architecture are recognized by the DoD in the Unmanned Systems Integrated Roadmap FY2011 – 2036: "to enhance competition, lower life-cycle costs, and provide warfighters with enhanced unmanned capabilities that enable commonality and joint interoperability on the battlefield."[57] Although open architectures are mandated in the roadmap, an open architecture needs to be more than just open, it needs to evolve into a standard where everyone uses it to fully realize the stated benefits. To fully achieve the advantages in cost savings, interoperability, and optimization, programs need to utilize the same set of standards. Open architecture evolves into industry standards when standards are adopted and utilized by the majority of the industry. Some key principals of the best standards are "cooperation among standards organizations, transparency, balance and openness in standards development, commitment to technical merit and interoperability, availability of standards to all, and voluntary adoption."[58]

Standards in the computer industry have allowed that industry to flourish. Two standards almost everyone in the world uses are the Universal Serial Bus (USB) and Transmission Control Protocol/Internet Protocol (TCP/IP). The USB standard is completely industry driven while TCP/IP was led by the DoD. . These global standards exemplified the power of open standards in action,59 are market-driven, and are not confined by companies or even national boundaries.60 Governance bodies keep these standards relevant as technology changes. These standards allowed the IT industry to flourish. . They have reduced the barriers to entry for innovative companies to create everything from CD ROM drives to fiber optic Christmas trees, and all of it can come connected to whatever computer (i.e. Apple or PC) the users has.

The Willow Garage Robotic Operating Systems (ROS) and Microsoft Robotics Developer Studio (RDS) are emerging as key software tools to control robotic devices. ROS provides a baseline suite of open source reusable software programs to help facilitate development on their PR2 Robot. While some companies visited felt ROS needed some improvement for large-scale use, most agreed it provides a significant benefit for training new developers and programmers. RDS provides a software suite to help developers use sensors. The Microsoft Xbox game controller, the Kinect sensing system, and the smart phone are rapidly becoming great examples of de-facto robotic industry standards that emerge because of their relative low cost and ease of use. These types of tools, "lead to a paradigm where hardware costs are greatly reduced, and software and hardware architectures that are modular and extensible leading to more robust robots by facilitating rapid design-test-re-design iterations."[61] It is easier to train robotic programmers, software reuse allows programmers to focus on the unsolved problems quicker, and powerful hardware tools (such as the smart phone) are within the consumers reach – three critical factors of the tipping point for significant progress in robotics.

Within DoD the most prominent initiative to mandate open standards is the AEODRS program. AEODRS aims to develop a system capable of being developed by independent entities through a competitive procurement process limiting or eliminating vendor lock-in. These systems will have modular "plug and play" components, maximize business competition, and foster new and innovative ideas.[62] Reducing vendor lock-in for the entire system will potentially reduce future upgrade costs while simultaneously reducing the barriers to entry for companies who may just want to work on one part of the robot (i.e. the sensors). Additionally, a significant amount of work has been done to develop standards for communicating with the robot. Some key military examples include the NATO Standardization Agreement (STANAG) 4586 and the Joint Architecture for Unmanned Systems (JAUS). STANAG 4586 standardizes the ground control interfaces for UAS to help enable systems interoperability.[63] JAUS was developed for Unmanned Ground Vehicles (UGVs). However, both standards are now being applied to multiple types of unmanned systems and are unfortunately duplicating effort and overlapping.[64]

While these efforts show tremendous progress, robust security remains problematic. One leading researcher commented that a robot using standard wireless encryption could be hacked in less than an hour. Once the communication lines were hacked, the hacker can gain full control of the robot and all of the associated systems (sensors, movement, and manipulation). Certainly, the DoD has more sophisticated encryption techniques than a standard wireless connection; however encrypting the communications links will only provide so much protection. Many robotic interfaces are built on current information technology standards (such as Ethernet), which are known to be inherently insecure. As the industry moves towards open architecture and mass production of robotic parts, security will become an even greater concern. Security in the robotic field is vastly more important than in the arena of IT because robots exist in the physical world. A computer virus may delete important data, steal money from your virtual bank account, or deface a website; however, a robotic virus can physically injure or even kill people. A more secure interoperability standards needs to be found.

