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Industry Study

Final Report
Robotics and Autonomous Systems Industry

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ROBOTICS AND AUTONOMOUS SYSTEMS 2011

ABSTRACT: While the promise of robots has intrigued humans for years, the technology to fulfill those promises has lagged. However, recent advances in robotics technology herald a future that intersects with long-held expectations. Some Asian and European countries now look to robotics as solutions for various societal, demographic, and economic problems. Despite its future importance, the United States is not the foremost world leader in all market segments of the industry. The U.S. Government, in fact, is principally interested in robots for military purposes, a result of ten years of war in Iraq and Afghanistan. The robotics industry is comprised of industrial and service robotics markets. The industrial robotics market is comprised of the manufacturing and logistics segments, and the service robotics market is comprised of the domestic and professional segments. Military robotics is a portion of the professional service robotics market segment. This industry study concentrated on industrial manufacturing and military service robotic segments. Though the industry faces several challenges, it is well poised to support U.S. national security goals and objectives.

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AAI Textron Systems (Hunt Valley, MD)
Aurora Flight Sciences (Manassas, VA)
House Subcommittee on Science and Innovation (Washington, DC)
Naval Explosive Ordnance Disposal Technology Division (Indian Head, MD)
Northrop-Grumman (Patuxent River, MD)
Robotic System Joint Project Office (Warren, MI)
Joint Robotics Repair Facility (Selfridge ANGB, MI)
Army Tank Automotive Research, Development and Engineering Center (Warren, MI)
Robotics Industries Association (Rochester Hills, MI)
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iRobot (Bedford, MA)
QinetiQ North America (Waltham, MA)
Boston Dynamics (Waltham, MA)
Worcester Polytechnic Institute (Worcester, MA)
Bluefin Robotics (Quincy, MA)
ADEPT Mobile Robots (Amherst, NH)
Massachusetts Institute of Technology (Cambridge, MA)
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Korea Association of Robot Industry (Seoul, Korea)
Korean Defense Acquisition Program Administration (Seoul, Korea)
Yujin Robot (Seoul, Korea)
Hanool Robotics Corporation (Seoul, Korea)
American Institute in Taiwan (Taipei, Taiwan)
Ministry of Economic Affairs (Taipei, Taiwan)
Shin Kong Security Company (Taipei, Taiwan)
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INTRODUCTION

Robotics and autonomous systems proffer a future of economic prosperity; a world in which robots perform tasks unsuitable – dull, dirty, or dangerous – for humans, give independence and mobility to the elderly, perform delicate surgery, and manufacture consumer products and even other robots. The reality of today is different. While the promise of robots has intrigued humans for years, the technology to fulfill those promises has lagged. However, recent advances in robotics technology herald a future that intersects with long-held expectations. Some Asian and European countries now look to robotics as solutions for various societal, demographic, and economic problems. Despite its future importance, the United States is not the foremost world leader in all market segments of the industry. The U.S. government, in fact, is principally interested in robots for military purposes, a result of ten years of war in Iraq and Afghanistan.

What do the terms robot, robotics and autonomous systems mean? This industry study group uses the following definitions. A robot is a device, either mechanical or virtual, that performs tasks on its own or by following instructions. Robotics is the science and technology of using robots. An autonomous system is a device with the capacity and freedom to act independently without human intervention. Autonomy is defined along a continuum from remote control to interpreting data and making decisions based on programmed parameters. Given the state of technology *today* there are no fully autonomous systems.

The purpose of this industry study report is to assess the health and viability of the Robotics Industry and to determine whether it is capable of supporting the U.S. national security strategy. The report and the resulting conclusions derive from extensive academic and field research. This industry study team met with companies, research institutions, industry associations, and government and military organizations in the United States, South Korea and Taiwan.

This industry study report begins with an overview of key markets, and then examines in detail the two most relevant to the study's purpose: the industrial robotics market and the service robotics military market segment, along with their respective challenges and outlook. The analysis yields four recommendations for U.S. government actions aimed to support and develop the Robotics Industry. The report concludes with five essays exploring the following issues and topics in detail: Accountability and Autonomous Robotics, A Consequence of Rapid Acquisition, Industrialized Asia: A Robotics Revolution, "Save Your Factory,"[1] and Medical Robotics.

THE INDUSTRY DEFINED

The Robotics Industry ranges from garage tinkerers to multi-billion dollar companies, from inexpensive toy robots to $100 million dollar unmanned aircraft. "R2D2" from Star Wars, "Data" from Star Trek, or the "Terminator" are popular exemplars; however, the reality of robotics is far more pedestrian and usually found in a factory or on the battlefield.

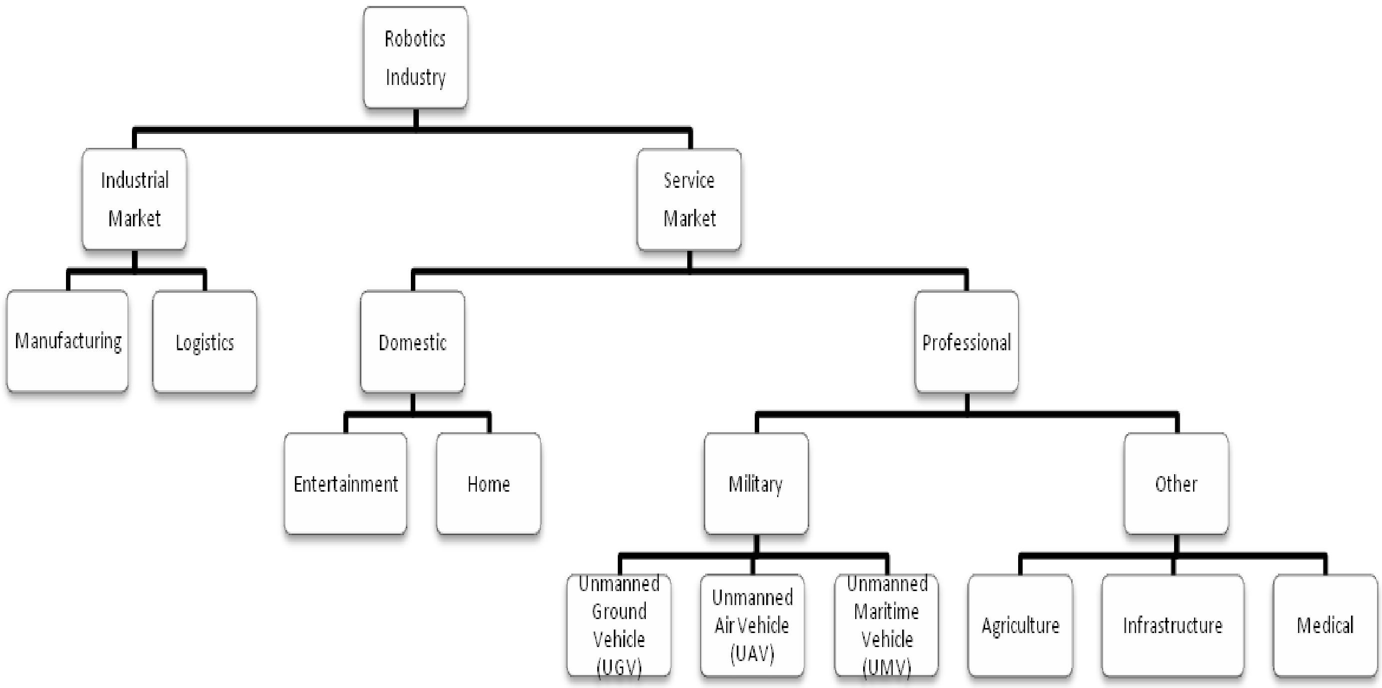

Figure: Robotics Industry study group depiction of industry market segments. The report focuses on the industrial and military robotics market segments.

