# Spring 2012
# Industry Study

# Final Report
## *Robotics and Autonomous Systems Industry*

**The Industrial College of the Armed Forces**
National Defense University
Fort McNair, Washington, D.C. 20319-5062

# ROBOTICS AND AUTONOMOUS SYSTEMS 2012

**ABSTRACT**: Revolutionary advances in robotics and autonomous systems (RAS) will fundamentally change how we conduct our lives, business, diplomacy, and wars. New applications of robotics and autonomous systems, paired with advances in mobile and networked computing power, will revolutionize military, industrial, and commercial operations. Historically, the Department of Defense (DoD) has led the development of many useful and fundamental technologies. However, looming cuts to the federal and DoD budgets risk stunting the robotics revolution. To maintain technological superiority and reduce future operational costs, DoD should sustain and foster continued research, development, and implementation of robotics technologies. This report provides analysis of the current robotics and autonomous systems industry, compares and contrasts developments in domestic and international markets, yields insight into some of the daunting challenges facing the continued advancement of robotics, and offers recommendations for government and industry to ensure that both economic and security interests are well served with a common set of investments.

## ACKNOWLEDGEMENT

Our industry study group was privileged to meet with senior leaders from companies, research institutions, industry associations, and government and military organizations in the United States, South Korea and Japan. We are deeply grateful to all those who shared their insights, perspectives, and valuable time with us. We also wish to thank the ICAF faculty—Dr. Stephen Ford, Mr. Ted Mann, and Col David Gerber, USAF—for their hard work organizing the broad array of interaction with the robotics industry and their expert guidance and advice.

Mr. Michael Burkly, U.S. Agency for International Development
Mr. Jack Crisler, Lockheed Martin
Lt Col Erich Hernandez-Baquero, U.S. Air Force
Lt Col Eric Krystkowiak, U.S. Air Force
Col Geoffroy Lenglin, Direction Generale de l'Armement
Lt Col Kendra Mathews, U.S. Air Force
Mr. Timothy O'Hara, National Security Agency
CDR Fred Pyle, U.S. Navy
Lt Col Eric Ropella, U.S. Marine Corps
CDR Arlene Shoults, U.S. Navy
COL David Shugart, U.S. Army
Ms. Susan Tomaiko, Department of Navy
LTC William Turmel, U.S. Army
Col John Wilson, U.S. Air Force
Ms. Lynn Wright, Defense Intelligence Agency
Dr. Stephen Ford, Faculty
Mr. Ted Mann, Department of State, Faculty
Col David Gerber, U.S. Air Force, Faculty

# PLACES VISITED

**Domestic:**

AAI Textron Systems (Hunt Valley, MD)
AeroVironment (Simi Valley, CA)
Applied Minds (Glendale, CA)
Aurora Flight Sciences (Manassas, VA)
Bluefin Robotics (Quincy, MA)
General Atomics Aeronautical (Poway, CA)
GT Aeronautics (Simi Valley, CA)
iRobot (Bedford, MA)
Jet Propulsion Laboratory (Pasadena, CA)
Kiva Systems (Boston, MA)
Massachusetts Institute of Technology Humans and Automation Laboratory (Cambridge, MA)
National Robotics Engineering Center (Carnegie-Mellon University) (Pittsburgh, PA)
Naval Explosive Ordnance Disposal Technology Division (Indian Head, MD)
Naval Research Laboratory for Autonomous Systems Research (LASR) (Washington, DC)
Northrop-Grumman (Palmdale, CA)
Quality Life Technology Center – University of Pittsburgh (Pittsburgh, PA)
RedZone Robotics (Pittsburgh, PA)
re2 (Pittsburg, PA)
Seegrid Corporation (Pittsburgh, PA)
Space and Naval Warfare Center (San Diego, CA)

**International:**

**Korea**
Korea Advanced Institute of Science and Technology
Korea Association of Robot Industry
Defense Acquisition Program Administration
Ministry of Knowledge Economy
Samsung Techwin
U.S. Embassy Country Team

**Japan**
Ministry of Economics, Trade and Industry
Ministry of Defense, Advanced Technology Center
Advanced Institute of Science and Technology
Komatsu
Toyota
Denso Wave
U.S. Embassy Country Team
U.S. Army, International Technology Center Pacific

## ORGANIZATIONS BRIEFING AT ICAF

Association of Unmanned Vehicle Systems International (AUVSI)
Defense Advanced Research Projects Agency (DARPA)
Israeli Aerospace Industries (IAI) North America
Office of Science and Technology Policy (OSTP), Executive Office of the President
QinetiQ North America

**Unmanned Aerial Vehicle (UAV) Panel**
Air Force: HAF/A2CU
Army: UAS Division, HQ Department of the Army, G-3/5/7
Navy: OPNAV N2/N6
US Marine Corps: Navy and Marine Corps Small Tactical Unmanned Aircraft Systems

**Unmanned Maritime Vehicle (UMV) Panel**
Navy: UMV Systems, PMS-403
Naval Undersea Warfare Center

**Unmanned Ground Vehicle (UGV) Panel**
Joint Ground Robotics Enterprise, OSD AT&L
Robotics Systems Joint Program Office (RS JPO)

## INTRODUCTION

Revolutionary advances in robotics and autonomous systems (RAS) will fundamentally change how we conduct our lives, business, diplomacy, and wars. Since their introduction in the late 1950s, industrial robotics augmented and eventually displaced humans on assembly lines worldwide, tirelessly conducting repetitive actions with unmatched precision. The last decade has seen tremendous growth in the use of robots in a broad range of applications such as warfare, surgery, agriculture, and home care. New applications of robotics and autonomous systems, paired with advances in mobile and networked computing power, will revolutionize military, industrial, and commercial operations. Advances in autonomy will improve how man and machines integrate and collaborate, transitioning from "man-in-the-loop" to "man-monitoring-the-loop." Eventually, networked and robotic homes will enable aging populations to delay and potentially prevent the transition to assisted-care facilities. While some of these technologies are at inflection points, others are still at a basic research level. Thus, significant long-term investments are still required.

Historically, the Department of Defense (DoD) has led the development of many useful and fundamental technologies. However, looming cuts to the federal and DoD budgets risk stunting the robotics revolution. To maintain technological superiority and reduce future operational costs, DoD should sustain and foster continued research, development, and implementation of robotics technologies. Because this development also benefits other government and commercial sectors, the effort should be part of a national strategy for robotics linked to the national security strategy, national military strategy, joint operational concepts and doctrine, and executive policies driving technology priorities, incentives for research, education, and regulatory reforms.

This report analyzes the current robotics and autonomous systems industry and its overall health, compares and contrasts developments in domestic and international markets, and reviews some of the daunting challenges facing the continued advancement of robotics. It concludes by offering recommendations for government and industry to solve those challenges, while sustaining the continued revolution in robotics.

## THE INDUSTRY DEFINED

The RAS industry comprises many markets in two major segments: industrial and service. Industrial robots have demonstrated revolutionary potential in manufacturing by dramatically increasing scalability, cost-effectiveness, reproducibility, and quality in mass production. Industrial robotics is a mature market – industrial robots continue to be deployed at a sustained rate of 120,000 units per year modernizing manufacturing and spurring global economic growth.[1] Service robot markets are less mature but more diverse—and likely to grow significantly in the next ten to twenty years. This segment is the focus of this industry study. The figure on the next page is a graphical representation of the industry, divided into industrial and service segments.

The service robotic segment is divided into domestic and professional applications. Professional applications perform commercial or government tasks where systems are operated by trained operators while domestic applications perform non-commercial tasks where systems are operated by laypeople.[2] Professional service robots in the commercial sector can include those used in agriculture, mining, space, logistics, infrastructure inspection, and medical markets. In the government sector, markets include unmanned ground vehicles (UGVs), space research systems, unmanned air vehicles (UAVs) (also referred to as unmanned air systems (UASs)), and unmanned underwater vehicle systems (UUVs). Domestic service robot markets include services such as vacuuming, lawn mowing, security, and personal assistants that monitor medical status.

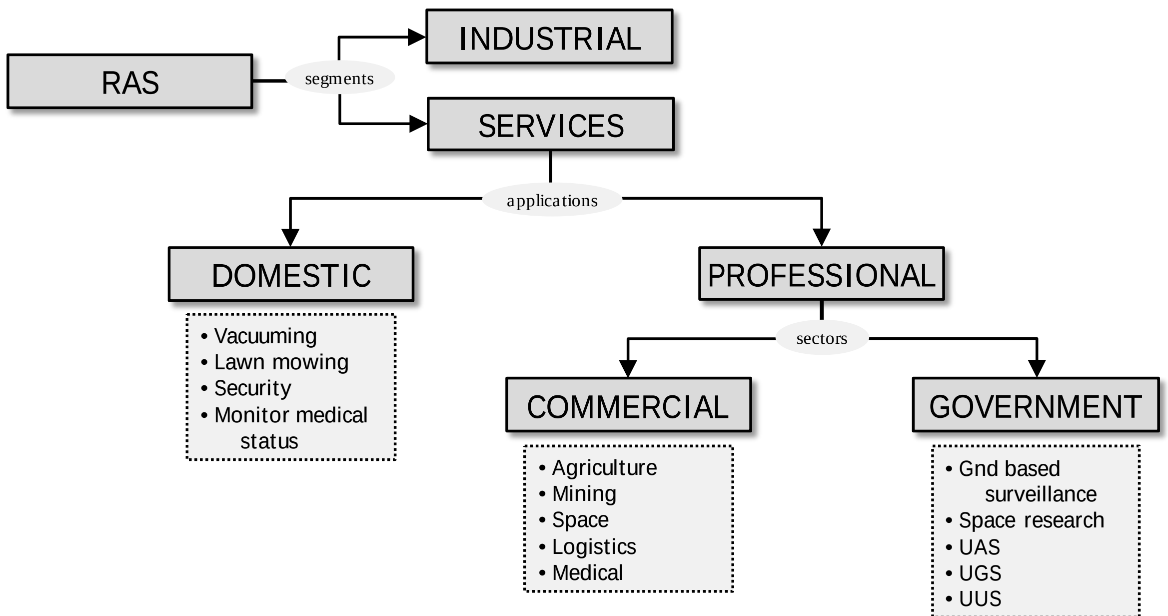


Figure: Schematic of the Robotic and Autonomous Systems Industry.

The service robotic segment is divided into domestic and professional applications. Professional applications perform commercial or government tasks where systems are operated by trained operators while domestic applications perform non-commercial tasks where systems are operated by laypeople.[3] Professional service robots in the commercial sector can include those used in agriculture, mining, space, logistics, infrastructure inspection, and medical markets. In the government sector, markets include unmanned ground vehicles (UGVs), space research systems, unmanned air vehicles (UAVs) (also referred to as unmanned air systems (UASs)), and unmanned underwater vehicle systems (UUVs). Domestic service robot markets include services such as vacuuming, lawn mowing, security, and personal assistants that monitor medical status.

Due to the wide range of applications and similarity to other technologies, it is important to clearly define robots and autonomous systems. For the purposes of this study, robots are defined as devices that can sense their environment, make decisions about their role in that environment, and take action to alter the state of the environment to accomplish a task or mission.[4] The utility of a robot is a function of how well it can accomplish its assigned mission and to what extent it can do so at a level of autonomy that is consistent with that mission.[5] Finally, a robot's autonomy refers to its ability to accomplish assigned tasks in a real-world environment without human intervention.

The RAS industry reflects the characteristic strengths and weaknesses inherent in robots. Robots are fast, precise, and tireless. Conversely, they are significantly limited in perception, reasoning, and adaptability—enablers for autonomy. Consequently, many robots currently operate via remote control or within highly controlled environments. Without autonomy, robot utility will remain constrained. Additionally, robots are typically networked at the operator control unit level and not at the robot-to-robot level, thus limiting robotic collaborative behavior and efficiency. Partly because of these limitations, robotic systems are heavily tailored to specific applications leading to significant market segmentation.

## CURRENT CONDITION

Combat has been a major force driving advances in service robotics in the United States over the past decade. Today, tens of thousands of DoD robots operate on land, sea, air, space and cyber domains and battlefield injuries have prompted significant advances in robotic prosthetics. Worldwide, professional and domestic markets have seen continuous growth of over 20% per year.[6] However, due to limitations and cost of technology, broader adoption and integration of service robots is lagging. Thus, governments and robotics manufacturers invest heavily in research and development (R&D) and maintain close collaborative ties with research laboratories and academia. In the U.S., this "web of innovation" is a complex array of public and private activity that taps into dynamic investment markets. In Japan, there is a similar structure with higher barriers to entry and limited entrepreneurship. In South Korea, the government plays a large role aligning public and private investment and "creating demand" for service robots.