Many "DARPA hard" problems remain to be solved before the industry can truly take off. Computer security has always been important, but cyberspace became a battleground when computers were all connected together. The same will hold true in robotics. Before we can fully implement swarming, real time common operational pictures for all operators based on all sensors on the battlefield, and armed or fully autonomous robots, the security problem must be fixed. While traditional IT interfaces have pushed the robotics technology as far as it has, insertion of a discontinuous technology that could ensure security while being affordable may in fact be the last factor for robotics to take off in the commercial sector as well as other areas in DoD. If the USG, in concert with academia and industry, can solve the immense security problem, applications across the entire global economy (not just robotics) become viable. The DoD is positioned to make the next great leap forward like when it enabled the creation TCP/IP.

The USG should continue to invest and encourage industry to utilize open architectures and develop industry standards to enable a modular system. These standards will take a few years to develop because solving some of the most difficult problems (i.e., 3D vision, high-dexterity manipulation, high-fidelity sensors, and intuitive human-robot interaction) are happening now. Many of these technological issues are "dual-use," meaning they can be used to satisfy both military and commercial goals and objectives.[65] The DoD should not constrain innovative to a standard too soon, without the proper governance structure to update the standards as the technology matures. The goal should be voluntarily adopted standards because having open standards or even a single organization defining standards does not guarantee future compatibility or interoperability.[66]

The Department of Defense has been directly responsible for phenomenal technical advances in the IT industry from software programs to interface standards that enabled the industry to grow. Technological advancements are being made very rapidly in the robotics field, but they still lack the common standards that will launch the industry. The DoD needs to aggressively work the problem from two fronts: work with industry to create modular "plug and play" hardware platforms and upgrade the security baseline. It will take leadership to develop and enforce the configuration the wartime environment requires. The DOD has the opportunity, maybe even the responsibility, to shape the coming robotic future.

Industrial Robots

Competition:

1: Low – established companies

Threat of entrant:

1: Low – High cost

2: Med – Many new small/mid companies

Threat of substitutes

Low – Proven efficient technology

Power of buyer

1: Low

Power of suppliers

1: Low

Interactive Robots Commercial

Competition:

Low – Few companies in each market segment

Threat of entrant:

Low – High cost, regulatory barriers, especially in medical segment

Threat of substitutes

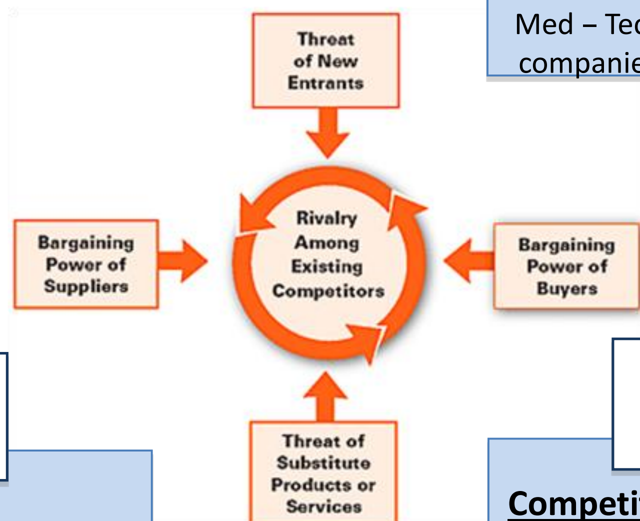
Med – Many low-cost/low-tech capabilities exist with human-operators

Power of buyer

High – Ability to substitute, demand lower price for service or product

Power of suppliers

Med – Technical expertise limited, some companies use single-source supplier



Interactive Robots Home

Competition:

Med – global market/diverse products

Threat of entrant:

Low – High price point limits ability to achieve economies of scale in production

Threat of substitutes

High – human-operated products sometimes better and cheaper

Power of buyer

High – Many substitutes, can demand lower price for product or service

Power of suppliers

Low – Many substitutes

Interactive Robots Government

Competition:

Low – existing programs of record, fewer research $$$, very few new programs

Threat of entrant:

1: High – low-tech, many possibilities

2,3,4: Low – high cost, very tight DoD $$

Threat of substitutes

1,3: High – low-tech manned capabilities

2,4: Low – proven tech, replaces humans

Power of buyer

High – DoD/Govt funding of R&D

Power of suppliers

1,2,3: Low – integration

4: High – single-source, high-tech parts, few companies

1: Ground
2: Air
3: Maritime
4: Space

ENDNOTES

[1] Geoffrey A. Moore, *Crossing the Chasm: Marketing and Selling High-tech Products to Mainstream Customers* (New York: HarperCollins E-books, 2009), Kindle edition.