The figure above is a graphical representation of the Robotics Industry, divided into industrial and service markets. Industrial robots perform a wide-range of repeatable tasks with precision, speed, and consistent quality.[2] In almost all cases, whether performing manufacturing tasks such as welding, packaging, painting or preparing food, the robot performs these tasks faster, better, and more cost-effectively than humans. Segments of the service robotics market range from entertainment and home maintenance to medical and infrastructure. This report primarily focuses on military service robots due to their direct tie to national security.

The military robotics market segment ranges from small research projects to multi-billion dollar contracts for large unmanned air vehicles. The growing market for military unmanned systems is a direct result of both the demand coming from the battlegrounds in Iraq and Afghanistan and improved robotic technology. This market segment is heavily reliant on the U.S. government for sales as well as research and development funding. The monopsonistic power of the U.S. government buyer is a key concern for the future health of this market segment upon the conclusion of the current conflicts. Will the U.S. military continue to require these technologies? If so, will Congress continue to fund the acquisition of military robotic systems in the coming era of tighter budgets? In addition, can these companies develop and grow a commercial market for their technologic niche? These and other related questions served to focus this report's analysis.

CURRENT CONDITION

Although all robots share common underlying technology such as sensors and processing capability, the nascent Robotics Industry lacks the homogeneity sometimes found in more mature industries. Robotics firms do not compete across all market segments; instead, they compete selectively within discrete segments. This portion of the paper compares and contrasts the mature industrial robotics market with the relatively less developed military robotics market segment.

Industrial Robotics

Market Structure: This market consists of the manufacturers of robotic hardware and the integrators who create innovative solutions for industrial processes using robots. The robot manufacturing market is characterized by monopolistic competition with a few large foreign companies, such as FANUC, Hyundai, and Kuka, dominating the market. Barriers to entry are substantial for manufacturers, requiring technical expertise, a line of quality products, and significant manufacturing capability while barriers to entry for integrators are deceptively low; requiring only the skill, the intelligence, and the creativity to leverage and apply the advantages of robots towards a wide-range of industries. Sales of industrial robots, the hardware, account for one-third of the worldwide $12 billion industrial robotics market.[3] Fully two-thirds of market sales derive from the application of software, peripherals, and processes to the hardware.[4]

Firm Conduct: Where industrial robotics companies once focused on selling to the automotive industry, technological improvements, notably in sensors and processing power, are responsible for new sales in non-automotive industries. These new applications include packaging, sorting, food processing, and high-tech manufacturing. Consequently, larger firms have acquired smaller firms with specialties in the kinds of technology driving this shift or have attempted to develop these technologies on their own. The shift has created new opportunities for robotics integrators. The manufacturer-integrator model is successfully employed by FANUC Robotics America, a U.S. subsidiary of a Japanese robot manufacturing company, with a network of 500 integrators developing "faster, better and cheaper" automation processes for non-automotive businesses using FANUC industrial robots.

Market Performance: Sales of industrial robots grew steadily over the past two decades, only dipping in 2009 because of the worldwide economic crisis[5]. Demand rebounded strongly in 2010, almost doubling the number of robots sold compared to 2009[6], lifting expectations that growth will remain strong at least through 2013[7]. In 2009, the worldwide market for sales of industrial robotic systems was $12 billion and the current worldwide inventory of industrial robots is 1.0 – 1.3 million units.[8]

From a consumer standpoint, the United States ranks ninth in robot density—the number of robots per 10,000 manufacturing employees—trailing Japan, Singapore, South Korea, Germany, Sweden, Italy, Finland, and Belgium in that order.[9] Robot density can also be used to understand the structure of the market for industrial robots across various industries. The automotive industry has the highest robot density of any industry worldwide averaging more than 400 per 10,000 workers. The automotive industry in Japan tops the list at 2100, or 1 robot per 5 workers, allowing some companies in Japan to operate "lights out" factories, where robots perform manufacturing around the clock.

Military Robotics

Market Structure: The military robotics market segment divides into four physical domains in which the systems are used: space, air, ground and maritime. Space is a unique operating environment with challenges beyond the scope of this study; therefore, this report focuses solely on the other three domains.

The unmanned maritime vehicle market segment is relatively immature and lacks the well-defined requirements and capabilities common to the other military robotic market segments. This lack of development is primarily due to the technology gap in autonomy and the difficulty of building vehicles to withstand the harsh environment of the sea and undersea domains. Autonomy is a key driver for the marine environment due to communications difficulties and the inability to monitor the device's actions. Technology capable of providing the required level of communication and autonomy is just now entering the research pipeline at major Department of Defense (DOD) research labs and supported companies.

Unmanned Ground Vehicles (UGV) have been around for at least twenty years, primarily for Explosive Ordnance Disposal (EOD) applications, but their value to the U.S. military grew following the frequent use of Improvised Explosive Devices (IED) in Iraq and the subsequent adoption of IEDs by the Taliban in Afghanistan. The rapid acquisition strategy, particularly for small UGVs, led to a plethora of systems accomplishing similar tasks but without the inter-system compatibility. While this strategy encouraged market competition, it also created training and support challenges. (See the essay A Consequence of Rapid Acquisition.)

The Unmanned Air Vehicle (UAV) market is the most mature and well defined of military robotic market segments. The U.S. UAV industry is the most dominant in the world, capturing almost a 70% share of the worldwide market.[10] Unlike the marine or even the ground environment, the air domain offers greater accessibility and freedom of movement due to outstanding communications capabilities. As a result, more nuanced and varied forces shape this market. In the small UAV market segment, there is much more competition and the barriers to entry are low. Consequently, this segment is fractured, particularly for ground control systems due to yet undefined government and industry standards for system architecture and control. The medium UAV market segment is well structured and stable with a few suppliers influencing the market; although the government, as the primary buyer, still wields the preponderance of purchasing power. The large UAV market segment is similarly structured and very much resembles the major aircraft weapons systems market for complex and expensive products.

To date the power of a single buyer, the U.S. government, dominates this market preventing normal market-competition forces from developing the best solutions, and rapid acquisition processes coupled with near-direct fielding of technology demonstrators effectively limits full competition and raises barriers to entry.

Firm Conduct: In all military robotics market segments, the purchase of smaller companies, especially those with a unique technological niche or skill, by larger firms is common. Small companies often collaborate with large defense contractors to leverage program management and defense acquisition expertise, and to bridge the gap between research and development and productization. For UGVs and small/medium UAVs, leading companies attempt to protect market share by maintaining niche capabilities and brand recognition, often marketing direct to soldiers in combat zones to lock in sales. Their focus also resists commoditization of sensors, control systems, and vehicles. In doing so, these firms attempt to reduce competition by raising barriers to entry for new companies.