Because of the wide range of applications, cost, performance, actors, and attributes associated with all the markets in the RAS industry, it is impractical to analyze the structure, conduct, and performance of the industry as if it were one unified market. Therefore, this study will focus on specific markets for UAVs, UGVs, medical robotics, and domestic service robots as illustrative of the major forces and dynamics in the RAS industry (see appendix for application of the Five Forces Model to each market).[7]

### UAV and UGV Markets

Counterinsurgency operations in Iraq and Afghanistan spawned and sustained an unprecedented demand and use of UGVs and UAVs. Not surprisingly, the defense industry grew rapidly to meet this demand. For many of the firms in these markets, DoD represents the majority of their revenue growth in the last ten years. Thus, UAV and UGV markets are strong monopsonies.

UAVs with Intelligence, Surveillance, and Reconnaissance (ISR) and offensive capabilities have rapidly grown in numbers. The DoD UAV inventory has grown from fewer than 50 in 2000 to over 6,800 in 2010.[8] The U.S. is on track to spend $26 billion on UAV Research, Development, Testing, and Evaluation (RDT&E) between 2001 and 2013. In the Fiscal Year (FY) 2013 budget submission, DoD requested $5.78 billion in procurement and development funding for UAVs.[9] While UAVs account for just 8% of the warplane budget they represent more than 30% of total aircraft flown.[10] Systems range from small UAVs, such as the RQ-11 Raven, to large High Altitude Long Endurance (HALE) UAVs, such as the RQ-4 Global Hawk. These platforms operate with different performance characteristics and form separate markets, where large and small defense contractors compete fiercely.[11] Significant UAV industries exist internationally. In Israel, for example, the market is very competitive and firms have expanded to international markets, especially to the U.S., Europe, and Latin America.

UGVs remain a narrow and specialized field within DoD except for the proliferation of remotely operated Explosive Ordinance Disposal (EOD) robots and mine-clearing vehicles used to counter Improvised Explosive Devices (IEDs) in Iraq and Afghanistan. DoD's rapid and large purchases of commercial off the shelf (COTS) EOD robots to meet urgent war demands led to a market dominated by two manufacturers – QinetiQ North America and iRobot. While technological barriers to entry are relatively low, DoD is likely to consolidate its investment in these systems and standardize configurations, making it difficult for new entrants to compete in this market.[12] Additionally, the market has not been lucrative enough to attract competition from large defense companies.[13] In South Korea, the market for ground robots is heavily influenced by the security environment driving demand for sentinel vehicles and posts. In Japan, the aftermath of the Fukushima disaster has created an impetus to develop rescue robots.

As opposed to the UAV industry's attempt to create new domestic markets with access to the National Airspace System (NAS), UGV manufacturers—with some exceptions—appear content to sell their current products to DoD, international military customers, and U.S. law enforcement organizations. Though DoD experiments with other UGV systems and technologies such as driverless truck convoys, exoskeleton robots to assist warfighters, and autonomous infantry squad-level logistical vehicles, these systems remain technologically immature. There are, however, some commercial applications where the technology is beginning to take hold. UGVs are bringing efficiency to warehouse operations and driverless car technology is evolving from Cadillac's "supercruise" to full automation with Google's experimental effort.[14] Most of the firms tapping into these technologies represent a strong substitution threat to incumbents in the market and come from markets and sectors of the economy that do not normally provide direct support to defense. (See Appendix for Five Forces model of the UAV and UGV markets)

**Medical Market**

Medical robotics is a growing industry that is earning revenue through new technical advances to meet the unique demands of medicine and health. Innovations in the medical robotics field fall into several sub-segments including assisted surgery, prosthetics, mobility assistance, needs-assistance robots, and intelligent homes for the disabled and the elderly. Each sub-segment is generally a monopolistic competition with a handful of companies combining electro-mechanical technology with medical expertise. Rival companies differentiate products and services based on capability improvements. Intuitive Surgical, which produces the Da Vinci surgical robot in use in thousands of hospitals, is a good example of the lifecycle of a medical robotics firm.[15] The market is also susceptible to new entrants that do not normally serve medical markets (e.g., Toyota in Japan).

The business model for medical robotics in the U.S. often involves a company that is able to apply intellectual property (IP) to fill an existing need in a better way than the equipment currently on the market. Often, the IP is generated from joint ventures that include the government, academia and/or industry. Venture capitalists provide start-up funds until the company can return a profit and operate on its own. A company must then develop a prototype and conduct tests to prove the device's safety and efficacy in order to enter the regulatory approval phase. Once the product or procedure receives approval, it can be offered for sale to the public. Successful start-up companies, along with their IP, are often acquired by large medical devices firms.[16] Performance in this market is thus heavily influenced by investment patterns and specific market strategies.

Some U.S. investment companies see the Patient Protection and Affordable Health Care Act as detrimental toward investing in medical robotics or the larger medical devices field since the Act focuses on low cost solutions over high cost, high technology devices. Further, a new excise tax on medical devices could also negatively impact the U.S. medical robotics industry.[17] These concerns may be inhibiting venture capitalists from investing in the medical devices industry sector. While investment in all sectors declined dramatically during the "great recession" of 2008-2009, investment in medical devices has returned to only 76% of its peak value compared to 92% for all sectors combined.[18] In South Korea, the government actively funds medical service robots as an "industrial core technology" and began a pilot project in 2012.[19] In Japan, the government focuses on safety standards, test, verification, and certification requirements while industry and academia develop partnerships to transition technology into marketable products. (See Appendix for Five Forces model of the medical market)

**Domestic Service Markets**

Domestic service robot markets are characterized by worldwide monopolistic competition among many small companies and a few large corporations. Barriers to entry include high capital costs that can prevent firms from achieving the economies of scale needed to remain competitive in a global market. Small companies risk losing intellectual property to larger companies that can afford to license and patent their IP. Extensive standardization activities, by both industry and government, are lowering some barriers to entry and ensuring the quality of the robotics products that will be brought to the commercial market. To meet market demands and consumer expectations, firms increasingly have to improve domestic service robots reliability[20] and reduce prices.[21]

The U.S. domestic service robotics industry has been enhanced by strategic partnerships, like that of iRobot with Texas Instruments[22] and with InTouch Health[23], which has promoted new market penetration, both horizontally and vertically. Startup companies, like GeckoSystems, are expected to continue to create and foster innovative ideas and products in the domestic service robotics market; including the home health care robotics segment. Additionally, U.S. domestic service robotics companies are seeing penetration into the European and Asian markets that has enhanced overall company strength. For the U.S. military industrial complex, strength in the domestic service robotics industry can provide the enduring base necessary to enable robotics companies to weather defense budget reductions. Companies such as iRobot that have strategically diversified their robotics portfolio to include both defense and commercial products, have successfully been able to transfer technologies between both market segments.[24] Companies that remain innovative and maintain strong R&D philosophies will continue to foster technologies that can be applied to defense systems now and in the future.

In 2010, over 1.4 million domestic service robots were sold worldwide with a value of over $369 million[25]; a 44% increase from the previous year. However, domestic service robots account for only 10% of the total sales of service robots (professional and domestic). (See Appendix for Five Forces model of the domestic service markets)

## OUTLOOK

**Defense Markets**

In the next one to five years, the new defense strategy and federal budget reductions will create a much different domestic environment for the RAS industry. With the U.S. drawdown in Afghanistan, DoD will begin consolidating its inventory of 4,000 unmanned systems and instituting configuration management.[26] The Defense Logistics Agency intends to declare hundreds of robots and unmanned systems as excess defense articles and make them available to law enforcement agencies and first responders.[27] The RAS industry will realize two new opportunities if these programs prevail. First, the excess robots and unmanned systems will have to be de-militarized and reconfigured with sensors and equipment specific to their new missions. Second, lifecycle maintenance will likely emerge from service repair and overhaul shops and depots to create a market for commercial sustainment. At the same time, the new defense strategy pledges support for emerging technologies including specifically, robotics.[28] UAVs may be one area of growth or sustained acquisition. The Teal Group estimates that UAV spending will almost double over the next decade from current worldwide UAV annual expenditures of $6.6 billion to $11.4 billion, for a total of over $89 billion in the next ten years. Additionally, "…the U.S. will account for 62% of the worldwide RDT&E spending on UAV technology over the next decade, and 55% of the procurement." The same study also predicts that sensor and payload upgrades and integration into UAVs will grow from $2.7 billion in 2012 to $6 billion before 2021. Specifically, the UAV ISR and electronic warfare markets will see massive 20.2% compounded annual growth rate (CAGR) from FY12 to FY17.[29] These opportunities are not limited to the U.S. Visiongain, a European business intelligence company, recently released a report that analyzes ISR capabilities for the unmanned systems industry. Visiongain forecasts that greater access to unmanned systems will grow the global demand for ISR on robots and unmanned systems beyond the eight billion Euros mark in 2012.[30] Notwithstanding these positive forecasts, there will likely be a reduction in the procurement of small tactical UAVs as the Army and Marine Corps force structure is reduced.

The near-term outlook for military UGVs is not as favorable. In its FY13 budget, the Army will only spend $112 million on UGVs while spending $796 million on UAVs.[31] A niche capability area, the DoD UGV market will remain limited to the purview of small to medium companies that can capitalize on product improvements and RDT&E funds. Other than improved sensors and manipulator arms/tools for EOD robots,[32] there does not appear to be cost-effective and reliable solutions to address near-term DoD needs. Consequently, the medium UGV manufacturing sector will more than likely see a contraction commensurate with the reduction in DoD procurement as U.S. ground forces will no longer face a significant IED threat. Small UGV manufacturers and those who produce subsystems should survive the defense budget downturn because DoD will continue to maintain robust funding of RDT&E in UGV technologies.[33] Thus, while some sectors will be adversely affected, the future presents several opportunities for the RAS defense industry.

The long-term future (five to fifteen years) also bears much promise for the RAS defense industry as robotic systems are likely to grow more pervasive across DoD capabilities. Several factors point towards this trend: the need to reduce the life-cycle cost of capabilities for enduring military missions; the growing need for persistent and responsive theater C4ISR and quick strike capability across the globe; and the prevalent trend to reduce the risk to warfighters in the battlefield. However, to reduce life-cycle costs, robotic systems will need to be more autonomous and reduce manpower requirements. From 2000 to 2012, DoD's military compensation costs grew over 50%, or $60 billion, with only a 1% growth in the total force, while medical costs rose from 14% to over 24% of total compensation costs during the same period.[34] This growth trend is not likely to abate in the future and will continue to crowd-out other military cost accounts. Thus, autonomous robotic systems will increasingly be used in functions such as security, convoys, reconnaissance, and maintenance with minimal human supervision. Robotic system offensive and defensive capabilities are also likely to improve, including the use of larger smart munitions and directed energy systems.

**Commercial Markets**

Worldwide, the financial outlook is positive for service robot markets. The International Federation of Robotics predicts the service robot market will double in the next three years, for professional use, personal use, entertainment and education.[35] Security, health and personal assistance are the main field of expected growth. In January 2011, the Korean Ministry of Knowledge Economy expected service robotics to skyrocket from about $7.8 billion in 2011 to $45 billion in 2016 and to reach 85% of the overall robotics market.[36] The Ministry of Economy, Trade, and Industry (METI) of Japan forecasts long-term robotics growth from $20 billion in 2015 to $120 billion in 2035 with service robots making up 40-50% of sales.[37] The aging population in developed countries[38] and the expansion of Asian markets present growth opportunities.

In the commercial sector, there is a strong case to be made that robots can add significant value to businesses in the near future. First, speed and accuracy are becoming a dominant measure of business performance. Speed is critical at various levels, from production to strategy, as organizations adapt to a rapidly changing environments.[39] Second, robots and unmanned systems will increasingly integrate sophisticated software and analytical tools to improve business operations. Today, warehouse robotic systems, like those developed by Kiva Systems, are examples of how the technology is beginning to create value in business. Third, robotic systems can reduce manpower in low-value segments of the supply chain reducing the overhead associated with salaries, health care, retirements, or other personnel costs. Finally, there will be continued exponential growth and progress in Information and Communications Technology (ICT) and a proliferation of sensors. This has already led to the "big data" problem and a demand for cloud computing and next-generation analytics to aid informed decision-making in business.[40] The solution to these problems will require cognitive algorithms that will increasingly look like artificial intelligence.[41] The technology is likely to have ancillary benefits in a wide range of fields, as recent applications to finance,[42] medicine,[43] and astronomy[44] demonstrate. Thus, there will be significant growth in near-term demand for intelligent agents and automation.