[2] Bill Gates, "A Robot in Every Home," *Scientific American* (January 2007) http://www.scientificamerican.com/article.cfm?id=a-robot-in-every-home (accessed April 16, 2013).

[3] Wolfgang Heller, ed., "Crossing the Robotic Chasm," *Robotland* (blog), October 25, 2011, accessed May 14, 2013, http://robotland.blogspot.com/2011/10/crossing-robotic-chasm.html.

[4] Martin Wilcox, comment on "Crossing the Chasm (Geoffrey Moore)," *The WHY Organization* (blog), September 15, 2009, accessed May 13, 2013, http://blogs.knowledgegenes.com/2009/09/crossing-the-chasm-geoffrey-moore-coded-by-martin-wilcox.html.

[5] Lucintel, *Growth Opportunity in Global UAV Market*, issue brief (Las Colinas, TX: Lucintel, 2011), accessed May 15, 2013, www.lucintel.com/LucintelBrief/UAVMarketOpportunity.pdf; and Josh McBee, *Unmanned Aerial Vehicle (UAV) Manufacturing in the US*, Industry Report (June 2012), accessed May 8, 2013, IBISWorld (OD4424).

[6] Jeremiah Gertler, *U.S. Unmanned Aerial Systems*, report no. R42136, January 3, 2012 (Congressional Research Service), accessed March 23, 2013, http://www.fas.org/sgp/crs/natsec/R42136.pdf.

[7] Ibid.; and McBee, *Unmanned Aerial Vehicle (UAV) Manufacturing in the US.*

[8] Michael W. Isherwood, "Unmanned Systems and the Joint Team," *Unmanned Systems and the Joint Team*, no. 58 (3rd quarter 2010): 58, http://www.ndu.edu/press/unmanned-systems.html.

[9] Valerie Insinna, "Sequester Looms over Unmanned Vehicle Conference," *National Defense Magazine*, February 12, 2013, accessed March 24, 2013, http://www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?List=7c996cd7-cbb4-4018-baf8-8825eada7aa2.

[10] iRobot, "iRobot First-Quarter 2013 Conference Call Script," news release, April 24, 2013, iRobot Investor Relations: News and Events, accessed May 14, 2013, http://investor.irobot.com/phoenix.zhtml?c=193096&p=irol-eventDetails&EventId=4897482.

[11] Defense Systems Staff, "QinetiQ to Furnish Talon Robot to Czech and Polish Militaries," Defense Systems, November 28, 2012, accessed May 14, 2013, http://defensesystems.com/articles/2012/11/28/qinetiq-talon-robot-central-europe-sales.aspx.

[12] Antoine Martin, "U.S. Expands Use Of Underwater Unmanned Vehicles," *National Defense Magazine*, April 2012, accessed May 2, 2013, http://www.nationaldefensemagazine.org/archive/2012/April/Pages/USExpandsUseOfUnderwaterUnmannedVehicles.aspx.

[13] "Service Robot Statistics: World Robotics 2012 Service Robots," International Federation of Robotics, accessed April 26, 2013, http://www.ifr.org/service-robots/statistics.

[14] "Consumer Robotics Market to Reach $6.5 Billion in 2017, While More Complex Personal Robots Lay Just Out of Reach," ABI Research, April 8, 2013, accessed May 14, 2013, http://www.abiresearch.com/press/consumer-robotics-market-to-reach-65-billion-in-20.

[15] "Envisioning the Future of Robots in Surgery, Drug Delivery, and Beyond," Medical Design Briefs, May 1, 2011, accessed May 14, 2013, http://www.medicaldesignbriefs.com/component/content/article/9925.

[16] "Industrial Robot Statistics," International Federation of Robotics, accessed March 24, 2013, http://www.ifr.org/industrial-robots/statistics/.

[17] Ibid.

[18] Veronica Franco, "Market Research Projects Industrial Robotics Market at $33 Billion by 2017," Yahoo! Finance: Market Wired, July 12, 2012, accessed May 8, 2013, http://finance.yahoo.com/news/market-research-projects-industrial-robotics-100800260.html.

[19] "Industrial Robot Statistics."

[20] Paul Chapman, "Service Robotics Market to Grow at a CAGR of 17.4%," Companies and Markets.com, July 12, 2012, accessed May 8, 2013, http://www.companiesandmarkets.com/News/Information-Technology/Service-robotics-market-to-grow-at-a-CAGR-of-17-4/NI4304.