Market Performance: Performance varies across markets and domains. Current DOD spending on UAVs is tenfold higher than in FY 2002. Spending has increased from $0.5 billion to approximately $5 billion.[11] Today, a significant portion of U.S. government purchases of military robotic systems cam from Overseas Contingency Operations (OCO) funds. Many of the firms rely exclusively on government funds and grants to sustain their business. Firms with Programs of Record (PoRs) perform well and create value for their stockholders. Firms relying on OCO funding and Commercial off the Shelf (COTS) acquisitions are performing well today, but their future performance could be in jeopardy as OCO funds decrease.

CHALLENGES

Despite the differences between the industrial robotics market and the service-military robotics market segment, there are two overarching challenges. The first is that the current state of robotics technology does not meet consumer expectations. Robotics is heavily dependent on advances in information technology, material sciences, and sensor development. Many researchers, both in the United States and abroad, are laying the technological foundation with essential research on fundamental robotic functionality. While the industry has made significant advances, it is clear there remains a gap between consumer expectations and technologic reality. The second challenge is social acceptance of robotics technology. Whether it is allowing UAVs into the national air space or investing in industrial robotics, many people remain uncomfortable with robots, as they exist today. While uncommon, robots designed to look exactly like humans push the bounds of social acceptance.[12] A common misunderstanding regarding robotics is the idea that robots replace people or at least require fewer people to operate than manned systems. At least in the world of military robots, this is not the case.

Besides the two overarching challenges, each market segment deals with its own unique issues. The following four challenges rank as the most significant confronting the industrial and military robotics market segments.

Technological Challenges Limit Military Robot Capabilities

The historically slow rate of progress developing compact power sources imposes trade-offs between size, weight and capability when designing mobile robots. Nowhere is this more evident than with military robots, such as UGVs and UAVs, where all sub-systems such as motors, sensors, cameras, lights, and gripper arms require reliable power. The imposed trade-offs significantly limit mission objectives for military robots.

Secure communications between the robot and the human operator is another challenge of great importance for both military and commercial mobile robotic systems. The inability to communicate securely with, and thereby control, unmanned systems may negatively influence public confidence. Military organizations mitigate some portion of the risk by operating these systems in restricted operating areas; however, the proximity of these areas to public spaces still poses risks in the event of loss of control.

The lack of common standards and interoperability among unmanned systems, exasperated by rapid acquisition processes, negatively affects maintenance, operation, and training. Accessories for one type of UGV rarely work on any other UGV even from the same manufacturer. Universal control units do not yet exist for any class of unmanned system, and the lack of convergence towards a standard is becoming a significant issue.

Post War Funding Threatens Military Robotics

The conflicts in Iraq and Afghanistan displayed the usefulness of military robots in the air and on land. That unmanned air and ground vehicles have a future in the military is a safe assumption; however, future large-scale acquisition of these vehicles in a post-conflict environment is not certain. Firms with existing government contracts for the production of military robots or with strategies built on gaining government R&D funds performed well during the wartime period. Reduced war funding could negatively affect the financial performance of these companies. Future research and development programs are also at risk. Commercial diversification is essential for firms operating in all military robotics market segments. Of the three segments, firms operating in the maritime segment appear the most vulnerable to reduced military spending as that commercial market is the least developed.

Export Controls Limit Market Development for U.S. Military Robots

U.S. export controls, such as the International Traffic in Arms Regulations (ITAR) or Missile Technology Control Regime (MTCR), attempt to balance national defense with the capacity to create the innovative technologies necessary to maintain a prosperous country. Export controls grew out of the need to protect technology advancements from potential adversaries during the Cold War. Today, overly stringent ITAR and MTCR reduce exports for many U.S. robotics companies. Weak U.S. economic conditions drive companies to seek unrestricted access to global markets. In August 2009, President Barack Obama issued an export control reform directive. The directive changes the current export control regulations by reducing bureaucratic obstacles and improving the export licensing process while minimizing the risk of transferring advantageous technology to U.S. adversaries. ITAR rules affect not only foreign sales but also the type of research American universities conduct and the hiring practices of firms doing business with the U.S. military.

Manufacturing Capacity Needs Industrial Robots

Asian and European companies dominate the market for industrial robots; and, in the United States, their subsidiaries account for the majority of robot sales. U.S. companies, on the other hand, make up the majority of robotics integrators within the U.S. robotics market. The real area of foreign competition is not in the robotic hardware production but in the use of industrial robots as a contributor to national manufacturing capacity. From that perspective, industrial robotics contributes far more to the economic capacity of Japan, Korea, and Germany, three of the countries at the top of the robot density list, than it does for the United States. China, the world's second largest manufacturing country and long accustomed to cheap and plentiful labor, is the "most rapidly growing robot market in the world in the past few years"[13] China's acquisition of industrial robots signifies an important recognition of its changing demographics and workforce shortages. As mentioned previously, the United States ranks ninth in robot density, a position incongruent with the idea of economic supremacy and, unlike the Chinese, suggests ambivalence towards greater acceptance of robots in the workplace.

OUTLOOK

This portion of the industry study report looks into the future to assess the health and viability of the Robotics Industry and to determine whether it is capable of supporting the U.S. national security strategy. While the outlook is generally positive for the industry as a whole, it is highly segmented with little behavioral correlation between market segments. For example, the forces affecting the long-term outlook for military robots are very different from those affecting the industrial robotics market segment. Technology improvements and widespread acceptance of robots are not only fundamental challenges but also vital drivers for the future success of the industry.

Industrial Robotics

Short term (1-5 years). Japan, Korea and Germany will continue to dominate the industrial robotics market. The United States is unlikely to gain significant market share without a massive investment. High unemployment rates in the U.S. will likely continue for the next few years, hampering the greater use of industrial robots for fear of even more job losses. However, continued technological breakthroughs and the cumulative impact of the large network of U.S. robotics integrators lay the groundwork for long-term success.

Long-Term (5-20 years). Technological improvements will drive increased efficiency and productivity contributing to the success of robotics firms and manufacturers in the long-term. Improvements in artificial intelligence, sensors, and material sciences will open new areas for the use of industrial robots. While the United States is unlikely to become the preeminent industrial robot manufacturer, the application of robotics to the world's largest economy and manufacturing base will enable the United States to retain its unrivaled position in both areas. Robots add value to industry only through the skillful application of robotics to industrial processes. Much as Apple's "app store" unleashes the possibilities of the iPhone or iPad through the creativity of numerous developers, skilled robotics integrators exploit a robot's potential through creativity and innovation. The example of Japan's high robot density shows strong growth opportunities for increased robot use in U.S. manufacturing. Robotics integrators can take advantage of low overall robot density in the United States to develop and expand the robotics market, which will help maintain continued U.S. competitiveness.