There is also a growing trend in mobile ICT. The next step in the evolution of the technology is to go from smartphones and tablets to wearable devices such as watches and glasses.[45] Biotechnology and nanotechnology will enable even smaller sensors and computing devices. Recent advances in biocompatible sensors have enabled invasive implants that monitor neural activity in the brain with very high fidelity.[46] These sensors improve brain-machine interfaces (BMI) dramatically by measuring individual neural cell output.[47] Ultimately, this could lead to the human brain being directly "wired" to computing devices and the internet. While this technology is still ten to twenty years out, it follows a pattern that has been in place throughout the 20$^{th}$ century. Additionally, nanotechnology is already enabling the creation of nanobots that can be used to treat a wide range of diseases, including cancer.[48] In the long term, nanobots could become part of a standard set of treatments and immune-boosting regimens offered in preventive medicine.

As labor markets become more globalized, there will be increased demand for telepresence (i.e., the ability for people to interact physically from a remote location). The technology is perhaps the most mature in medicine, where telepresence surgery has been in place since the 1990's.[49] Recent trends indicate that medical robots will branch out to a broader set of applications to "…allow fewer doctors to service more patients in more places."[50] In the long-term, these robots could become ubiquitous in various sectors, including education, elder care at home, entertainment, etc. There is also a trend of increased social activity and networking in virtual environments (e.g., Facebook, Google+, etc.), which will eventually lead to wider social acceptance of telepresence as an effective means to interact and collaborate remotely.

In the long term, robots will become more ubiquitous and will work closely with humans. This will be disruptive to society as it will affect how people interact, collaborate, and even wage war. Additionally, safety requirements and standards will be increasingly important. Once technological problems are solved, these may be the issues that will define future robotic products and markets (*see essay for in-depth discussion*).

## CHALLENGES

The RAS industry faces several major challenges that include outdated regulatory frameworks, high cost of technology, lack of international standards, and reduction in defense budgets. U.S. competitiveness in global markets is further affected by restrictive export controls and eroding science, technology, engineering, and mathematics (STEM) education. The latter issues, while not unique to robotics, have significant bearing on the industry.

**Regulatory hurdles restrict opportunities.** Three near-term regulatory roadblocks for wider deployment of robotic systems domestically are the integration of UASs in the NAS, quite literally developing the 'rules of the road' for driverless cars on the nation's roads and highways, and the expansion of robotic medical devices. The issues related to UAS integration into the NAS are primarily safety, interoperability, and the protection of civil liberties (*see essay for an in-depth discussion*). For driverless cars, states have authority over many of the rules and regulations allowing testing and deployment of vehicle technologies. To date, Nevada is the only state that has passed legislation allowing driverless cars to operate publicly.[51] Finally, providers of medical robots must overcome several legal, regulatory, and bureaucratic hurdles that limit innovation and discourage participation in the market (*see essay for an in-depth discussion*).

**High cost of technology inhibits product commercialization**. Currently, the high cost and immature state of key robotic technologies inhibits effective transition from basic research to product development except in unique markets. Technology advances have led to significant improvements in RAS but long-term investments are still required to achieve levels of autonomy that enable more effective and efficient human-robot collaboration (*see essay for an in-depth discussion*). Few robotics companies, however, have business models that can manage long-term investments and product development cycles. In fact, the trend in the market is to ever-decreasing product development cycles leveraging mature technologies. The ability of the RAS industry to bring to market relevant capabilities at the right price point for its new commercial and international customers will be a significant near-term challenge.

**Lack of commonly accepted standards limits industry growth.** A lack of standards significantly contributes to RAS industry fragmentation and inhibits potential growth. Potential technology adopters face uncertainty comparing robot suppliers, implementation methods, and safeguarding mechanisms due to the lack of performance specifications, standardized test methods, and technical guidance.[52] Until integrating RAS capabilities into existing commercial or home systems is as easy as installing a new piece of computer hardware or a new dishwasher, the RAS industry will not reach the tipping point of acceptance and will not realize the benefits of increasing network externalities (*see essay for an in-depth discussion*).

**Reaction to drawdown from war efforts and reduced defense budgets**. In response to declining DoD procurement budgets, RAS companies heavily leveraged by defense contracts, are transitioning to adjacent markets. In doing so, the industry will adapt its processes to satisfy new international and domestic customers with unique requirements. Companies will struggle to budget current operations and research and development to maintain a technological advantage, in order to strategically position themselves for future business with DoD. Consequently, defense companies depend on sound DoD vision and future requirements, as well as solid DoD technology roadmaps to justify corporate investment. Finally, the RAS industry has a stronger need to have systems appropriately categorized by export control authorities and, ultimately, obtain export licenses for hardware and services.

**Export controls limit international market development for U.S. military robots.** While controls are necessary,[53] updates to the existing processes, procedures, interpretation, and implementation could preserve industry's innovation while providing transparency and predictability. Many in Congress and industry argue that the existing set of export controls are outdated, restrictive, and limit the ability of industry to compete internationally. In response to criticism of U.S. export controls, the Obama administration launched a comprehensive review in August 2009. The results were announced in April 2010 by then Secretary of Defense Robert Gates. Secretary Gates outlined the new rules, or the "four singularities": 1) single export control licensing agency for both dual-use and munitions exports, 2) unified control list, 3) single enforcement coordination agency, and 4) single supporting integrated information technology (IT) system. The RAS industry's reaction to reforms has been generally positive although there is ongoing RAS stakeholder concern that the intent of the four singularities will not be maintained.[54]

**Erosion of STEM education undermines American innovation.** Currently, inadequate STEM education is a major factor contributing to America's loss of its innovative edge (the U.S. ranks 23rd in science and 31st in mathematics worldwide).[55] Minorities (with the exception of some Asian groups) and women are underrepresented in STEM fields, and the most proficient students—regardless of background—are choosing other professions.[56] Additionally, foreign students that study STEM in U.S. universities return to their countries depriving the U.S. of the benefits of their skills. Finally, workers face the threat of unemployment if they do not receive retraining to gain technical skills that are compatible with new technologies (including robotics).[57] Thus, to lead the global robotics industry, the U.S. must increase the output of STEM professionals.[58]

## GOVERNMENT GOALS, ROLES, AND RELATED RECOMMENDATIONS

The U.S. Government has a fundamental role in the development and adoption of robotic and autonomous systems. It can perform that role by implementing smart policies and investments that benefit national economic and security interests. The following recommendations offer pragmatic courses of action that will significantly improve the outlook for U.S. leadership in this critical industry.

**Recommendation 1: Establish efficient and effective regulatory frameworks that promote safety without stifling innovation.** New frameworks are required in at least three areas: streamlining medical certification processes, facilitating access to the National Air Space, and creating incentives and protections for driverless car manufacturers and users. To streamline medical certification processes, the FDA should continue the Innovation Pathway initiative and the Centers for Medicare and Medicaid Services (CMS) should explore redesigning the reimbursement process. To facilitate access to the NAS, the Department of Transportation (DoT) should take a more active role directing efforts across the government. The FAA has significant responsibility in this effort but its main role is to define safety standards and operational procedures. Consequently, it will be DoT's responsibility to advocate for access for commercial entities. To create incentives for driverless cars, the federal government will have to work closely with state governments to create a limited-liability regime such as that used for vaccines in the 1986 National Childhood Vaccine Injury Act. Such a regime would indemnify manufacturers while still providing redress to consumers.

**Recommendation 2: Improve the coordination of public and private R&D and increase government investments in robotic technology to enhance security and long-term economic growth.** The U.S. government should establish a national robotics technology roadmap. Such a roadmap, coupled with national strategies, would provide guidance to develop the capabilities needed to achieve national security and economic objectives. To achieve this, the U.S. needs to expand the National Robotics Initiative beyond a conglomeration of basic research activities sponsored by uncoordinated executive agency efforts. From a defense and security perspective, it is imperative for the U.S. to maintain a lead in robotic weapon systems, particularly in the face of technology diffusion and potential peer competitors. In the near-term, investment strategies should maximize the effective use of resources through the implementation of various incentives such as competitions for national prizes, tax incentives, and grants. Additionally, the U.S. Government should adopt technology portfolio management processes to more effectively coordinate R&D investments across executive agencies.

**Recommendation 3: Develop a broad standard for robotic performance metrics and interfaces.** The efforts of the National Institute of Standards and Technology (NIST) to standardize sensing and perception, manipulation, mobility, and autonomy metrics for manufacturing robots should be expanded to apply against a broader set of robotic applications. This can be used to set a baseline for robotic metrics, performance measurements, and testing criteria. This expanded study should be conducted in conjunction with and concurrently with current NIST efforts. This timeframe also coincides with the congressionally mandated 2015 integration of unmanned aircraft into the NAS. Establishing a common set of basic performance metrics and testing criteria will encourage open competition and increase transparency inside this nascent industry without sacrificing proprietary intellectual property.

**Recommendation 4: Position the Department of Defense to readily adopt future robotic capabilities.** Sustaining RAS RDT&E investment is an important step in ensuring that funding required to upgrade existing systems with RAS technology is available. Furthermore, the services should incorporate RAS technology and RAS capable subsystems into new and legacy platforms. With "drive-by-wire" components, a legacy platform could transition more easily to unmanned systems. The military services can thus create the institutional awareness and modernization capacity for future RAS capabilities. DoD should conduct business case analyses to determine and drive long-term manpower and operations and maintenance cost savings with RAS. Finally, DoD should adopt lessons-learned from rapid acquisition in war to the development of new operational concepts that leverage RAS commercial market developments.

**Recommendation 5: Enhance current export control reforms and provide opportunities for rational assessment of RAS capabilities.** The U.S. should ensure that ongoing efforts to reform export controls are in keeping with the original intent of the reforms. In addition, the U.S should create a national defense and security cooperation export strategy to better integrate policies across agencies. Such a strategy can also provide a framework for more meaningful engagement with industry associations to ensure policy impacts are understood. Finally, the U.S. should find ways to recognize the uniqueness of RAS when combining the United States Munitions List (USML) and Commerce Control List (CCL) such as the creation of a discrete listing category that does not conflict with the strategic non-proliferation initiatives of the Missile Technology Control Regime (MTCR) and Wassenaar arrangements.

**Recommendation 6: Foster STEM education through a wide range of policies.** The U.S. Government should adopt a set of policies that improve education programs and promote commercial investments in training and education. Providing funding for research and development, education programs and the National Robotics Initiative are imperative but are just the tip of the iceberg. Tax incentives for companies should be offered to re-train workers for the use of autonomous systems in preparation for higher technical job requirements in the future. Immigration reform should also be addressed to allow students earning STEM degrees in the U.S. to stay in country after graduation and put their education to work right here in America. Finally, the U.S. should offer funding and/or tax incentives for mentorship programs to bridge the experience gap between retiring and younger workers. This could help the country in other ways as well such as extending employment time for older workers lessening the burden on social security and Medicare and possibly motivating even adolescents in middle and high school to pursue STEM professions.

## CONCLUSION

Robotic and autonomous systems will continue to revolutionize many aspects of human endeavor. As technology becomes more diffuse and the benefits of globalization are more equally shared across the world, the U.S. will need to make a concerted effort to maintain a lead in this crucial technology. Fortunately, the U.S. has an advantageous position. Past investments in defense and other national capabilities have spurred technological innovation inside and outside of government. The U.S. R&D capacity is the best in the world and industry is well-poised to take advantage of it. In some cases, ideas born in government will take hold and be developed commercially, ultimately providing a benefit back to government in the future. This is evident in key technologies such as the internet and computing, and is likely to be the case for future technologies like driverless cars. In other cases, significant public and private research and development is needed before technologies can transition to the commercial sector, such as with UASs, artificial intelligence, and human-machine interfaces. As in many other areas, investments in these technologies have national economic and security implications. Smart policies, like those advocated in this report, can ensure that both economic and security interests are well served with a common set of investments. The 20th century was the "American Century" in large part because of U.S. leadership in the industrial age and, subsequently, the information age. The 21st century will see the rise of a robotic age, an age with great opportunity for the United States if it adopts a thoughtful, forward-looking national robotics policy.