[21] McBee, *Unmanned Aerial Vehicle (UAV) Manufacturing in the US.*

[22] "U.S. Military Unmanned Aerial Vehicles (UAV) Market Forecast 2013-2018," Market Research Media, April 9, 2013, accessed May 8, 2013, http://www.marketresearchmedia.com/?p=509.

[23] *Global Underwater Robotics Market 2012-2016*, report (TechNavio, 2012), accessed May 8, 2013, http://www.marketresearchreports.biz/analysis-details/global-underwater-robotics-market-2012-2016.

[24] "MarketsandMarkets: Global Service Robotics Market Worth U.S. $21 Billion by 2014," MarketsandMarkets, accessed May 8, 2013, http://www.marketsandmarkets.com/PressReleases/robotics.asp.

[25] "Industry Snapshots: OD4074 - Robotic Surgery Equipment Manufacturing," IBISWorld, accessed April 26, 2013, http://www.ibisworld.com/snapshot/industry/default.aspx?page=industry.

[26] "Industrial Robot Statistics."

[27] "Service Robot Statistics: World Robotics 2012 Service Robots," International Federation of Robotics, accessed April 26, 2013, http://www.ifr.org/service-robots/statistics.

[28] Ibid.

[29] United States, Department of Defense, *Unmanned Systems Integrated Roadmap FY2011-2036*, Corrected Copy Approved for Publication, Reference Number: 11-S-3613 (Washington, DC), 5, http://www.acq.osd.mil/sts/docs/Unmanned%20Systems%20Integrated%20Roadmap%20FY2011-2036.pdf.

[30] Ibid.

[31] Eric M. Nelson, *Open Architecture: Technical Principles and Guidelines*, technical paper, OSR Case 07-S-2723 v. 1.5.8 (IBM Federal CTO Office, September 30, 2008), 8, https://acc.dau.mil/adl/en-US/170302/file/38742/OA%20Architectural%20Principles%20and%20Guidelines%20v.1.5.8.pdf.

[32] Katherine Noyes, "Want Freedom from Vendor Lock-in? Survey Says: Choose Open Source," PCWorld, May 25, 2012, http://www.pcworld.com/article/256189/want_freedom_from_vendor_lock_in_survey_says_choose_open_source.html.

[33] Ibid.

[34] Michael Barnes and A. William Evans, "Soldier-Robot Teams in Future Battlefields: An Overview," in *Human-robot Interactions in Future Military Operations*, ed. Florian Jentsch and Michael Barnes (Burlington: Ashgate Publishing Company, 2010), 11.

[35] Robert Skidelsky, "Rise of the Robots: What Will the Future of Work Look Like?," The Guardian, February 19, 2013, accessed April 16, 2013, http://www.guardian.co.uk/business/2013/feb/19/rise-of-robots-future-of-work.

[36] P. W. Singer, *Wired for War: The Robotics Revolution and Conflict in the Twenty-first Century* (New York: Penguin Press, 2009), 54.

[37] Dan Parsons, "Aerial Drones Face Mounting Pressure From All Directions - Blog," *National Defense Magazine*, April 2013, accessed April 15, 2013, http://www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?ID=1059.

[38] Ibid.

[39] Sandra I. Erwin, "Drone Manufacturers Aim to Change Image - Blog," *National Defense Magazine*, February 15, 2013, accessed April 15, 2013, http://www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?ID=1060.

[40] Tom Curry, "Lawmakers Voice Concerns on Drone Privacy Questions," NBC Politics, March 20, 2013, accessed April 17, 2013, http://nbcpolitics.nbcnews.com/_news/2013/03/20/17389193-lawmakers-voice-concerns-on-drone-privacy-questions?lite.

[41] Ken Stier, "States Prove Weak Link in Supporting Research Universities," Pacific Standard, August 5, 2011, accessed May 14, 2013, http://www.psmag.com/education/states-prove-weak-link-in-supporting-research-universities-34687/.

[42] Rising Above the Gathering Storm Committee (U.S.) Staff, National Academy of Sciences (U.S.) Staff, and National Academy of Engineering (U.S.) Staff, *Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5* (Washington, DC: National Academies Press, 2010), In ebrary.