Military Robotics

Short term (1-5 years). The need for UGVs and UAVs for the wars in Iraq, Afghanistan, and now Libya is sufficiently strong that the U.S. government will continue to purchase new devices and maintenance support. Research and development funding will continue to improve existing capabilities as well as build new ones. The United States is and will remain the preeminent leader in military robots during this timeframe; however, its lead in the UGV and small/medium UAV segment is intimately tied to a decade-long war, which enabled an industry, flush with defense dollars, to saturate the military market. Should the wars conclude in the next year or two, the existing stockpile of unmanned systems would meet future peacetime requirements. For example, as the Iraq War winds down, the military Services are faced with trying to determine what to do with the hundreds of UGVs being returned from field. The excess UGVs, UAVs, and an immature maritime market segment, presents possibly debilitating challenges for military robotic manufacturers as supply looks to exceed demand sometime in the next five years. Unless the government defines maritime requirements soon and begins to procure systematically UMV capabilities or the commercial market becomes viable, maritime firms face an unpromising future. Similar ends may await UGV makers without commercial diversification in the absence of either a PoR or OCO funding. Performance for small UAV firms mirrors the above situation for the same reasons, but the medium and large UAV market segments should continue to perform well based on proven wartime capability and secure PoR funding streams.

Overseas competition in the small UGV market segment will not be sufficient to unseat the United States as a world leader in the short term. While Asian firms are just now delving into the military robotics market segment, they trail U.S. firms by 3-5 years in technology and tend to lack true innovation, seeming instead to recreate tried and true ideas in military robotics. However, while these firms are not likely to achieve all they claim in robotic technology, they will undoubtedly close the technological gap with the U.S., increasing the likelihood of real competition in small UGVs sometime in the near future. For the general service robotics market, Korea and Taiwan have robust plans for robotic technology growth and commercialization and are funding research and development in service robotics. Taiwan, in particular, has an active review process continually aligning plans to the reality of technological development. Discussions with firms, on the other hand, revealed mixed data on the efficacy and influence of these central plans, with only some firms benefiting from government funding. While these plans tend to reach too far and over-promise on technology, one cannot ignore the central role of government planning in the rapid technological rise of some Asian nations.

Long-Term (5-20 years). On the positive side, military robots have established a secure place in the U.S. arsenal. The ongoing conflicts and the worsening U.S. fiscal situation pose noteworthy challenges for the industry in the long-term. While the expectation that research and development funding will continue is reasonable, the level of funding is uncertain due to bipartisan political pressure to cut government spending. Excess capacity with limited demand will force consolidation within market segments, through mergers or bankruptcy, as firms engage in survival behavior. Consolidation of the industry will likely improve interoperability as the market settles on a few winning firms and products. As such, the market is likely to move toward commoditization (for instance in sensors, manipulators, control mechanisms, etc.) and modularity. Whether done by industry, DOD, or in combination, standards will evolve from closed and proprietary architectures to enable commoditization and modularity. Small firms that rely solely on military sales of full systems are at the most risk unless they develop new markets or adapt to the new market structure. Large defense firms, who have partnered or acquired smaller firms specializing in unmanned systems, may weather the downturn by relying on PoRs, but some may close small robotic systems divisions. Regardless, the technologies enabling large/strategic unmanned platforms (Global Hawk, Predator, etc.) are resident in these large firms and such systems are virtually indistinguishable from other manned major weapons systems from a programmatic standpoint. As such, the United States is positioned to maintain preeminence over the next twenty years in these kinds of systems. Whether or not the President's export control directive will facilitate export sales is unknown, but foreign sales, either commercial or military, likely will prove highly beneficial to these firms.

The cumulative effect of continued research and development will eventually yield technological solutions to the previously mentioned challenges for mobile military robots. Continued improvements in the capabilities of existing devices and the development of new ones will raise the expectation that military robots will result in a reduction of human capital requirements along with concomitant changes in force structure. Given how intertwined the military is within the U.S. political process, addressing these issues will most likely occur at the distant end of the long-term time horizon.

GOVERNMENT GOALS, ROLES, AND RELATED RECOMMENDATIONS

The United States does not lead in all Robotic Industry market segments, it follows in some, and it will continue to do so until U.S. policymakers recognize and act upon the transformational potential of robotics. Germany, Italy, and Sweden, for example, look to robotics to stay economically competitive. Japan and Korea look beyond robotics as simply automation tools to increase manufacturing output and see a solution for intractable social, demographic and economic problems. Sound policies, emphasis on research and development, and focused investments support their embrace of the coming robotics revolution. The United States confronts many of the same problems but without the focused approach for resolving the aforementioned challenges.

Trailing in any race always requires extra effort to pull ahead. Should the U.S. government choose to make this effort, here are four policy recommendations designed to boost national security and economic prosperity by supporting the robotics revolution. In doing so, these policy recommendations also support the National Security Strategy critical objective for ensuring that "the most innovative ideas take root in America."[14]

Recommendation 1: Develop a Cohesive National Strategic Plan for Robotics

The first and foremost policy recommendation for the U.S. Government with respect to robotics is to develop a strategy encompassing the whole industry. While several departments and entities, such as DOD and the Congressional Robotics Caucus have published road maps, these disparate guidelines must be melded into a realistic, cohesive strategic plan. The important potential of this industry is highlighted by both Korea and Taiwan declaring, emphasizing and investing in robotics as a strategic engine of growth. The U.S. should as well.

However, unlike Korea and Taiwan, which developed and implemented near-term, centralized governmental plans in an attempt to drive growth, the United States should focus on specific market segments and prioritize efforts and resources. The United States does not need to lead in every segment of the industry, but this plan must define what markets to maintain or gain dominance. The importance of the industry is not the robot per se, but the ability of the U.S. to leverage the technologies to improve national productivity. This strategy must also address the social acceptance of robots, where some see a threat as well as the need for continued technological growth.

Recommendation 2: Create a Strategic Robotics Research and Development Plan

Meeting the President's goal of investing three percent of GDP towards technology research and development is a critical overarching goal for U.S. competitiveness. Developing a strategic robotics plan outlining research and development investments is a key first step toward this goal and the second recommendation. The U.S. Government should target investments in the advancement of power sources for mobile systems and improved secure communications across all domains. In addition, new technologies the greater market will not support, such as domestic service robots assisting the care of the elderly and incapacitated, require significant attention and investment. A coherent investment strategy will strengthen the industrial base in the robotics field and ensure the efficacious use of scarce resources, reducing waste and redundancy. However, this must not result in a bailout plan for firms as wartime funding is reduced. Market forces along with mergers and acquisitions should be allowed to play out to the extent national security is not harmed.

Recommendation 3: Bolster Holistic Engagement with Industry

A third critical policy recommendation is for the U.S. government to bolster proactive and congruous engagement with industry. This engagement can take many paths, but we believe worthy focal points include industry associations such as National Defense Industrial Association (Robotics Division), Association for Unmanned Vehicle Systems International, Robotics Technology Consortium, and Robotics Industries Association. The principle goal of this engagement should be increased public knowledge. The study group believes greater public knowledge will spawn greater public trust in and societal acceptance of robotics, thereby engendering the industry's opportunities.

Integral to this engagement are emphases duly placed on three key areas. First, as with any maturing discipline, the industry needs a common language. To this end, the U.S. government should support the development and establishment of a robotics lexicon encouraging common and shared understanding. Second, for the sake of interoperability, the U.S. government should lead industry towards a common and standard architecture for unmanned systems. The purpose of this architecture would be similar to military engineering standards and NATO standardization agreements (STANAG). Finally, the U.S. government should institute a Robotics and Autonomy Advisory Council with research, academia and industry partners to focus on legal, legislative and ethical challenges facing the future application and adoption of robotics within the American culture. The intentional, necessary and natural byproduct of this effort is the populace's better understanding of the viability of robotic applications, spanning both the industrial and service robotic market segments.