## ESSAYS ON MAJOR ISSUES AND TOPICS

### TECHNOLOGY DEVELOPMENT AND TRENDS

The word "robot" typically conjures Hollywood images of friendly robots like C3PO and R2-D2, or sinister villains like HAL and the Terminator. The contrast between the capabilities of these futuristic robots and current systems often leads to skepticism that robots will ever amount to anything more than a toy, a niche application, or inspiration for science fiction. Will robots ever reach a "tipping-point" after which they will be pervasive?

In broad terms, three conditions must be met for robots to reach a tipping-point: 1) society generally accepts robots as part of daily life; 2) the cost of technology reaches a level that satisfies potential markets; and 3) the technology offers compelling utility compared to other alternatives. In social science, "the tipping point" refers to that moment when an obscure event, person, or place suddenly becomes part of the mainstream. Arguably, robots have passed this point, as manifested in media and pop culture. There is, however, a wide range of opinions about the utility and desirability of these systems. When it comes to cost, diverse markets set a wide range of tolerable prices. For example, the unit cost of military UAVs range from $5,000[59] to $70 million[60]; medical robots are, on average, are around $1.5 million[61]; and consumer items like iRobot's vacuum cleaners are in the sub-$500 category. Finally, the utility of robotics technology is only beginning to provide a case for its adoption over other alternatives. Robots found a niche in counterinsurgency operations in Iraq and Afghanistan, particularly in ISR missions to track highly sensitive moving targets, and EOD missions to counter IEDs. Meanwhile, robots are quietly carving a niche in various civil markets. Today, robots provide remote presence for physicians, automated vacuum cleaners in homes, and mobile applications such as the iPhone's Siri. Thus, recent trends indicate that robotic technologies are reaching a tipping point. There are, however, significant market demands yet to be met.

Robotic technologies must enable artificial devices to sense, think, and act with some level of autonomy to complete a specified mission in a real-world environment. Thus, the demands on technology differ depending on the mission. The military, for example, has adopted robots that operate almost exclusively in a teleoperated mode. Military advocates of the technology say more autonomy would be useful, but it is unclear if full autonomy is desirable in these missions.[62] Some medical applications have similar technology demands as military applications. For example, remote presence by physicians or remote surgical applications will also require robots with improved mobility and effector dexterity. In contrast, the prostheses field has been pushing robotic technology towards miniaturization, low-power consumption, and sophisticated human-robot interaction architectures. Although the military and medical markets are significant, they are effectively niche areas compared to the mass consumer market.

Today, the mass consumer market is characterized by an insatiable appetite for information technology like mobile phones, tablet computers, and internet applications. Not surprisingly, this market is driving robotics technology to be as pervasive as information technology. Indeed, the transition between information technology and robotics can be blurry. For example, tablets are viewed as highly portable computers. Yet, these devices exhibit a great deal of sensing, thinking, and acting, albeit not all integrated in a single robotic application. Tablets have cameras, GPS receivers, microphones, and accelerometers for sensing. Recently, applications such as Siri and Evi—as well as intelligent search engines like Wolfram Alpha, Bing, and Google—have introduced rudimentary artificial intelligence (AI) to these devices. In addition, tablets have been used as platforms for remote control of home systems, computers, and even “robot” aerial vehicles. Not only can these devices sense, think, and act with unprecedented capability, they are more connected than ever through the internet, giving them access to a huge knowledge bases and arrays of outlets for interacting with the environment. Finally, a tighter integration of these devices with mechanical and moving platforms is already underway, such as the Ava system iRobot is developing. Thus, advances in wireless communication, computing power, miniaturization, artificial intelligence, and low-power electronics will be critical to robotic technology penetration in this market. While the consumer, medical and military markets have unique characteristics, basic research and development of robotic technologies can enable further utility in all markets.

The last decade has seen significant advances and exponential growth in robotic technologies. In the medical field, biocompatible sensors have enabled invasive implants that monitor brain neural activity with very high fidelity.[63] Experiments with this technology have demonstrated improvements in brain-machine interfaces (BMI) to control basic prostheses and future efforts will explore bidirectional control loops that can also stimulate the brain with haptic feedback from the robotic prostheses.[64] Haptic systems that provide tactile feedback either to other robot control elements[65] or to a remote user continue to improve.[66] Versatile 3D sensors that can generate a point-cloud representation of the environment in real time enable effective simultaneous localization and mapping (SLAM) and navigation functions. In recent years, laser systems have provided high quality representations, as demonstrated in the DARPA Urban Challenge.[67] However, small and cheap 3D sensors, such as Microsoft’s Kinect, have expanded the range of robotic applications and potential users.[68] In the area of artificial intelligence, improvements in computing power, as well as research in neurology, biology, cognitive science, psychophysics, and robotics, have yielded significant insights. As of November 2011, the fastest supercomputer just tops $10^{16}$ floating-point operations per second,[69] which inventor Ray Kurzweil estimates to be the computational power required to achieve the functional equivalence of the human brain.[70] Given trends in microelectronics technology,[71] it is likely that computational power will not be the limiting factor in achieving human-like AI. Meanwhile, artificial intelligence algorithms based on neural networks, genetic evolution, multivariate statistics, semantic search, and Bayesian probability continue to improve. One notable example is IBM's Watson computer, the computer that beat human Jeopardy champions at the game.[72] Watson combines many types of sophisticated algorithms to parse English text, establish semantic meanings and relationships, weigh relevance of evidence, draw inferences, test hypotheses, and determine confidence levels in its conclusions—functions that approach elements of human logic.[73]

Mobility technology for wheeled vehicles, tracked vehicles, and legged systems also continues to improve. While wheeled and tracked vehicles leverage mature mobility technology, legged systems are only beginning to demonstrate satisfactory stability maintenance and mobility control in uncontrolled environments. Research in this area, such as Boston Dynamics' various animal-like robots, try to simulate the physiology of biological organisms.[74] Advances in data bus speeds and microprocessor technology have facilitated the optimization of algorithms and implementation of hierarchical control structures. These same advances also enable the control of more sophisticated robotic manipulators and effectors (e.g., arms and hands).[75] One example is the Shadow Hand used in NASA's Robonaut, which has a large number of movements and degrees-of-freedom with direct mapping to human hands.[76] As this brief survey demonstrates, technology continues to push the performance envelop that allows a robot to sense, think, and act.

Given the state-of-the-art of technology, what remains to be done for robotics and autonomous systems to reach a tipping point? It seems that robotics is following a similar path as information technology. As utility improves and costs decrease, the enhanced productivity obtained from these systems leads to a *de facto* widespread adoption and acceptance of the technology. Thus, utility, cost, and social acceptance are interrelated factors that should be addressed simultaneously with coordinated efforts. To improve utility, robots need to achieve a level of autonomy that enhances the collaborative performance of humans and robot teams. This requires improvements in all sensors, computing, and mobility technologies that enable autonomy but also in the physiological and psychological understanding of humans, their work environment, and tasks to be accomplished. To improve cost, the technology needs to mature enough to develop a set of standards that enable modular designs. Standards and modular designs lead to lower cost because of competition from more market participants, and more importantly, because they eliminate expensive system development costs. Finally, cost decreases as the technology becomes more ubiquitous and benefits from economies of scale. Finally, to achieve social acceptance, the *de facto* adoption needs to be supported by laws, regulations, and policies that balance free-market forces with social and ethical needs.

The U.S. Government and the Department of Defense have a fundamental role in this process. At the national level, the U.S. government should establish a robotics roadmap similar in scope to the 2009 roadmap sponsored by the Computing Community Consortium and the Computing Research Association.[77] Such a roadmap, coupled with national strategies, would provide guidance to the capabilities needed to achieve national security and economic objectives. This would focus public and private investments on capabilities that improve utility (e.g., autonomy and human-machine interfaces), coordinate efforts to transition to standards (with a goal to lead in the development of international standards), and provide a framework to develop appropriate laws, regulations, and policies that facilitate the smooth widespread adoption of the technology. To achieve this, the U.S. needs to expand the National Robotics Initiative beyond just a conglomeration of basic research activities sponsored by uncoordinated executive agency efforts. South Korea and Japan have national strategies that explicitly coordinate government, industry, and academia efforts. In South Korea, the strategy is implemented through the Ministry of Knowledge Economy. The strategy is comprehensive and approximately $1.4 billion per year funding is allocated to research and development, creating demand, building infrastructure, and establishing cooperation systems. In Japan, the strategy acknowledges the maturity of the industrial robotic industry and promotes development of rescue and service robots. To do so, the Japanese government is focused on creating safety and verification standards, sponsoring field tests, and working on regulatory reform.

## NATIONAL AIRSPACE REGULATION AND UAVs

The requirement for integration of Unmanned Aerial Systems (UAS) into the U.S. National Airspace System (NAS) is widely accepted. With the successful use of these systems by the DoD as a tool in operations in Iraq, Afghanistan, and other areas during the war on terrorism, the transfer of this technology to commercial and domestic use is already underway. A roadblock in the way of the domestic use of this technology is the current regulatory restrictions that severely restrict the flight of UASs in the NAS.

The use of UASs has become commonplace for the military, but only in unrestricted/uncontested airspace such as the airspace over Afghanistan. To many, the use of UASs in the NAS is an entirely different matter. Currently, unmanned aircraft may only operate in the NAS in extremely limited circumstances. A special exemption must be granted by the FAA that usually requires a ground observer and a chase plane to minimize the potential for accidents. This makes flying a UAS in the NAS complicated, expensive, restrictive and extremely limited.

On the military side, waivers have been granted for testing and training for flight of UASs in various FAA designated restricted areas. This does not help the commercial and civil entities who have a requirement to operate UASs in non-restricted airspace. For example, police and fire departments see a use for law enforcement and fire detection and fighting. As is already done in other countries, farmers and agribusiness could use UAS technology for crop dusting and crop inspection. On a larger scale, oil companies and air cargo companies are interested in UAS technology for things like pipeline inspection and flying packages between major shipping hubs. These would all require a UAS to share the national airspace with manned aircraft.

The main roadblock to this integration is the issue of safety. One aspect concerning safety is reliability and controllability. Can these systems be reliable enough to not fall out of the sky, run into other aircraft and will their control systems be good enough to prevent a loss of control resulting in them to become unguided missiles? The hundreds of thousands of flight hours on UASs of all shapes and sizes used in overseas operations should provide the confidence that these are manageable at or above the current level of manned aircraft. A more difficult aspect of safety to work through will be what is called Detect, Sense and Avoid (DSA). The ability of any type of unmanned system to be able to see other obstacles (aircraft, radio/cell towers or tall buildings) and then to safely avoid them is a major hurdle that must be overcome for all types of unmanned systems whether they operate on land, sea or in the air. There are numerous companies trying to either adapt current DSA technologies or to create new ones. One UAS industry expert predicted that whoever can develop a UAS DSA system will be able to create a new capability that will be applicable to both military and commercial markets.

In response to Section 935(c) of the National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2010, Public Law 111-84, DoD and DoT were tasked with jointly developing a plan for providing expanded access to the national airspace for Unmanned Aircraft Systems (UAS) of the DoD.[78] A UAS Executive Committee (ExCom) was formed. Members of the UAS ExCom include the FAA, DoD, DHS and NASA. The UAS ExCom developed a plan, the "National Airspace System Access Plan for Federal Public Unmanned Aircraft Systems" which provides policy recommendations, implementation milestones, and outlines a process for identifying resource requirements necessary to achieve expanded access for federal public UAS.[79] The plan includes a goal for the FAA to develop control and communication performance standards and procedures in order to enable certification of public, civil- and *commercial-use* UAS operations. However, this is the only specific reference to commercial UAS operations in the document. It is recommended that the UAS ExCom expand its scope to include addressing access to the NAS by commercial entities.

The challenge of integrating UASs into the NAS has been gaining momentum over the last couple of years and as a result, this past February, Congress passed a law whereby the FAA has three years to integrate unmanned aircraft into the NAS. The law directs the FAA to develop a plan for integrating UAS into the NAS and to establish a rulemaking initiative to develop regulations with regard to operating UAS aircraft in the NAS. This rulemaking initiative includes the design and equipage of UAS aircraft (i.e. a DSA system), and training and qualifications of the pilots who operate them remotely. Also included in this rulemaking would be operator certification standards that commercial operators would have to meet in order to operate these aircraft in the NAS.