[43] George W. Bush, "State of the Union Address 2006," The White House: The State of the Union, January 31, 2006, accessed May 14, 2013, http://georgewbush-whitehouse.archives.gov/stateoftheunion/2006/.

[44] Rising Above the Gathering Storm Committee (U.S.) Staff, National Academy of Sciences (U.S.) Staff, and National Academy of Engineering (U.S.) Staff, *Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5*.

[45] Senate, Committee on Commerce, Science, and Transportation, *Five Years of the America COMPETES Act: Progress, Challenges, and Next Steps: Hearings before the Committee on Commerce, Science and Transportation*, 112 Cong., 2d sess., S. Doc., September 12, 2012, http://www.commerce.senate.gov/public/index.cfm?p=Hearings&ContentRecord_id=cb59b16e-886e-4622-8d41-613e8c1167a6&ContentType_id=14f995b9-dfa5-407a-9d35-56cc7152a7ed&Group_id=b06c39af-e033-4cba-9221-de668ca1978a&MonthDisplay=9&YearDisplay=2012.

[46] United States, Government Accountability Office, *Science, Technology, Engineering, and Mathematics Education: Strategic Planning Needed to Better Manage Overlapping Programs across Multiple Agencies*, January 2012, accessed May 14, 2013, http://www.gao.gov/products/GAO-12-108.

[47] Stephen D. Nelson, *Encyclopedia of Education*, comp. The Gale Group, s.v. "Federal Funding for Academic Research," 2002, http://www.encyclopedia.com/topic/Research_funding.aspx.

[48] Ibid.

[49] United States, Department of Commerce, Bureau of Export Administration Office of Industrial Resource Administration, *National Security Assessment of the U.S. Robotics Industry* (March 1991), beta-www.bis.doc.gov/index.php/forms-documents/doc_view/55-national-security-assessment-of-the-u-s-robotics-industry-1991.

[50] Georgia Institute of Technology et al., *A Roadmap for US Robotics: From Internet to Robotics*, report, sponsored by Computing Community Consortium and Computing Research Association (May 21, 2009), http://www.us-robotics.us/reports/CCC%20Report.pdf.

[51] Paul Basken, "Obama Calls on University Research to Help Create Manufacturing Jobs," *The Chronicle of Higher Education*, June 2011, http://chronicle.com/article/Obama-Calls-On-University/128023/.

[52] P. W. Singer, *Wired for War: The Robotics Revolution and Conflict in the Twenty-first Century* (New York: Penguin Press, 2009), Kindle edition.

[53] Ibid.

[54] "History," Internet Architecture Board, accessed April 16, 2013, http://www.iab.org/about/history/.

[55] Nelson, *Open Architecture: Technical Principles and Guidelines*.

[56] Noyes, "Want Freedom from Vendor Lock-in? Survey Says: Choose Open Source."

[57] United States, Department of Defense, *Unmanned Systems Integrated Roadmap FY2011-2036.*

[58] "Standards of Greatest Value," OpenStand: The Modern Paradigm for Standards, accessed April 16, 2013, http://open-stand.org/stdsgreatestvalue/.

[59] Ibid.

[60] Ibid.

[61] United States, Robotics Virtual Organization, *A Roadmap for U.S. Robotics: From Internet to Robotics, 2013 Edition*, March 20, 2013, accessed April 16, 2013, http://robotics-vo.us/sites/default/files/2013%20Robotics%20Roadmap-rs.pdf.

[62]Byron Brezina, "Advanced EOD Robotic Systems Briefing" (Updated Briefing Presented to NDIA Robotics Division Quarterly Meeting, June 14, 2012), accessed April 16, 2013, http://www.ndia.org/Divisions/Divisions/Robotics/Documents/Quarterly%20Meetings/14%20June%202012/Mr.%20Byron%20Brezina.pdf.

[63] "Unmanning the Future," Lockheed Martin, accessed April 16, 2013, http://www.cdlsystems.com/index.php/stanag4586.

[64] National Defense Industry Association, *Interoperability Standards Analysis: A Report by the Standards Committee of the National Defense Industry Association Robotics Division*, November 2007, accessed April 16, 2013, http://www.ndia.org/Divisions/Divisions/Robotics/Documents/Content/ContentGroups/Divisions1/Robotics/Interoperability%20Standards%20Analysis%20(ISA).pdf.