Recommendation 4: Define Realistic Regulatory Requirements

The fourth policy recommendation is to define realistic regulatory requirements to facilitate emerging technology. Streamlining and creating mechanisms to fast track promising technology enables industry to respond to potential applications and markets. Several areas of potential regulatory reform include export controls, National Airspace System management, and budgetary and acquisition processes.

Secretary of Defense Gates describes the bureaucratic apparatus of export control as a "Byzantine amalgam of authorities, roles, and missions scattered around different parts of the federal government."[15] The U.S. government should consolidate inter-agency efforts under a single body to "streamline the review process and ensure export decisions are consistent and made based on the real capabilities of the technology."[16] ITAR reform can improve U.S. industry's access to international markets while enhancing interoperability between allies.

Separately, significant effort to set the conditions for better integration of UAVs into the national airspace should continue in order to preclude every flight requiring Certificates of Waiver or Authorization. The Unmanned Aerial System Executive Committee, which includes the DOD, Department of Transportation, the Department of Homeland Security, and the National Aeronautics and Space Administration, should work with industry to identify and resolve issues in order to improve UAV integration in the national airspace.[17]

Additionally, with the expected decline in defense budgets, regulation and acquisition reform pertaining to robotics and unmanned systems is required. As military robots proved their utility, war fighters capitalized on the agility of the rapid acquisition process to incorporate technology advancements by upgrading platforms. The DOD's ability to capitalize on advance technology requires an efficient acquisition and life cycle management strategy that enables technological refreshes. These reforms should promote cross-platform commonality, modularity, and standardization and focus the life-cycle management strategy to integrate emerging technology insertion and refreshes.

ESSAYS ON MAJOR ISSUES AND TOPICS

ACCOUNTABILITY AND AUTONOMOUS ROBOTICS ESSAY

One of the ethical issues surrounding robots in civilian and military use is "where responsibility would fall in cases of unintended or unlawful harm…the possibility of serious malfunction and robots gone wild; capturing and hacking of military robots that are then unleashed against us."[18] In order for a legal system to hold up, responsibility and accountability are required. This is equally true for civil or criminal law and for the laws of war. As such, before we field robotic systems for civilian or military use, we must answer questions about whom or what is responsible for things that may go wrong.

Accountability and responsibility are the cornerstones of justice. It underlies all of civil law and the Just War tradition from which springs International Humanitarian Law, or the Law of War. Michael Walzer, the Just War philosopher says, "The assignment of responsibility is the critical test of the argument for justice[19]… [and] there can be no justice in war if there are not, ultimately, responsible men and women."[20]

The legal challenge for industry in fielding autonomous robots revolves around the concept of product liability.[21] Several legal constructs apply, but we will only consider the concept of "due care"[22] here for its immediate relation to the determination of accountability and as a possible concept of future courses of action in research, development, and fielding of autonomous robots. Manufacturers, recognized experts on their products, are responsible for anticipating reasonable risks.[23] However, due care means the manufacturer may be held accountable for uses of the product not specifically warned against.[24] This is obviously troublesome to manufacturers of autonomous robots. It also seems troublesome as a construct for military use as war fighters are notorious for using equipment in ways no one could have foreseen. At some point, at least for the military, we will likely have to take responsibility for the things we acquire from defense contractors.

The question we are about to face is best posed by Daniel Dennett in the title of an essay called *When HAL Kills, Who's to Blame?* Dennett says accountability is a foundation, which starts in the realm of morality and parallels Just War and civil law concepts. We require intentionality and consequence recognition before punishing for actions outside societal norms. Our machines are a long way from this ability.

Manufacturers and designers are often held liable under the due care provision mentioned above, but they should be judged separately. It seems clear we have to separate the manufacturer from the designers of the system, but even then, it may not be a good idea to make them responsible for the later actions of lethal autonomous robots. In simple cases of autonomy, programmers and designers often know how the systems will react.[25] However, as artificial intelligence (AI) progresses, the concept of programmer accountability becomes more tenuous. If the programmer gave the system appropriate information, but the autonomous system is supposed to make its own decisions, it seems hard to argue how the programmer could be responsible for the actions of the machine.[26] It seems then, there is no supportable case, at least in military operations, where the commander or user will not be accountable, and this may apply in civilian use. How do we propose to grant to the user the responsibility that ought to accompany accountability when they are clearly not as knowledgeable as the manufacturer?

Military commanders are certainly accountable for their actions in combat and for the actions of their men and women. They are accountable, because they are also responsible—responsible for training and equipping their unit, for selecting the leadership positions below them, and for grooming their chain of command to act consistently in their absence. Accountability is contractually bound to responsibility, but the complexity of autonomous systems may affect this contract. As the systems get more complicated, responsibility becomes more diffused. Dr. Robert Sparrow of Monash University, Australia, has said it would be immoral to field autonomous robots because the manufacturer, designer, and user will all lack accountability.[27] There are effective ways of deconstructing the fielding question,[28] but these do not directly address the more subtle point of Sparrow's argument. At its heart lies the diffusion of responsibility.

The commander of autonomous lethal systems or the civilian authority fielding autonomous robots will have nothing to do with programming them. There is no analogy to the current system where the commander or user is both responsible and accountable due to his involvement in the training of his soldiers. It is also unlikely the using authority has the ability to understand all the ramifications of the advanced programming for systems under their control. This inability obviously becomes more pronounced as the systems gain greater degrees of autonomy. At this point holding the military commander or fielding authority responsible is "non-satisfying" as the systems have the capability to make their own decisions.[29] While commanders are responsible for their soldiers, they do so only because of the influence they exert in training those soldiers. For autonomous robotics, there is no such influence. Responsibility may eventually become so diffused it can no longer serve as the basis for accountability.

This diffusion of responsibility is the ultimate problem for solving the accountability issues in autonomous systems. The law, both civil and the law of war, operates on the presumption there is a responsible party, and the diffusion of responsibility when dealing with autonomous systems will make it difficult to resolve. One possible solution is the concept of differential apportionment of liability, a concept already used in product liability cases.[30] This "could be a useful tool when considering issues in robot ethics…This implies that engineers need to think carefully about how the subsystem they are working on could interact with other subsystems—whether as designed or in unintentional partial breakdown situations—in potentially harmful ways."[31] In the diffused responsibility realm of autonomous robotics, the challenge will be in determining apportionment. Perhaps, at least for the military, this too will be unsatisfying and we will be left with a commander who may be unjustly held accountable without the benefit of responsibility. It remains to be seen.