As the DoD, along with many civil and commercial entities put pressure on the government and FAA to allow for integration of UAS into the NAS there is also a notable resistance to allowing this integration that generally focuses on three issues – safety, trust, and civil liberties. The issue of safety and the issue of trust go hand in hand. As discussed, UASs are generally quite safe. Hopefully, once safety issues like DSA are resolved, demonstrated and proven, trust will naturally come. That is why many in the business and the U.S. Air Force are recommending the use of the term "Remotely Piloted Aircraft" (RPA) versus Unmanned Aerial System (UAS). The use of the word "unmanned" makes it sound like there are no humans involved and there is no pilot. In actuality, there is a pilot; he just isn't in the plane.

The third issue is potential violations of civil liberties. The American Civil Liberties Union and many other non-governmental organizations have voiced concerns overUASs flying over private property and collecting information without oversight. These organizations and several members of Congress have asked the FAA to address their privacy concerns.

The challenge to integrating UASs into the NAS is formidable. Although the FAA has been charged with a huge portion of that task, many think it's timeline is unachievable. It is recommended that milestones and due dates be put in place to monitor the progress of the FAA. Additionally, it is recommended that an effort be made to better educate the public to make them more familiar with unmanned systems technology and current air regulations (i.e., stop using the word "drone," and explain how unmanned systems will be following the same rules and regulations as manned aircraft, etc). Finally, as in all aspects of RAS for commercial use, cost is a principal factor affecting usage and market penetration. A key towards making UASs safe enough to convince the FAA that they can be integrated into the NAS will be adapting or repurposing FAA certifiable military technologies for use with small lightweight commercial UASs, at costs the market can absorb.

## STANDARDS AND INTEROPERABILITY

To today's warfighter, robots are viewed as just another tool, important yet not essential to mission accomplishment. In the not too distant future, robots could represent vital team members, capable of man-to-machine and machine-to-machine integration and collaboration. Currently, DoD's *Unmanned Systems Integrated Roadmap for FY2011-2036* states the number one challenge for unmanned systems is interoperability.[80] Overall, there is a fundamental disconnect within DoD which has two distinct views on interoperability. One camp, comprised of industry, the Robotic Systems Joint Program Office (RS JPO), and the tri-service Unmanned Aircraft System control-segment working group (UCS-WG) take a narrow view of interoperability. This camp confines the definition to *integration on one platform* of various sensors, communications devices, manipulators, etc. *that can be controlled by any operator control unit or common ground station*. Conversely, DoD Unmanned Systems Integrated Roadmap (published by the Office of the Secretary of Defense or OSD) views interoperability as *collaborative across platforms*, similar to the currently accepted views on manned joint operations. Despite DoD directives mandating a requirement to acquire systems that are interoperable,[81] unmanned systems are not aligned to achieve DoD's desired levels of interoperability.

Joint Publication 1-02 defines interoperability as "the ability to operate in synergy in the execution of assigned tasks."[82] DoD's Unmanned Systems Roadmap interpreted this in the following manner:

> "The interoperability goal for Unmanned Systems is an ability to provide data, information, material, and services to and accept the same from other systems, units, or forces … and to use the exchanged data, information, material, and services to enable them to operate effectively together."[83]

Despite the interoperability definition in JP 1-02 and DoD's interpretation for unmanned systems, the RS JPO gives a significantly narrower definition of interoperability:

> "The ability of software or hardware systems or components to operate together successfully with minimal effort by end user. Further attributed with functional, behavioral, lifecycle, and architectural scopes, and, therefore, can be delineated in terms of control and can be categorized into levels, types, or degrees in application programs. Facilitated by common or standard interfaces."[84]

The RS JPO Interoperability Profile (IOP) Version 0 defines capabilities and functionality of fielded systems, and also establishes standard message sets and requirements for cross-platform interoperability. It is important to note the DoD organization responsible for integrating unmanned systems confines its IOP to interoperability of modules onboard the platform and the operator control unit. This interpretation of interoperability is aligned with industry's view and is not aligned with the overarching DoD Roadmap interoperability theme.

Of all the unmanned vehicle domains, the air domain is currently the best postured for increased interoperability along the stated DoD themes. In 2009, DoD implemented an initiative to break down proprietary barriers and establish a common ground control station (GCS) to enable any operator to control any Group 2-5 UAS (all UAS over 20 pounds maximum takeoff weight) in the DoD inventory.[85] The GCS serves two functions. First is command and control (C2) of the UAS flight and payload(s). The second is communication to the larger C2 network, and the ability to send the UAS data to other nodes in the network.[86] To carry out this initiative, the Pentagon set up a tri-service UAS control-segment working group (UCS-WG) to define an open architecture for ground control systems. The UCS-WG outlined the following top-level objectives for a successful architecture: 1) modular open systems architecture with defined interfaces; 2) support for airworthiness, security, and safety; 3) no specific computer operating system and no common operating environment; 4) hardware independent; 5) geographical separation of modules via networking; 6) scalable from full scale launch and recovery capability to limited payload receipt function; 7) support interoperability requirements; 8) extensible to support mission-specific functionality; and 9) support rapid integration of new aircraft, sensors, weapons, technology and applications.[87]

Discounting the vague reference to "support interoperability requirements," the majority of DoD's overarching interoperability goals are not nested in the working group's objectives.

As a specific example, currently there are two primary DoD-supported unmanned vehicle architectures: the NATO Standardization Agreement (STANAG) 4586, primarily used by air vehicles, and the Society of Automotive Engineers (SAE) Joint Architecture for Unmanned Systems (JAUS) Aerospace Standards Version 4 (AS-4) for unmanned ground and surface vehicles.[88] Both standards serve similar functions, yet there is currently not a working interoperability interface to bridge the two standards.[89] Because these two standards do not communicate, the ability to meet the DoD Roadmap interoperability theme is significantly hindered.

Of the available DoD guidance, the Unmanned Systems Integrated Roadmap offers the broadest range of options for increased interoperability of unmanned systems, from the platform level to combined operations. In order to align unmanned operations to meet the desired spectrum of DoD goals, this paper offers the following recommendations:

1) All DoD unmanned stakeholders should adopt a common definition of interoperability to include "a collaborative ability to provide data, information, material, and services to and accept the same from other systems, units, or forces … and to use the exchanged data, information, material, and services to enable them to operate effectively together."

2) The RS JPO should be designated as the executive agent to develop the ability to merge JAUS and STANAG 4586 under a common architecture and to mandate this common standard on all unmanned air, ground, surface, and underwater vehicles.

3) The Undersecretary of Defense for Acquisition, Technology, and Logistics should mandate that for future DoD unmanned vehicle development and procurement, the U.S. government have full administration and ownership rights to the core C2 software and interfaces above the module level.

These three recommendations would allow for a common definition and a common architecture across multiple domains, encourage competition through an open architecture format while still preserving the intellectual property rights of industry at the module level. Only by breaking down the stove-piped standards of the domains can the robotics and autonomous systems industry meet DoD's collaborative interoperability needs in the upcoming twenty-five years.

## MEDICAL ROBOTICS

The developed world is growing older and the available healthcare workforce is not keeping up. Robotic devices can enhance the capability of health care providers and decrease the burden on caregivers for the disabled or elderly. Medical applications of robotics include several sub-segments: assisted surgery, prostheses, mobility assistance, service robots, and intelligent homes for the disabled and the elderly. As researchers increase the abilities of robots through enhanced artificial intelligence, haptic sensing and other improvements, the applications and numbers of medical robots will expand.

The aging U.S. population represents significant market growth opportunity. In America, the number of persons over eighty years of age is expected to increase from 9.3 million in 2000 to 19.5 million in 2030.[90] The same period will see a growth in diabetes from 17 million to more than 30 million cases.[91] The diabetes numbers also imply demand for prosthetics, wheelchairs and for smart homes with robotic capabilities. Europe is the second-largest geographical market for the medical robots and computer-assisted surgery (MRCAS) market with a little less than one-quarter of the market[92]. The Asia-Pacific region is the fastest-growing market, with a 2011-2016 CAGR of almost 17%. These global demographic issues imply a huge demand for caregivers which robotics could partially fill. Faced earlier with these demographic challenges, Japanese companies are vigorously pursuing the use of robots to care for their aging populations.[93]

Projected market growth for medical applications of robotics is higher than that of the overall medical devices sector, which is expected to outperform most industrial sectors. Growth estimates through 2016 for the MRCAS market are 11.1% CAGR while growth for the highly diversified medical devices industry is estimated at 6.8%. The U.S. accounts for more than two-thirds of the global MRCAS market and is expected to maintain that share through 2016. This market segment presents a significant opportunity to improve lives while providing high-paying jobs through U.S. research, manufacturing and service firms. To realize the potential for patient welfare and economic benefits, the U.S. government must ensure that over-regulation or excessively high taxation does not severely harm the industry.

The quality and quantity of R&D is a competitive strength in U.S. medical robotics. A government study found that the U.S. definitely leads the world in research for medical applications of robotics but other countries (Japan, Korea, China and Europe) are closing the gap. The U.S. also holds a competitive advantage in R&D in several robotics component fields such as microelectronics, software development, telecommunications and instrumentation.[94] Government sponsored R&D at academic institutions often leads to new start-up companies. A leading university researcher stated that one of his greatest contributions to this field is developing researchers who use their technical expertise to begin their own start-up businesses.

DARPA is a significant asset for U.S. medical robotics research and the agency already has several big wins in this field. DARPA initiatives in the 1980s led to robotic surgery systems that are gaining wide acceptance today. In 2006, it issued the Revolutionizing Prosthetics challenge seeking to perfect the upper body prostheses and a second challenge in tele-surgery.[95] In three years, the Revolutionizing Prosthesis challenge led to the DARPA Arm, an electro-mechanical arm that is a vast improvement from the standard, split-hook arm prosthesis that had been in use for hundreds of years.

Existing and new robotics companies face several threats. The power of suppliers can be strong as competition for technical expertise and venture capital funding can be high. U.S. Food and Drug Administration (FDA) controls the new device approval process and the Department of Health and Human Services' Centers for Medicare and Medicaid (CMS) sets reimbursement guidelines of Medicare, Medicaid and private insurers. Both governmental processes are lengthy and complex. Medical applications of robotics usually involve cutting edge technology so the threat of substitutes is generally high from newer, improved versions of equipment.

The ability to successfully shepherd a new device through the regulatory process is a strategic advantage enjoyed by larger companies. Some corporations hire advisers to navigate through this process and the red tape can bury small start-up companies.[96] The government needs to provide the right balance between protecting users from potential harm while encouraging the market to develop technical and manufacturing advances that enhance lives. The FDA's new Innovation Pathway initiative may provide the answer and its pilot subject is the brain-controlled version of the DARPA arm. Under the Innovation Pathway, the FDA could reduce the time to conduct premarket reviews of new or modified products.[97] To increase transparency, they should consider a program that makes FDA personnel available to help small business through the approval process as they do with the Innovation Pathway.

In addition to the FDA device approval process, medical device manufacturers face an uncertain future in the area of reimbursement. CMS sets the guidelines for appropriate charges for all approved medical procedures and products. Private insurance companies and workman's compensation organizations follow those guidelines. In determining rates, the device manufacturer must use a prototype and conduct extensive studies to show safety and efficacy. All of these steps add up to a significant regulatory burden on businesses and imply that resources are spent on administrative areas and not innovation.[98]

The U.S. taxes corporations at the highest rate in the world and is now adding an additional 2.3% excise tax to the medical devices industry. [99] Corporations are predicting the additional tax liability will require companies to reduce costs and/or raise prices. Each of these actions will impede innovation.

The medical robotics industry will improve healthcare while providing high paying jobs to the domestic workforce. However, regulatory and tax burdens could severely impede innovation and industry growth. The FDA should continue with initiatives like Innovation Pathways that streamline the regulatory process and the CMS should simplify the reimbursement process. The government should carefully monitor whether the added tax burden compels companies to send jobs offshore or gives foreign manufacturers an unfair advantage. If these impacts are apparent, they should consider repealing the new tax. Medical robotics is an extraordinary opportunity to leverage U.S. innovation but we need to achieve the right oversight balance for corporations, workers, patients and tax revenues.