[65] United States, Robotics Virtual Organization, *A Roadmap for U.S. Robotics: From Internet to Robotics, 2013 Edition.*

[66] "An Open Source Platform for Personal Robots," Willow Garage, accessed April 16, 2013, http://www.willowgarage.com/open-source-stance.

BIBLIOGRAPHY

Barnes, Michael, and A. William Evans. "Soldier-Robot Teams in Future Battlefields: An Overview." In *Human-robot Interactions in Future Military Operations*, edited by Florian Jentsch and Michael Barnes. Burlington: Ashgate Publishing Company, 2010.

Barry, Keith. "Can Your Car Be Hacked?" *Car and Driver*, August 2011. Accessed April 13, 2013. http://www.caranddriver.com/features/can-your-car-be-hacked-feature.

Basken, Paul. "Obama Calls on University Research to Help Create Manufacturing Jobs." *The Chronicle of Higher Education*, June 2011. http://chronicle.com/article/Obama-Calls-On-University/128023/.

Brezina, Byron. "Advanced EOD Robotic Systems Briefing." Updated Briefing Presented to NDIA Robotics Division Quarterly Meeting, June 14, 2012. Accessed April 16, 2013. Http://www.ndia.org/Divisions/Divisions/Robotics/Documents/Quarterly%20Meetings/14%20June%202012/Mr.%20Byron%20Brezina.pdf.

Bush, George W. "State of the Union Address 2006." The White House: The State of the Union. January 31, 2006. Accessed May 14, 2013. http://georgewbush-whitehouse.archives.gov/stateoftheunion/2006/.

Chapman, Paul. "Service Robotics Market to Grow at a CAGR of 17.4%." Companies and Markets.com. July 12, 2012. Accessed May 8, 2013. http://www.companiesandmarkets.com/News/Information-Technology/Service-robotics-market-to-grow-at-a-CAGR-of-17-4/NI4304.

"Consumer Robotics Market to Reach $6.5 Billion in 2017, While More Complex Personal Robots Lay Just Out of Reach." ABI Research. April 8, 2013. Accessed May 14, 2013. http://www.abiresearch.com/press/consumer-robotics-market-to-reach-65-billion-in-20.

Curry, Tom. "Lawmakers Voice Concerns on Drone Privacy Questions." NBC Politics. March 20, 2013. Accessed April 17, 2013. http://nbcpolitics.nbcnews.com/_news/2013/03/20/17389193-lawmakers-voice-concerns-on-drone-privacy-questions?lite.

Defense Systems Staff. "QinetiQ to Furnish Talon Robot to Czech and Polish Militaries." Defense Systems. November 28, 2012. Accessed May 14, 2013. http://defensesystems.com/articles/2012/11/28/qinetiq-talon-robot-central-europe-sales.aspx.

"Envisioning the Future of Robots in Surgery, Drug Delivery, and Beyond." Medical Design Briefs. May 1, 2011. Accessed May 14, 2013. http://www.medicaldesignbriefs.com/component/content/article/9925.

Erwin, Sandra I. "Drone Manufacturers Aim to Change Image - Blog." *National Defense Magazine*, February 15, 2013. Accessed April 15, 2013. http://www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?ID=1060.

Exec. Order No. 13603, 3 C.F.R. (2012).

"Export Control Reform News." ECR Library. Accessed April 14, 2013. http://export.gov/ecr/eg_main_023180.asp.

Franco, Veronica. "Market Research Projects Industrial Robotics Market at $33 Billion by 2017." Yahoo! Finance; Market Wired. July 12, 2012. Accessed May 8, 2013. http://finance.yahoo.com/news/market-research-projects-industrial-robotics-100800260.html.

Franzen, Carl. "President Obama's 2014 Budget Would Slash Drone Spending." The Verge. April 10, 2013. Accessed April 26, 2013. http://www.theverge.com/2013/4/10/4209084/obamas-2014-defense-budget-cuts-drone-spending.

Gates, Bill. "A Robot in Every Home: Scientific American." *Scientific American*, January 2007. Accessed April 16, 2013. http://www.scientificamerican.com/article.cfm?id=a-robot-in-every-home.

Georgia Institute of Technology, University of Southern California, Johns Hopkins University, University of Pennsylvania, University of California, Berkeley, Rensselaer Polytechnic Institute, University of Massachusetts, Amherst, University of Utah, Carnegie Mellon University, and Tech Collaborative. *A Roadmap for US Robotics: From Internet to Robotics*. Report. Compiled by Computing Community Consortium and Computing Research Association. May 21, 2009. http://www.us-robotics.us/reports/CCC%20Report.pdf.