Accountability resides at the core of civil and criminal law and the law of war. Autonomous robotics will challenge this foundation as we seek to find responsible parties when things do not go as planned. Current product liability law lays a good foundation for discussions on this subject, but may not be wholly sufficient to answer questions on the responsibility issue. There is no moral or legal foundation for holding our machines accountable, and as long as there is transparency from manufacturers and designers, holding them fully accountable for their autonomous systems' later actions is unsatisfying. The concept of due care is instructive for end users, but even it may not hold up when autonomous, possibly adaptive or learning systems, act in ways neither the producer or user could have foreseen. As systems become more autonomous, they grow in complexity, and this tends to diffuse responsibility for the system's actions even further. End users, normally responsible because they control training, attitudes, and cultures in organizations, may lose responsibility based on the complexity of the programming of autonomous systems. Differential apportionment of liability is the best model to address this issue. However, it is unclear whether it will be sufficient and determining apportionment between those with moral agency for the things our autonomous robots do remains a difficult problem.

A CONSEQUENCE OF RAPID ACQUISITION

While science fiction and movies predicted wide proliferation of robots and autonomous systems in the general public, only a handful of industries readily embrace the technology. The mantra "dull, dirty, or dangerous" defines the environment where robots thrive to prove their utility, seen most recently in Japan's support request for robotic systems to combat the nuclear reactor catastrophe ravaging their nation.[32] DOD experience is similar as EOD teams requested robots to fight the emerging IED threat in 2003. In 2004, no single vendor could produce the initial request for 162 EOD robots, and DOD relied on five separate vendors to fulfill the order. The robots proved their military utility, but as the IED threat grew, so did the requests for additional robots. From 2005 to 2009, the demand for robots grew from approximately 1,800 to over 7,000 systems.[33] During this period, two manufacturers emerged as industry leaders. They developed two ubiquitous COTS robots, which the Robotics Systems Joint Project Office (RSJPO) and Naval EOD Technology Division (NAVEODTECHDIV) procured through two separate program offices and with slightly different strategies. This lack of coherency led to difficulties in sustainment and significantly contributed to the fractured small UGV market.

Though EOD robot use started in the 1970s, the infrastructure to handle the logistics of such a large growth in demand did not exist. Because these two dominant EOD robots were procured through the rapid acquisition process and did not represent programs of record, the program offices faced a dilemma—disregard sustainment or use supplemental appropriations to build an ad-hoc supply chain strategy from scratch. RSJPO created a pseudo-depot maintenance facility, the Joint Robotic Repair and Fielding (JRRF) facility, at Selfridge Air National Guard Base for repairs that could not be done in the field. The JRRF, manned by activated reserve personnel and government civilians, acted as an inventory control point (ICP), training and depot-level repair facility. To responsively support the robots forward in theater, Joint Robotic Repair Detachments (JRRDs) stood up in Iraq and Afghanistan to perform rapid intermediate-level maintenance. RSJPO also utilized activated reserve personnel and government civilians while establishing these detachments.[34] Funding for the entire project, including disparate robotic systems performing the same function, was with OCO funds. Additionally, personnel for robot maintenance at the JRRDs were taken "out of hide." Neither the Marines nor the Army is creating a career field or even an additional skills identifier for trained intermediate maintenance personnel. As such, there is no personnel system visibility on soldiers trained for this specialized task. Finally, the services must react to the decisions of two commercial companies when it comes to upgrading systems or ensuring backwards compatibility for fielded systems when the contractors decide to alter code or architecture. Though DOD's March 2008 Congressional Report on Business Transformation cites RSJPO and NAVEODTECHDIV for these heroic efforts,[35] the fact is none of this on-the-fly supply chain construction would have been necessary if there had been a coherent acquisition plan for EOD robots.

Due to proliferation of IEDs and the evolving tactics of the enemy, Joint Urgent Operational Need statements continue to demand additional robots and modifications. These requests present configuration management challenges for COTS systems procured outside of a PoR. In a 2008 report to Congress, DOD reported on the difficult, though successful, integration of no less than 15 levels of configuration management for over 4,000 robots.[36] Since these systems were "born" into service, reliability and life cycle data did not exist forcing program offices to track failures and depot level repairs and perform failure trend analysis to identify systemic issues as they emerged. Such efforts are further complicated by proprietary design of the main manufacturers, which inhibit commonality and modularity. For example, after engineers at NAVEODTECHDIV successfully designed a new manipulator add-on for one manufacturer's robotic arm, the manufacturer changed the arm design without coordination with the program office and made the newly designed add-on instantly obsolete. No amount of successful configuration management tracking can account for events such as this.

DOD's reliance on these COTS systems and its own configuration management data issues highlight the fractured nature of the small UGV market. Though 4,000 robots may seem like a large number, it is not enough to sustain a healthy market. As such, manufacturers continue to modify their products searching for the differentiation that will set them apart. This serves to feed the vicious cycle of changing configurations and hampers market stabilization.

DOD robots, in the hands of EOD teams, became an exceptional capability to counter emerging and adaptive threats. In 2008, robots conducted over 25,000 combat missions in Iraq and were responsible for clearing over 15,000 IEDs.[37] As the COTS solution was rapidly fielded and modified, the program offices' supply chain management strategy was critical to success, but it came at a significant cost in labor, time and OCO funding. Two separate program offices fielded similar capabilities as war demands allowed for redundancy, but those offices were forced to create an ad-hoc sustainment plan. Redundancy in program management did not lead to commonality or modularity in fielded systems. In fact, the monopolistic power of the robot manufacturers complicates configuration management and serves to keep the small UGV market in a fractured state. The long-term effects of this lack of coherency in acquisition strategy remain to be seen.

INDUSTRIALIZED ASIA: A ROBOTICS REVOLUTION

Some countries expect a robotics revolution to change their societies. The robotics industry is already a key contributor to economic prosperity in industrialized Asian countries like Japan, Korea, and Taiwan. Japan and Korea in particular look past industrial robotics, which already significantly support their export driven economies, to service robotics as the solution for looming societal and demographic problems. These countries have national policies offering stronger support for the robotics industry than the United States, raising the question as to whether the United States sufficiently appreciates robotics' potential for social good. These countries also believe robotics has the potential to transform their economies and societies, and only through strong government leadership will the benefits and transformative effects come to fruition.

The effects of such revolutions are remarkable. From agriculture to information, revolutionary changes brought great gains to humanity. The underlying assumption of this essay is the widespread acceptance and use of robots and robotics technology will be on par with the positive changes experienced from the agrarian, print, industrial, and information revolutions, and that the Japanese and Koreans understand that robotics is the next big thing. Consequently, those countries understand that assisting this revolution is a key role for their policymakers.

The lack of capable robots to deal with the Fukushima Daiichi nuclear power plant crisis in Japan (March 2011) surprised many people accustomed to Japan's leadership in the field of robotics. With a robot density twice their nearest competitor, a strong desire to build human-like robots to work next to or entertain humans, and a plan to add one million industrial robots by 2025[38] (currently Japan has approximately 315,000)[39], the Japanese are clearly world leaders in this industry. "For Japan, the robotics revolution is an imperative. With more than a fifth of the population 65 or older, the country is banking on robots to replenish the work force and care for the elderly."[40] The Japanese calculation is a single robot replaces about 10 employees[41], thus one million new robots either replaces ten million workers (15% of Japan's current workforce) or it boosts manufacturing output by the equivalent of ten million workers, either way robots are viewed as an economic "workforce multiplier."[42]

Plans are for Japan's rapidly aging population to rely on domestic service robotics "to enable sustained personal autonomy."[43] While the Japanese might believe they have no other option than robotics to solve their demographic problems, they clearly anticipate robotics will transform their society – which is a truly revolutionary mindset. Just as the Japanese and Koreans look to robotics to solve the problems of an aging population so too must the United States. While the demographic problems of an aging population are more severe in Japan and Korea than in America, the United States is not immune to these demographic forces. Projections show the number of retirees as a percentage of the workforce doubling to 40% by 2030.[44]

The Koreans are not much different from the Japanese when it comes to recognizing the revolutionary impact of robotics. They have called for an intelligent service robot in every home by 2020, only nine years from now, and South Korea's Ministry of Commerce, Industry and Energy has even begun "drawing up a code of ethics to prevent human abuse of robots – and vice versa."[45] They even intend to have the ethical standards programmed into robots.