## AUTONOMY AND HUMAN-ROBOT INTERACTION

How humans and robots interact as robots become more autonomous is a crucial strategic issue for the future of the robotics industry. The perception of what a robot is, and what it does, will change drastically over time as robots move closer to full autonomy. The shift of robots towards increased autonomy will profoundly affect their interaction with humans in a host of new and expanded markets.

It is important to frame a timeline surrounding robot autonomy and human/robot interaction. At present, it is very unlikely that a reasonable person would view robots as being in any way similar to sentient, autonomous beings. However, if one allows for the possibility that robot capacity and self learning may grow exponentially in the future, it is impossible to say exactly what robots will be in, for example, 20 years. Experts, such as information age pioneer Ray Kurzweil, envision a possible future where robots may not be considered *de jure* as humans, but will act in some ways as *de facto* humans, performing many of the same tasks, autonomously adjusting their behavior as a result of feedback, and thus "learning" from their actions.[100]

It may well be that robots do not progress far along the continuum to full autonomy. However, if they do reach full or near complete autonomy, then a host of ethical and strategic issues will need to be considered.[101] First, human/robot interaction is a crucial strategic factor in the development of robotics. If the robot of the future does attain more autonomy, then it becomes incumbent on the humans who use the services provided by robots to consider this as they define the roles that robots will have in the marketplace and in daily life. The role of robots will likely fundamentally change, with humans and robots both modifying their behavior in response to the behavior of the other. Second, from an ethical perspective, one can generalize that as robots become more advanced and have more "human" aspects in the future, there will likely be new ethical issues which will arise around their interactions with humans. These ethical issues may shift over time from being primarily focused on the programming actions of the human directing the robot to beginning to look at the autonomous actions of the robot itself. Third, the ethical considerations regarding human/robotic interaction will become more and more central (and complicated) over time as robots become more and more autonomous. The niche market of several types of companion and assistance robots will likely grow, and will likely present ethical and moral dilemmas both for manufacturers as well as consumers. For example, society as a whole will need to determine how much caregiving for elderly people it wishes to cede to robots, and how much should be left to humans alone. Finally, new military strategic ethical issues surrounding human-robot interaction will become more pressing and complex over time. For example, many new issues will enter the ethical equation, not the least of which is the use of robots in the battlefield, where there exists the possibility one day of robots taking human life, possibly without human guidance or direction.

In sum, both in daily as well as in military use, more research and study will be needed to better understand human/robot interaction, and to guide informed decisions and policy so that robots may be optimally incorporated in a useful and ethical way, as robots become increasingly more autonomous over time.

# APPENDIX

## UGV

**Competition**:
Low – two dominant EOD robot manufacturers (iRobot and QinetiQ)
**Threat of entrant**:
Low – High cost / Selective DoD $
**Threat of substitutes**:
Low – Proven life saver
**Power of buyer**:
High - DoD/Gvt funding of R&D
**Power of suppliers**:
Low - Integrators and component builders numerous

## Domestic

**Competition**:
Med – global market / hard to protect intellectual property
**Threat of entrant**:
Low – limited ability to achieve economies of scale
**Threat of substitutes**:
High – humans are often better and cheaper
**Power of buyer**:
High – lots of substitutes so can demand low price
**Power of suppliers**:
Low – lots of substitutes


## Medical

**Competition**:
Low - (1, 2, 4, 5)
Med - (3) Growing # of manufacturers
**Threat of entrant**:
Low - (All) High cost/regulatory hurdles
**Threat of substitutes**:
Medium - Existing, low-tech, low cost options)
**Power of buyer**:
High – Govt regulatory agencies approve & set pricing guidelines
**Power of suppliers**:
Medium - Technical & medical expertise is limited, key to success

Medical segments
1) Surgery
2) Prosthetics
3) Mobility
4) Services
5) Smart homes

## UAS

**Competition**:
Low (1&2) Few manufacturers
High (3&4) Lots of manufacturers
**Threat of entrant**:
Low (1&2) High cost / Selective DoD $
High (3&4) low cost / many nerds
**Threat of substitutes**:
Low – good bang for buck & human out of harms way
**Power of buyer**:
High - DoD/Gvt funding of R&D
**Power of suppliers**:
Low - Integrators rule

UAS segments
1) HALE: High Alt Long End.
2) MALE: Med Alt Long End.
3) Small UAS
4) Micro / Nano UAS

Endnotes

[1] International Federation of Robotics (IFR), "Executive Summary,", *World Robotics 2011 Report: Industrial Robots*, http://www.worldrobotics.org/uploads/media/2011_Executive_Summary.pdf, accessed April 16,2012.
[2] Martin Hägele, *World Robotics – Service Robots 2011*, International Federation of Robotics, 2.
[3] Martin Hägele, *World Robotics – Service Robots 2011*, International Federation of Robotics, 2.
[4] Nominally electromechanical, though conceivably advances in biotechnology and nanotechnology could lead to a fundamentally different basis for robot architectures.
[5] This definition recognizes that more autonomy does not necessarily translate to more utility. In some applications, it may be more useful to have the robot under supervision and work in collaboration with a human being.
[6] World Robotics 2011, pg 1.
[7] Michael E. Porter, *Competitive Strategy: Techniques for Analyzing Industries and Competitors*, (New York: The Free Press, 1998), 4.
[8] General Accountability Office, "Unmanned Aircraft Systems - Comprehensive Planning and a Results-Oriented Training Strategy Are Needed to Support Growing Inventories," GAO-10-331, http://www.gao.gov/assets/310/302236.pdf, March 26, 2010, pg 1.
[9] This figure is down 13% from FY 2012 and 17% from FY 2011 UAV funding levels. Department of Defense, *Fiscal Year 2013 Presidential Budget Submission*, February 2012. http://www.dtic.mil/descriptivesum/Y2013/, accessed April 08, 2012.
[10] Aaron Saenz, "The Era of Robotic Warfare Has Arrived – 30% of All US Military Aircraft are Drones," http://singularityhub.com/2012/02/09/the-era-of-robotic-warfare-has-arrived-30-of-all-us-military-aircraft-are-drones/, February 9, 2012.
[11] The HALE and Medium Altitude Long Endurance (MALE) UAV market is dominated by two companies - Northrop Grumman and General Atomics. Northrop Grumman manufactures the Global Hawk, Unmanned Combat Air System, and Fire Scout vertical takeoff and landing UAVs. General Atomics manufactures the Predator and Reaper. AeroVironment (AV) is a small UAV manufacturer based in Simi Valley California. Over 83% of AVs sales are in the small UAV market and their Wasp and Raven UAVs make up the majority of the UAV inventory in the DoD. See appendix for market structure analysis.
[12] One notable exception is the Advanced EOD Robot System (AEODRS) program at the Naval EOD Technology Division (NAVEODTECHDIV) which will standardize open interfaces. The goal is to have several small businesses compete to manufacture components to be integrated by a system integrator to be assigned by NAVEODTECHDIV.
[13] The US exception to the no major UGV defense industry player rule is Lockheed Martin (LM). LM was the primary contractor for the US Army's Multifunctional Utility/Logistics and Equipment Countermine and Transport Vehicle (MULE-CTV) to serve as an all-purpose autonomous "pick-up truck" for soldier loads and resupply. After eight years of development with no appreciable progress, the Army cancelled the program in August 2011. Kate Brannen, "Army Kills Off MULE Unmanned Vehicle," *Army Times*, August 1, 2011, http://www.armytimes.com/news/2011/08/army-mule-program-killed-081511w/.

[14] Danielle Kucera, "Amazon Acquires Kiva Systems in Second-Biggest Takeover," *Bloomberg News*, March 19, 2012, http://www.bloomberg.com/news/2012-03-19/amazon-acquires-kiva-systems-in-second-biggest-takeover.html; Susan Berfield, "Driverless Cars can be Licensed in Nevada," *San Francisco Chronicle*, February 23, 2012, http://www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2012/02/22/BU4E1NAK5L.DTL; Javed Anwer, "There's a Driverless Car Right Behind You." *Times of India*, March 5, 2012, http://articles.timesofindia.indiatimes.com/2012-03-05/computing/31123747_1_sebastian-thrun-driverless-car-car-drives; Ed Oswald, "Cadillac Self-Driving Cars: Out By 2015?" *PC World*, April 20, 2012, http://www.pcworld.com/article/254192/cadillac_selfdriving_cars_out_by_2015.html#tk.rss_news, .

[15] Intuitive Technology started as a result of a Defense Advanced Research Agency (DARPA) challenge in the mid-1980s. The California Institute of Technology (Cal Tech) won and received grant money to further explore their concepts. A small group of researchers left Cal Tech to form Intuitive Surgical, which is now traded publicly. Intuitive has been hugely successful and reported first quarter of 2012 revenue of $495 million, up 28% compared with $388 million for the first quarter of 2011 (Press Release: Intuitive Announces First Quarter Earnings 2012). In 2011, Intuitive Surgical sold 534 da Vinci surgical units (at approximately $1 million per unit) compared with 441 units in 2010. As of the end of 2011, there were 2,132 da Vinci units installed worldwide and they assisted with approximately 360,000 surgical operations. Intuitive considers cash generation through operating income and the exercise of stock options a corporate strength. Of the $495 million net income for 2012 they invested $140 million (8% of revenue) on R&D. While Intuitive's lifecycle is typical for the industry, their success has been at the top of the class.

[16] U.S. DARPA Administrator, Interview March 9, 2012

[17] Medical Robotics Company Representative Interview, March 16, 2012

[18] Press Release: Intuitive Announces First Quarter Earnings 2012

[19] Ministry of Knowledge Education, "Policy for Korean Robot Industry," presentation to the 2012 ICAF RAS Industry Study group, Seoul, South Korea, May 2, 2012.

[20] Frost & Sullivan. "Advances in Component Technologies Fuel Innovations in Personal and Service Robotics," *Targeted News Service*, March 03, 2011, http://ezproxy6.ndu.edu/login?url=http://search.proquest.com/docview/854909416?accountid=12686.

[21] David Bernstein, Remy Michaud, and Brian Silvia. 2010. *Consumer Robotics: State of the Industry and Public Opinion*. BS thesis, Worchester Polytechnic Institute, pg 57.

[22] Andrew Nusca, "Texas Instruments, iRobot partner on 'intelligent' robots." *SmartPlanet*, March 13, 2012, http://www.smartplanet.com/blog/smart-takes/texas-instruments-irobot-partner-on-8216intelligent-robots/24173.

[23] Unknown, "iRobot Invests $6 Million in InTouch Health." *BusinessWire*, January 31, 2012, http://www.businesswire.com/news/home/20120131005422/en/iRobot-Invests-6-Million-InTouch-Health.