Gertler, Jeremiah. *U.S. Unmanned Aerial Systems*. Report no. R42136. January 3, 2012. Congressional Research Service. Accessed March 23, 2013. http://www.fas.org/sgp/crs/natsec/R42136.pdf.

Global Underwater Robotics Market 2012-2016. Report. TechNavio, 2012. Accessed May 8, 2013. http://www.marketresearchreports.biz/analysis-details/global-underwater-robotics-market-2012-2016.

Heller, Wolfgang, Ed. "Crossing the Robotic Chasm." *Robotland* (blog). October 25, 2011. Accessed May 14, 2013. Http://robotland.blogspot.com/2011/10/crossing-robotic-chasm.html.

"History." Internet Architecture Board. Accessed April 16, 2013. http://www.iab.org/about/history/.

"Industrial Robot Statistics." International Federation of Robotics. Accessed March 24, 2013. http://www.ifr.org/industrial-robots/statistics/.

"Industry Snapshots: OD4074 - Robotic Surgery Equipment Manufacturing." IBISWorld. Accessed April 26, 2013. http://www.ibisworld.com/snapshot/industry/default.aspx?page=industry.

Insinna, Valerie. "Sequester Looms over Unmanned Vehicle Conference." National Defense. February 12, 2013. Accessed March 24, 2013. http://www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?List=7c996cd7-cbb4-4018-baf8-8825eada7aa2.

iRobot. "iRobot First-Quarter 2013 Conference Call Script." News release, April 24, 2013. iRobot Investor Relations: News and Events. Accessed May 14, 2013. http://investor.irobot.com/phoenix.zhtml?c=193096&p=irol-eventDetails&EventId=4897482.

Isherwood, Michael W. "Unmanned Systems and the Joint Team." *Unmanned Systems and the Joint Team*, no. 58 (3rd quarter 2010): 57-61. http://www.ndu.edu/press/unmanned-systems.html.

Lucintel. *Growth Opportunity in Global UAV Market*. Issue brief. Las Colinas, TX: Lucintel, 2011. Accessed May 15, 2013. www.lucintel.com/LucintelBrief/UAVMarketOpportunity.pdf.

"MarketsandMarkets: Global Service Robotics Market Worth U.S. $21 Billion by 2014." MarketsandMarkets. Accessed May 8, 2013. http://www.marketsandmarkets.com/PressReleases/robotics.asp.

Martin, Antoine. "U.S. Expands Use Of Underwater Unmanned Vehicles." *National Defense Magazine*, April 2012. Accessed May 2, 2013. http://www.nationaldefensemagazine.org/archive/2012/April/Pages/USExpandsUseOfUnderwaterUnmannedVehicles.aspx.

McBee, Josh. *Unmanned Aerial Vehicle (UAV) Manufacturing in the US*. Industry Report. June 2012. Accessed May 8, 2013. IBISWorld (OD4424).

Moore, Geoffrey A. *Crossing the Chasm: Marketing and Selling High-tech Products to Mainstream Customers*. New York: HarperCollins E-books, 2009. Kindle Edition.

National Defense Industry Association. *Interoperability Standards Analysis: A Report by the Standards Committee of the National Defense Industry Association Robotics Division.* November 2007. Accessed April 16, 2013. http://www.ndia.org/Divisions/Divisions/Robotics/Documents/Content/ContentGroups/Divisions1/Robotic s/Interoperability%20Standards%20Analysis%20(ISA).pdf.

Nelson, Eric M. *Open Architecture: Technical Principles and Guidelines*. Technical paper. OSR Case 07-S-2723 v. 1.5.8. IBM Federal CTO Office, September 30, 2008. https://acc.dau.mil/adl/en-US/170302/file/38742/OA%20Architectural%20Principles%20and%20Guidelines%20v.1.5.8.pdf.

Nelson, Stephen D. *Encyclopedia of Education.* Compiled by The Gale Group. 2002. http://www.encyclopedia.com/topic/Research_funding.aspx.

Noyes, Katherine. "Want Freedom from Vendor Lock-in? Survey Says: Choose Open Source." PCWorld. May 25, 2012. http://www.pcworld.com/article/256189/want_freedom_from_vendor_lock_in_survey_says_choose_open_source.html.