The Japanese and Koreans look beyond robotics as simply automation tools that increase manufacturing output, and see solutions for intractable social, demographic and economic problems. Sound policies, emphasis on research and development, and large investments support their embrace of the anticipated robotics revolution. From looking at these types of policies and large-scale investments, it is clear Japanese and Korean policymakers grasp the significant transformational impact robotics can have on their societies and economies. More significant is their willingness to act.

"SAVE YOUR FACTORY"[46]

Introduction

Throughout history, manufacturing processes continually mature. Whether it be the industrial or the information age, technology continues to rapidly transform every aspect of our lives. At present, one could say we are on the cusp of the robotics age. To quote the former Secretary of the Navy, Gordon England, "Unmanned systems are now on the threshold of delivering on the promise of transforming our military, and likely, our society."[47] If used wisely, harnessing robotics and other autonomous systems can increase the effectiveness and efficiencies of manufacturing, increasing American competitiveness, ultimately returning U.S. manufacturing capacity and productivity to our shores.

For decades, corporations moved production facilities from American soil in nearly all sectors to cheaper, but not necessarily better overseas manufacturing locales. The heyday of the United States being a single-source behemoth-manufacturing nation are in the past. As an example, the industry in which American revolutionary patriot, Paul Revere, was an artisan no longer exists in the U.S. Metal flatware ceased to be produced in the United States after the last flatware factory closing in Sherrill, N.Y., in August 2010.[48] Although there is a certain amount of American pride and nostalgia involved with the flatware industry, capital investment in robotic manufacturing processes can fundamentally change the business case for moving offshore.

Robots and Why We Need Them

Innovation and continuous process improvement through robotics can improve U.S. productivity. The Robotics Industries Association defines a robot as, "a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks."[49] The use of robotics can be viewed through the lens of creative destruction, which divests human capital from executing precise and repetitive tasks so they can focus on other tasks. The U.S. Robotics Roadmap states, "Robotics is a key transformative technology that can revolutionize manufacturing."[50]

Fundamentally, efficient manufacturing and robotics intersect at those tasks considered dull, dirty and dangerous. In the robotics vernacular, these are the "3 D's." Over the recent past, many members of the U.S. workforce have increasingly transitioned away from traditional "blue collar" work leaving an opportunity for businesses to leverage robotics in order to further increase productivity. One example of a "3 D" task in the manufacturing industry is palletization. In late 2007, the Walkers' snacks factory in Coventry, England replaced its manual pallet handling process with an automated sorting and palletizing system. Operating on a 24 hour, seven day a week schedule, three employees are able to palletize products for movement to the Walkers' distribution centers. The system handles around 800 pallets a day of products from any one of 26 stock-keeping units, randomly arriving at the rate of around 60 per minute, on 6 conveyors.[51] Walkers' automated process, the ability to move this quantity of product with only three employees, provides a distinct competitive productivity advantage.

Bring Manufacturing back to America

Fanuc FA America is a leading industrial robotics company, based in Detroit, Michigan, providing servomotors and large robotic arms to a broad range of firms. They are also the leading company, among 21 other companies, working with robotics and automation to return the manufacturing base back to America. In their grassroots effort called "Save Your Factory,"[52] they emphasize the importance of manufacturing to the United States gross domestic product (GDP). Manufacturing leads all other sectors in representing 14% of the U.S. GDP and about 11% of the total employment.[53] Manufacturing also leads in innovation, providing 67% of total private sector research and development (R&D), 90% of the nation's patents, and compensation that is 15% higher than the national average.[54]

Through the "Save Your Factory"[55] campaign, Fanuc FA America hopes to convince other manufacturing companies not to abandon existing domestic facilities for the promise of lower labor rates in Asia, India or Mexico. Instead, Fanuc is championing robotics among peer companies to improve efficiency and automating manufacturing processes. Fanuc's advocacy helps companies realize the potential benefits of remaining in North America versus offshore manufacturing. It includes an analysis of cost, looking also at the end-to-end processing – quality, productivity, inventory, labor, supply chain which effect manufacturing productivity. This assessment brings to light typical pitfalls and hidden costs, often not discussed during conversations associated with overseas manufacturing. Cumulatively, these are at least 24% of additional offshore costs. These additional costs include transportation at about 17%, quality issues at 4%, travel and communications at 1%, and finding a vendor at 1%.[56]

Of greater importance to a manufacturing company are the pitfalls, of which it likely has little or no control, affecting an overseas plant. These include such things as disruptions in the supply chain due to natural or manmade disasters, political unrest and unstable economies. Additional areas of concern include, but are not limited to, currency risk, long lead times, language barriers and lost intellectual property.

Conclusion

Robotics has not yet been widely accepted by many manufacturing sectors and in some cases perceived more as a novelty. However, robotics and autonomous systems ideally nest in the lean manufacturing processes, capable of generating significant cost savings. The Robotics Industry is on the cusp of becoming the industry of the future. It takes education, honest assessments, and rigorous analysis of the specific company's processes and objectives to decide whether robotics warrant the capital investment. However, robotics undoubtedly represents an opportunity for firms to improve manufacturing productivity and better compete globally.

MEDICAL ROBOTICS

This essay explores the medical robotics market to highlight how consumer demand, industry research and development, academia, and government regulation coexist and allows for growth and innovation. Additionally, two market segments will be discussed in order to highlight the aforementioned conditions. The first segment is surgical tele-robots, in which the surgeon remotely controls the robot conducting the surgery. The surgeon uses a combination of foot and hand controls to direct the surgical robots movements inside the patient. The robotic arms hold a variety of instruments, sensors, and cameras. The second is the prosthesis and orthosis market sector. Robotic orthosis is commonly known as exoskeletons.

The good news is that, overall, the medical robotics market is healthy and growing. The bad news is that one of the reasons it is growing is because the demand is as well. The Center for Disease Control and Prevention predicts a significant rise in the number of patients diagnosed with diabetes by 2050. This, combined with an increase in obesity, dramatically increases the likelihood of lower leg amputation.[57] In a 2009 brief to the Congressional Robotics Caucus, Microsoft Corporation's General Manager highlighted the growing medical requirements of an aging population coupled with the downward trend in numbers of healthcare professionals available to treat them.[58] The brief suggested medical, surgical, and healthcare robots as part of the solution to address this forecasted patient-caregiver gap.