[24] Unknown, "iRobot Announces New Appointments, Strategic Realignment." *Robotics Trends*, February 29,

2012,http://www.roboticstrends.com/consumer_education/article/irobot_announces_new_appointments_strategic_realignment.
[25] World Robotics 2011, pg 13.
[26] Nathan Hodge, "As Wars End, Robot Field Faces Reboot," *Wall Street Journal*, http://online.wsj.com/article/SB10001424052702303624004577337740196727630.html, April 11, 2012.
[27] Stew Magnusun, "Defense Department to Donate Hundreds of Surplus Robots to Law Enforcement," National Defense Industries Association, http://nationaldefensemagazine.org/blog/lists/posts/posts.aspx?ID=736, accessed April 18, 2012.
[28] Ibid.
[29] Teal Group, "Teal Group Predicts Worldwide UAV Market Will Total $89 Billion in its 2012 UAV Market Profile and Forecast," April 11, 2012, http://tealgroup.com/index.php?option=com_content&view=article&id=79:teal-group-predicts-worldwide-uav-market-will-total-89-billion-in-its-2012-uav-market-profile-and-forecast&catid=3&Itemid=16.
[30] Visiongain, "Military Video Surveillance Systems Market Worth &8.b1Bn in 2012," PR.com, www.pr.com/press-release/406134, accessed April/19, 2012.
[31] John Keller, "DOD Plans to Spend $5.78 Billion for Unmanned Vehicles Procurement and Research in 2013," *Military and Aerospace Electronics*, February 14, 2012, http://www.militaryaerospace.com/articles/2012/02/dod-unmanned-vehicle-spending-requiest-for-2013-announced.html.
[32] Jane's, *Executive Overview Unmanned Ground Vehicles and Systems*, July 8, 2011, http://client.janes.com.ezproxy6.ndu.edu/Search/documentView.do?docId=/content1/janesdata/binder/jugv/jugv0255.htm@current&pageSelected=allJanes&keyword=UGV%20market&backPath=http://client.janes.com.ezproxy6.ndu.edu/Search&Prod_Name=JUGV&#toclink-j35336521310052788655; "Robotics; A-T Solutions Announces Partnership with HDT Global." *Bioterrorism Week* (April 2, 2012): 3. http://ezproxy6.ndu.edu/login?url=http://search.proquest.com/docview/961078968?accountid=12686.
[33] Reliable and cost effective autonomous navigation across various terrains and road remains the primary obstacle and "Holy Grail" for UGV use in military and commercial applications. Robotic Systems Joint Project Office. *Unmanned Ground Systems Roadmap*, July 2011, pg 20 – 22, http://www.rsjpo.army.mil/images/UGS_Roadmap_Jul11_r1.pdf.
[34] Maren Leed and Brittany Gregerson, "Keeping Faith: A Sustainable Path for Military Compensation," (Washington DC: Center for Strategic & International Studies, October 2011), pg VII.
[35] International Federation of Robotics (IFR), the "World Robotics 2011 Report, Service Robots", http://www.worldrobotics.org/uploads/media/2011_Executive_Summary.pdf, April 16, 2012.
[36] Catherine Simon, "From Industrial Maturity to the "Robolution" Industrial and Service Robotics in Europe," Presentation for INNOROBO (August 2011), Business Resonance, Innovation Robotic Summit 2011, http://www.slideshare.net/bizresonance/robotique-industrielle-et-de-service-europe-aout-2011-8839337 ,accessed April 16, 2012.
[37] Ministry of Economy, Trade, and Industry, presentation to the ICAF RAS Industry Study group, Tokyo, Japan, May 7, 2012.

[38] Social factors impacting the outlook of the industry include the shortage of labor needed to sustain an aging population. People are living longer and birth rates are declining. This phenomenon is occurring in many countries including the United States. The result is that there are not enough younger workers to take care of the elderly and sustain the workforce. Robotics will provide not only automation so that less workers are required, but also direct care of the elderly with robotic companions that are able to dispense medication and carry out other daily needs of elderly patients.
[39] George Jr Stalk, *White Paper: Creating a Distribution Powerhouse: Why Rapid Deployment Matters* (Boston, MA: Boston Consulting Group,[2011]).
[40] Gartner, "Top 10 Strategic Technology Trends for 2012," http://www.gartner.com/technology/research/top-10-technology-trends/,accessed April 20, 2012.
[41] Derrick Harris, "Say Goodbye to Search and Hello to BrainSpace," *GigaOM*, 14 April 2012. http://gigaom.com/cloud/say-goodbye-to-search-and-hello-to-brainspace/,accessed April 20, 2012.
[42] Beth Jinks, "IBM's Watson Gets Wall Street Job After 'Jeopardy' Win," *Bloomberg*, 6 Mar 2012. http://www.bloomberg.com/news/2012-03-05/ibm-s-watson-computer-gets-wall-street-job-one-year-after-jeopardy-win.html,accessed March 19, 2012.
[43] Ariel Schwartz, "Using Big Data to Predict Your Potential Heart Problems," Co.Exist Blog, *Fast Company*, http://www.fastcoexist.com/1679654/using-big-data-to-predict-your-potential-heart-problems, accessed April 20, 2012.
[44] Ross Andersen, "How Big Data is Changing Astronomy (Again)," *The Atlantic*, 20 April 2012, http://www.theatlantic.com/technology/archive/2012/04/how-big-data-is-changing-astronomy/255917/.
[45] Frederic Lardinois, "Report: Wearable Computing Will Soon Intensify the Platform Wars," *TechCrunch*, 17 April 2012, http://techcrunch.com/2012/04/17/report-wearable-computing-will-soon-intensify-the-platform-wars/.
[46] A. V. Nurmikko, et al. "Listening to Brain Microcircuits for Interfacing With External World—Progress in Wireless Implantable Microelectronic Neuroengineering Devices," *Proceedings of the IEEE*, Vol. 98, Issue: 3 (2010): pg 375-388.
[47] Jose A. Carmena, "Becoming Bionic," *IEEE Spectrum* (March 2012): pg 24-29.
[48] National Cancer Institute, "DNA Nanorobot Targets Therapeutic Responses," April 2012. http://nano.cancer.gov/action/news/2012/apr/nanotech_news_2012-4-2e.asp, accessed April 20, 2012.
[49] SRI International, "Medical Robots and Telepresence," http://www.sri.com/robotics/telemedicine.html, accessed April 20, 2012.
[50] Clay Dillow, "Telepresence Robots Will Join Doctors on Their Rounds in Singapore Next Month," *Popular Science online*, 28 March 2012, http://www.popsci.com/technology/article/2012-03/telepresence-robots-will-join-doctors-their-rounds-singapore-next-month. Also, Christopher Drew, "For iRobot, the Future Is Getting Closer," New York Times, 2 March 2012. http://www.nytimes.com/2012/03/03/technology/for-irobot-the-future-is-getting-closer.html.
[51] California, Arizona, Hawaii, Florida, and Oklahoma are now also considering such laws.
[52] To date, standardization of robotics has largely been focused on automobile manufacturing where the large carmakers have been able to drive the standardization requirement. In general there are few robotics standards aside from International Organization of Standardization (ISO)

safety standards. Resolving the issue is problematic due to the current stove-piped nature of the industry, proprietary solutions, and diverse applications of the technologies. Currently, the National Institute of Standards and Technology (NIST) is embarking on a three-year effort to create standards, performance measures, and/or metrics specifically for manufacturing robots. Their focus is in four key areas: sensing and perception, manipulation, mobility, and autonomy. While a positive start, it does not address service robots. Meanwhile, DoD is slowly incorporating standards to its robotics and autonomous systems, but solutions appear to be limited to specific domains and even services.

[53] To protect U.S. technology, the U.S. has established controls to manage the release of capabilities that serve our national interests and the interests of our allies. Controls levied by the Department of State (DoS) on the RAS industry are codified in and implemented by the International Trafficking in Arms Regulations (ITAR). This legislation utilizes categories of inherently military equipment and Significant Military Equipment (SME) to generate the United States Munitions List (USML). The ITAR combines arms export policy with licensing processes, authorities, accountabilities, and implements the AECA. See Geoffrey Kemp, "The Continuing Debate Over U.S. Arms Sales: Strategic Needs and the Quest for Arms Limitations," *Annals of the American Academy of Political and Social Science* 535, no. 00027162 (2008), 146-146. http://search.proquest.com/docview/219580585?accountid=12686. Not all RAS capabilities that are not inherently military, warehousing robots for example, are controlled by the Department of Commerce (DoC) and are codified in the Export Administration Regulations (EAR), managed by the Bureau of Industry and Security, and documented in the Commerce Control List (CCL) . See Wendy H. Schacht, *Industrial Competitiveness and Technological Advancement: Debate Over Government Policy* (Washington DC: Congressional Research Service,[2011]).

[54] Some references made to the results of interviews with industry officials, trade associations representatives, and government officials are not attributed at their request while the export reform solutions are being developed and negotiated.

[55] OECD, Programme for International Student Assessment (PISA) 2009 Results; What Students Know and Can Do – Student performance in Reading, Mathematics and Science (Volume 1), 2010, pg 152, 135.

[56] President's Council of Advisors on Science and Technology (PCAST), "Prepare and Inspire: K-12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future," Executive Office of the President, September 2010, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-stemed-report.pdf, pg v.

[57] Because of globalization, companies are increasingly able to tap into global labor markets. This is useful to companies because they can shop around and get the cheapest labor they need for their production/supply chains. Unfortunately for the U.S. labor market, this means that many low-end jobs are disappearing and those that remain are under constant low wage pressure. Robotic and autonomous systems will put further pressure on this system as it will also replace menial work, further reducing labor opportunities at the low-end. Training is needed for technical skills so that people can take on the jobs offered by the new economy.

[58] If government, education, industry and non-profit organizations take the right steps, America will be back on top. The right steps include providing funded programs to improve STEM teachers and education, identifying potential STEM students as early as possible, motivating students with funded robotic programs, multiple STEM disciplines and mentorship programs,

providing opportunities for students to pursue higher education in STEM subjects, and sponsoring and funding research and development to stimulate excitement about the future of robotics.

[59] David Olive, "Predator UAV Costs – An Analysis of Alternatives that Needs Further Analysis," *Security Debrief*, George Washington University Homeland Security Policy Institute, http://securitydebrief.com/2011/02/02/predator-uav-costs-an-analysis-of-alternatives-that-needs-further-analysis/, accessed March 20, 2012.

[60] Government Accountability Office, "Unmanned Aircraft Systems: Global Hawk Cost Increase Understated in Nunn-McCurdy Report," GAO-06-222R, http://www.gao.gov/assets/100/93906.html, accessed March 20, 2012.

[61] World Robotics 2011, pg 13.

[62] It is debatable if this is solely because of the limits in technological capability or because autonomous systems do not fit the military operational concepts, service preferences, and professional military ethics. In any case, there is considerable debate about how the laws of armed conflict apply when robots are used in the battlefield.

[63] A. V. Nurmikko, et al. "Listening to Brain Microcircuits for Interfacing With External World—Progress in Wireless Implantable Microelectronic Neuroengineering Devices," *Proceedings of the IEEE*, Vol. 98, Issue: 3 (2010): pg 375-388.

[64] Jose A. Carmena, "Becoming Bionic," *IEEE Spectrum* (March 2012): pg 24-29.

[65] Alexander Schmitz, et al., "Methods and Technologies for the Implementation of Large-Scale Robot Tactile Sensors," *IEEE Transactions on Robotics*, Vol. 27, No. 3 (3 June 2011): pg 389-400.

[66] R. E. Sofronia, et al., "Haptic Devices in Engineering and Medicine," *IEEE International Joint Conferences on Computational Cybernetics and Technical Informatics*, Timisora, Romania (May 27-29 2010): pg 373-378.

[67] Radu Bogdan Rusu and Steve Cousins, "3D is here: Point Cloud Library (PCL)," http://www.pointclouds.org/assets/pdf/pcl_icra2011.pdf, accessed March 18, 2012.

[68] Trevor Taylor, "Kinect for Robotics," http://blogs.msdn.com/b/msroboticsstudio/archive/2011/11/29/kinect-for-robotics.aspx, accessed March 19, 2012).

[69] Unknown. Japan's "K Computer" achieved 10.51 Petaflop/s on the Linpack benchmark using 705,024 SPARC64 processing cores. http://top500.org/lists/2011/11/press-release, accessed March 18, 2012.

[70] Ray Kurzweil, *The Singularity is Near* (New York: Viking, 2005).

[71] Rachel Courtland, "3-D Chips Grow Up," *IEEE Spectrum*, January 2012.

[72] Ki Mae Heussner, "Watson Computer Crushes Humans in Night Three of 'Jeopardy!' Challenge," *ABC News*, 17 Feb 2011. http://abcnews.go.com/Technology/jeopardy-ibm-computer-watson-wins-million-man-machine/story?id=12940205

[73] IBM, "How Watson Works," http://www-03.ibm.com/innovation/us/watson/building-watson/how-watson-works.html, accessed March 19, 2012.

[74] Boston Dynamics, http://www.bostondynamics.com/bd_index.html, accessed March 19, 2012.

[75] George A. Bekey, *Autonomous Robots: From Biological Inspiration to Implementation and Control*, (MIT Press: London, 2005).

[76] Shadow Robot Company, http://www.shadowrobot.com/, accessed March 19, 2012.