"An Open Source Platform for Personal Robots." Willow Garage. Accessed April 16, 2013. http://www.willowgarage.com/open-source-stance.

Parsons, Dan. "Aerial Drones Face Mounting Pressure From All Directions - Blog." *National Defense Magazine*, April 2013. Accessed April 15, 2013. http://www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?ID=1059.

Rising Above the Gathering Storm Committee (U.S.) Staff, National Academy of Sciences (U.S.) Staff, and National Academy of Engineering (U.S.) Staff. *Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5*. Washington, DC: National Academies Press, 2010. In Ebrary.

"Robotics: Technologies and Global Markets." *MarketWatch, The Wall Street Journal*, April 8, 2013. Accessed May 4, 2013. http://www.marketwatch.com/story/robotics-technologies-and-global-markets-2013-04-08.

"Service Robot Statistics: World Robotics 2012 Service Robots." International Federation of Robotics. Accessed April 26, 2013. http://www.ifr.org/service-robots/statistics.

Singer, P. W. *Wired for War: The Robotics Revolution and Conflict in the Twenty-first Century*. New York: Penguin Press, 2009.

Singer, P. W. *Wired for War: The Robotics Revolution and Conflict in the Twenty-first Century*. New York: Penguin Press, 2009. Kindle Edition.

Skidelsky, Robert. "Rise of the Robots: What Will the Future of Work Look Like?" The Guardian. February 19, 2013. Accessed April 16, 2013. http://www.guardian.co.uk/business/2013/feb/19/rise-of-robots-future-of-work.

"Standards of Greatest Value." OpenStand: The Modern Paradigm for Standards. Accessed April 16, 2013. http://open-stand.org/stdsgreatestvalue/.

Stier, Ken. "States Prove Weak Link in Supporting Research Universities." Pacific Standard. August 5, 2011. http://www.psmag.com/education/states-prove-weak-link-in-supporting-research-universities-34687/.

United States. Department of Commerce. Bureau of Export Administration Office of Industrial Resource Administration. *National Security Assessment of the U.S. Robotics Industry*. March 1991. beta-www.bis.doc.gov/index.php/forms-documents/doc_view/55-national-security-assessment-of-the-u-s-robotics-industry-1991.

United States. Department of Defense. *Unmanned Systems Integrated Roadmap FY2011-2036*. Corrected Copy Approved for Publication, Reference Number: 11-S-3613. Washington, DC. http://www.acq.osd.mil/sts/docs/Unmanned%20Systems%20Integrated%20Roadmap%20FY2011-2036.pdf.

United States. Government Accountability Office. *Science, Technology, Engineering, and Mathematics Education: Strategic Planning Needed to Better Manage Overlapping Programs across Multiple Agencies.* January 2012. Accessed May 14, 2013. http://www.gao.gov/products/GAO-12-108.

United States. Robotics Virtual Organization. *A Roadmap for U.S. Robotics: From Internet to Robotics, 2013 Edition.* March 20, 2013. Accessed April 16, 2013. http://robotics-vo.us/sites/default/files/2013%20Robotics%20Roadmap-rs.pdf.

"Unmanning the Future." Lockheed Martin. Accessed April 16, 2013. http://www.cdlsystems.com/index.php/stanag4586.

U.S. Congress. Senate. Committee on Commerce, Science, and Transportation. *Five Years of the America COMPETES Act: Progress, Challenges, and Next Steps: Hearings before the Committee on Commerce, Science and Transportation.* 112 Cong., 2d sess. S. Doc. September 12, 2012. http://www.commerce.senate.gov/public/index.cfm?p=Hearings&ContentRecord_id=cb59b16e-886e-4622-8d41-613e8c1167a6&ContentType_id=14f995b9-dfa5-407a-9d35-56cc7152a7ed&Group_id=b06c39af-e033-4cba-9221-de668ca1978a&MonthDisplay=9&YearDisplay=2012.

"U.S. Military Unmanned Aerial Vehicles (UAV) Market Forecast 2013-2018." Market Research Media. April 9, 2013. Accessed May 8, 2013. http://www.marketresearchmedia.com/?p=509.

Wilcox, Martin. Comment on "Crossing the Chasm (Geoffrey Moore)." *The WHY Organization* (web log), September 15, 2009. Accessed May 13, 2013. http://blogs.knowledgegenes.com/2009/09/crossing-the-chasm-geoffrey-moore-coded-by-martin-wilcox.html.