Government and private interaction in the market is extensive. The Food and Drug Administration (FDA) oversees and regulates the medical industry. DOD and the Department of Veterans Affairs (VA) provide research funding and are consumers of these systems. Universities around the world conduct medical robotic research and development on device utilization. Private companies provide venture capital and technical components to the industry. Individual companies compete for customers in areas ranging from patients and the hospitals in which they are treated, to their insurance companies, who help pay for the procedures or devices.

Robotic tele-surgery provides a good example for how government regulation can be flexible enough to allow competition; although at first glance, this doesn't appear to be the case.

There is only one FDA approved tele-robot system in the U.S. giving Intuitive a monopoly in the U.S. market. It is the da Vinci system manufactured by Intuitive Surgical, a California based company. The da Vinci system has also been approved for use in Japan, Korea, and Europe. Intuitive's Price-Earnings Ratio has outperformed the industry by a large margin (Last 5 years of 87.20 compared to the industry of 67.32).[59]

The need to get FDA approval in order to use the product in the United States may seem to be a significant barrier to entry. The reality, however, is that many overseas companies have or are in the process of obtaining FDA approvals for their systems. In fact, Intuitive indirectly acknowledges this in their most recent annual 10-K report.[60] They list Alf-X and Titan Medical as competitors. Both companies manufacture tele-robot surgical systems and are attempting to enter the U.S. market. Alf-X is owned by the Italian company SOFAR. Titan Medical is a Canadian company that manufactures the Amadeus system, which is set for initial testing in New York at Rochester General Hospital.[61]

Government participation in the robotic prosthesis and orthosis market segment is less visible. Most prosthetics and orthosics fall under an FDA category that does not require federal testing and approval prior to being introduced on the market.[62] There are oversight and reporting requirements; however, the external devices do not go through the same process required of a surgical device. Devices that require surgery for implant require full FDA approval. This can be significant as there are nearly 1.7 million people in the United States with some form of amputation. This number allows for a vibrant, competitive marketplace.[63]

This competition facilitates the entry of small companies into the market. The availability of money for research also encourages new entrants. The VA was the largest funding source for iWalk's PowerFoot prosthetic device, which is certainly on the cutting edge of technology.[64] PowerFoot was the first foot and ankle prosthetic that did not rely on energy provided by the patient.[65] Since its introduction to the market, iWalk has secured significant private venture capital to continue research, development, and production.[66] Other federally funded prosthetic research grants include the VA's $14 million funding of Brown University's Center for Restorative and Regenerative Medicine and the Defense Advanced Research Projects Administration's (DARPA) funding of DEKA Research's prosthetic arm known as "Luke." Another source of funding is through licensing. For example, Berkeley Bionics' Human Universal Load Carrier exoskeleton was licensed to Lockheed Martin in 2009. In 2010, Berkeley Bionics introduced eLEGS, an exoskeleton designed to provide mobility to patients previously confined to wheelchairs.[67] As recently as May 2011, a University of California, Berkeley, paraplegic student was able to walk across the stage at his commencement ceremony with the assistance of the Berkeley Lower Extremity Exoskeleton (BLEEX). BLEEX is the result of a DARPA grant to develop a way for people to carry heavy loads over greater distances, but it could be a wheelchair alternative.

Given the predicted health conditions elaborated earlier, the future of the robotic prosthesis and orthosis market sector looks bright. There is sufficient government, industry, and private funding for research and development, as well as, venture capital for production to ensure innovation continues. This sets the stage for a competitive market both in the United States and abroad. Robotic technology will continue to serve as a driver of this competition and, ultimately, the patient will reap the benefits.

The FDA, as the principle entity governing the market segment, has a regulatory system that allows innovation from domestic and foreign companies. It has in place mechanisms to fast-track new technologies through the evaluation and approval process.[68] There is also venture capital available to support research and development. All of these factors, combined with the increasing demand for the devices, ensure a competitive market.

This is not to say funding from government organizations like the VA and DARPA are not beneficial. Relatively small amounts of grant money can go a long way, particularly in the prosthetic market segment. Therefore, in an environment of shrinking budgets, government organizations do not have to be the sole or even largest funding source. The government should monitor the market closely and determine where promising technologies are not being adequately funded. Government can then encourage private sector financing through incentives or use their own limited resources to enable research and development.

CONCLUSION

The Robotics Industry encompasses the industrial and service robotics markets. The industrial market is comprised of the manufacturing and logistics market segments, and the domestic and professional segments divide the service market. The professional service segment includes the military service robotics segment. This industry study concentrated on the industrial manufacturing and the military service robotic segments. Though the industry faces several challenges, these two specific segments are well poised to support U.S. national security goals and objectives.

The overall Robotics Industry faces two overarching challenges, while the manufacturing and military robotic market segments face four specific challenges for the short and long-term. The industry as a whole suffers from a mismatch between the state of robotic technology and consumer expectations. Technology, so far, lags consumer ideas about what robots ought to be able to do. The second overarching challenge is social acceptance of robots. The public remains wary of robotic technology, particularly where safety is concerned or where the perception is they affect employment. The FAA's reluctance to allow UAVs in the national airspace and the United States' lower robot density highlight this issue. The importance of industrial robotics to continued U.S. manufacturing primacy is a specific challenge for the industrial manufacturing market segment. However, due to relatively low robot density in the United States, robot manufacturers and integrators enjoy fertile market conditions for growth, which if harnessed will preserve U.S. manufacturing preeminence, thereby retaining the industrial base's ability to support the national security strategy's goals and objectives. The military robotic market segment faces technological challenges, specifically power and communications capabilities, the prospect of reduced OCO funding, and export controls limiting international market development. Despite these challenges, the segment's ability to support national security is sound.

Several questions focused the analysis found in this report. The first question asked if the U.S. military would continue to require these technologies. While there may be lean years in the short term for the military robotics market segment, the technology has clearly demonstrated the potential to be a force multiplier, and military robotic systems are now well-established components of the U.S. arsenal. The second question asked if Congress would continue to fund the acquisition of military robotics in the coming era of tighter budgets. The analysis concludes that military robotics supports national security requirements; therefore, Congress is likely to continue funding research and development in military robotics and acquisition of new systems over the long term. The third question asked if military robotics companies could develop and grow a commercial market for their products. The U.S. government will likely remain the primary buyer for military robotics systems for the near future. Commercial diversification, to include foreign sales, will be important within this market segment. As noted earlier in the report, specific U.S. government action can help ensure the long-term health of the Robotics Industry and its ability to continue supporting national security policies.

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[22] Ibid, 2-3.

[23] Ibid, 3.

[24] Lucas, *Industrial Challenges of Military Robotics*, 3.

[25] It may be surprising to know programmers and engineers do not always know exactly how a system will perform, but this is really the basis of experimentation and testing. We design systems and see if they do what we think they will do. In the grand scheme, they often do, but invariably engineers will find their machines reacting in ways they did not expect. This is what leads to better and better products. The problem is as machines get more and more complex, finding ways to test extensively gets harder and more expensive. There is no way to test absolutely everything, and therefore some systems that make it the market still have flaws. You know this implicitly if your car has ever been recalled.

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[27] Lin, Bekey and Abney, *Autonomous Military Robots: Risk, Ethics, and Design*, 64.

[28] Ibid

[29] Capurro and Nagenborg, *Ethics and Robotics*, 93.

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