[77] Computing Community Consortium and Computing Research Association, *A Roadmap for US Robotics: From Internet to Robotics*, 21 May 2009. http://www.us-robotics.us/reports/CCC%20Report.pdf.
[78] Department of Defense, Final Report to Congress on Access to National Airspace for Unmanned Aircraft Systems, October 2010, http://www.acq.osd.mil/psa/docs/report-to-congress-ana-for-uas.pdf, accessed May 17, 2012, pg 1.
[79] Ibid.
[80] Department of Defense, *The Unmanned Systems Integrated Roadmap FY2011-2036*, (Washington, DC: Joint Staff), http://www.defenseinnovationmarketplace.mil/resources/UnmannedSystemsIntegratedRoadmapFY2011.pdf, accessed March 17, 2012.
[81] Department of Defense, *DOD Directive 5000.1 Enclosure 1, paragraph E1.10*, (Washington, DC: Undersecretary of Defense for Acquistion, Technology, and Logistics, November 20, 2007), http://www.dtic.mil/whs/directives/corres/pdf/500001p.pdf, accessed March 15, 2012.
[82] Department of Defense, *Joint Publication (JP) 1-02, Department of Defense Dictionary of Military and Associated Terms*, (Washington, DC: Joint Staff, 8 November 2010 (as amended through 15 February 2012)), http://www.dtic.mil/doctrine/new_pubs/jp1_02.pdf, accessed March 15, 2012.
[83] Ibid.
[84] Mark Mazzara, "RS JPO Interoperability Profiles," briefing slides, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA548099, accessed March 20, 2012.
[85] Department of the Army, "10—Unmanned Aircraft System Control Segment Architecture Industry Days, Solicitation Number W58RGZ-INDUSTRY-DAYS, April 30, 2009, https://www.fbo.gov/?s=opportunity&mode=form&id=4a157aba6a8abab94e3eabcbb8d9b998&tab=core&_cview=0, accessed March 15, 2012.
[86] Unknown. "One for All: AAI Textron's UAV Control System," *Defense Industry Daily*, April 12, 2011, http://www.defenseindustrydaily.com/One-for-All-AAI-Textrons-UAV-Control-System-05412/, accessed March 14, 2012.
[87] Ibid.
[88] Jorgen Pedersen, Vice Admiral Joe Dyer USN (Ret), and Michael Dauth, *Interoperability Standards Analysis (ISA)*, (Washington, DC: National Defense Industry Association Robotics Division, November 2007), http://www.ndia.org/Divisions/Divisions/Robotics/Documents/Content/ContentGroups/Divisions1/Robotics/Interoperability%20Standards%20Analysis%20(ISA).pdf, accessed March 14, 2011.
[89] Interview with confidential source, March 20, 2012. Interviewee was a primary stakeholder in the development of JAUS and a subject matter expert on robotics, however is not currently affiliated with DOD and requested anonymity due to his views on DOD policy with respect to the DOD Unmanned Systems Roadmap.
[90] Centers For Disease Control, *Public Health and Aging: Trends in Aging --- United States and Worldwide.* http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5206a2.htm, accessed March 16, 2012.
[91] Cook, Curtiss B., et al. "Disparities in Diabetes-Related Hospitalizations: Relationship of Age, Sex, and Race/Ehtniciity with Hospital Discharges, Lengths of Stay, and Direct Inpatient Charges." *Ethnicity & Disease*, 2006: 126.

[92] Global Information, Inc. *Global Sales of Medical Robots and Computer-Assisted Surgery Equipment to Reach $3.6 Billion in 2016.* October 13, 2011. http://www.giiresearch.com/press/bc216643.shtml (accessed March 18, 2012).
[93] Japan Today. *New robot promises brighter future for Japan's elderly* . August 7, 2011. http://www.japantoday.com/category/technology/view/new-robot-promises-brighter-future-for-japans-elderly-population (accessed March 20, 2011).
[94] Yuang Zheng, George Bekey, Arthur Sanderson. *Assessment of International Research and Development in Robotics.* Baltimore: World Technology Evaluation Center, 2006, 71.
[95] Official, Government, interview by Timothy O'Hara. *DARPA expert* (March 9, 2012).
[96] Company, Representative of large medical robotics, interview by Timothy O'Hara. *Impact of Review and Reimbursement on Innovation* (March 16, 2012).
[97] Unknown. *FDA Launches Priority Review Program for Breakthrough Medical Products.* February 8, 2011. http://www.oandp.com/articles/news_2011-02-08_02.asp (accessed March 16, 2012).
[98] (Official 2012)
[99] Unknown. The Wall Street Journal. *The U.S. Is Number One* . March 19, 2012. http://online.wsj.com/article/SB10001424052970204781804577269791012344900.html, accessed March 19, 2012.
[100] Ray Kurzweil, *The Age of Spiritual Machines*, (New York: Viking Press, 1999), p. 253.
[101] Ibid, p. 101.

# Bibliography

Ahn, Jae Kook, Seung Jun Lee, and Seul Jung. "Force Control Application to a Mobile Manipulator with Balancing Mechanism." *36th Annual Conference on IEEE Industrial Electronics Society*, IECON 2010, 1528 – 1533.

Allen, Paul G. and Mark Greaves, "The Singularity Isn't Near." *Technology Review*, MIT, 12 October 2011. http://www.technologyreview.com/blog/guest/27206/ (accessed 19 March 2012).

Andersen, Ross. "How Big Data is Changing Astronomy (Again)," *The Atlantic*, 20 April 2012, http://www.theatlantic.com/technology/archive/2012/04/how-big-data-is-changing-astronomy/255917/.

Anwer, Javed. "There's a Driverless Car Right Behind You." *Times of India*, March 5, 2012, http://articles.timesofindia.indiatimes.com/2012-03-05/computing/31123747_1_sebastian-thrun-driverless-car-car-drives

Berfield, Susan. "Driverless Cars can be Licensed in Nevada," *San Francisco Chronicle*, February 23, 2012, http://www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2012/02/22/BU4E1NAK5L.DTL

Bernstein, David, Michaud, Michaud, and Silvia, Brian. 2010. *Consumer Robotics: State of the Industry and Public Opinion*. BS thesis, Worchester Polytechnic Institute, pg 57.

Boston Dynamics, http://www.bostondynamics.com/bd_index.html, accessed March 19, 2012.

Brannen, Kate. "Army Kills Off MULE Unmanned Vehicle," *Army Times*, August 1, 2011, http://www.armytimes.com/news/2011/08/army-mule-program-killed-081511w/. Bekey, George A. *Autonomous Robots: From Biological Inspiration to Implementation and Control*. MIT Press: London, 2005.

Carmena, Jose A. "Becoming Bionic." *IEEE Spectrum* (March 2012): 24-29.Coles, Timothy R. et al., "The Role of Haptics in Medical Training Simulators: A Survey of the State of the Art." *IEEE Transactions on Haptics*, Vol. 4, No. 1 (January-March 2011): 51-66.

Centers For Disease Control, *Public Health and Aging: Trends in Aging --- United States and Worldwide.* http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5206a2.htm, accessed March 16, 2012.

Company, Representative of large medical robotics, interview by Timothy O'Hara. *Impact of Review and Reimbursement on Innovation* (March 16, 2012).

Computing Community Consortium and Computing Research Association, *A Roadmap for US Robotics: From Internet to Robotics*, 21 May 2009. http://www.us-robotics.us/reports/CCC%20Report.pdf (accessed 20 March 2012).

Cook, Curtiss B., et al. "Disparities in Diabetes-Related Hospitalizations: Relationship of Age, Sex, and Race/Ehtniciity with Hospital Discharges, Lengths of Stay, and Direct Inpatient Charges." *Ethnicity & Disease*, 2006: 126.

Courtland, Rachel. "3-D Chips Grow Up." *IEEE Spectrum*, January 2012.

Department of the Army, "10—Unmanned Aircraft System Control Segment Architecture Industry Days, Solicitation Number W58RGZ-INDUSTRY-DAYS, April 30, 2009, https://www.fbo.gov/?s=opportunity&mode=form&id=4a157aba6a8abab94e3eabcbb8d9b998&tab=core&_cview=0, accessed March 15, 2012.

Department of Defense, *Fiscal Year 2013 Presidential Budget Submission*, February 2012. http://www.dtic.mil/descriptivesum/Y2013/, accessed April 08, 2012.

Department of Defense, Final Report to Congress on Access to National Airspace for Unmanned Aircraft Systems, October 2010, http://www.acq.osd.mil/psa/docs/report-to-congress-ana-for-uas.pdf, accessed May 17, 2012.

Department of Defense, *The Unmanned Systems Integrated Roadmap FY2011-2036,* (Washington, DC: Joint Staff), http://www.defenseinnovationmarketplace.mil/resources/UnmannedSystemsIntegratedRoadmapFY2011.pdf, accessed March 17, 2012.

Department of Defense, *DOD Directive 5000.1 Enclosure 1, paragraph E1.10,* (Washington, DC: Undersecretary of Defense for Acquistion, Technology, and Logistics, November 20, 2007), http://www.dtic.mil/whs/directives/corres/pdf/500001p.pdf, accessed March 15, 2012.

Department of Defense, *Joint Publication (JP) 1-02, Department of Defense Dictionary of Military and Associated Terms*, (Washington, DC: Joint Staff, 8 November 2010 (as amended through 15 February 2012)), http://www.dtic.mil/doctrine/new_pubs/jp1_02.pdf, accessed March 15, 2012.

DARPA Administrator, Interview March 9, 2012

Dillow, Clay. "Telepresence Robots Will Join Doctors on Their Rounds in Singapore Next Month," *Popular Science online*, 28 March 2012, http://www.popsci.com/technology/article/2012-03/telepresence-robots-will-join-doctors-their-rounds-singapore-next-month.

Drew, Christopher. "For iRobot, the Future Is Getting Closer," New York Times, 2 March 2012. http://www.nytimes.com/2012/03/03/technology/for-irobot-the-future-is-getting-closer.html.

Foundation for Critical Thinking. “Elements of Thought.” http://www.criticalthinking.org/ctmodel/logic-model1.htm (accessed 19 March 2012).

Frost & Sullivan. “Advances in Component Technologies Fuel Innovations in Personal and Service Robotics," *Targeted News Service,* March 03, 2011, http://ezproxy6.ndu.edu/login?url=http://search.proquest.com/docview/854909416?accountid=12686.

Gartner, “Top 10 Strategic Technology Trends for 2012,” http://www.gartner.com/technology/research/top-10-technology-trends/, accessed April 20, 2012.

Gates, Robert M. "Export Reform - 4 Singles a Speech to Business Executives for National Security." Washington DC, Department of Defense, April 20, 2010, 2010.

Global Information, Inc. *Global Sales of Medical Robots and Computer-Assisted Surgery Equipment to Reach $3.6 Billion in 2016.* October 13, 2011. http://www.giiresearch.com/press/bc216643.shtml (accessed March 18, 2012).

Government Accountability Office, United States. "Unmanned Aircraft Systems: Global Hawk Cost Increase Understated in Nunn-McCurdy Report,” GAO-06-222R, http://www.gao.gov/assets/100/93906.html (accessed 20 March 2012).

General Accountability Office, “Unmanned Aircraft Systems - Comprehensive Planning and a Results-Oriented Training Strategy Are Needed to Support Growing Inventories,” GAO-10-331, http://www.gao.gov/assets/310/302236.pdf, March 26, 2010.

Hägele, Martin. International Federation of Robotics. *World Robotics 2011: Service Robots*. 2011.

Harris, Derrick. “Say Goodbye to Search and Hello to BrainSpace,” *GigaOM*, 14 April 2012. http://gigaom.com/cloud/say-goodbye-to-search-and-hello-to-brainspace/,accessed April 20, 2012.

Heussner, Ki Mae. “Watson Computer Crushes Humans in Night Three of 'Jeopardy!' Challenge.” *ABC News*, 17 Feb 2011. http://abcnews.go.com/Technology/jeopardy-ibm-computer-watson-wins-million-man-machine/story?id=12940205 (accessed 19 March 2012).

Hodge, Nathan. "As Wars End, Robot Field Faces Reboot." *Wall Street Journal,* April 11, 2012, 2012, sec. U.S. News.

IBM. “How Watson Works.” http://www-03.ibm.com/innovation/us/watson/building-watson/how-watson-works.html (accessed 19 March 2012).

Jane's, *Executive Overview Unmanned Ground Vehicles and Systems*, July 8, 2011, http://client.janes.com.ezproxy6.ndu.edu/Search/documentView.do?docId=/content1/janesdata/binder/jugv/jugv0255.htm@current&pageSelected=allJanes&keyword=UGV%20market&backPath=http://client.janes.com.ezproxy6.ndu.edu/Search&Prod_Name=JUGV&#toclink-j35336521310052788655 (accessed May 21, 2012).

Japan Today. *New robot promises brighter future for Japan's elderly* . August 7, 2011. http://www.japantoday.com/category/technology/view/new-robot-promises-brighter-future-for-japans-elderly-population (accessed March 20, 2011).

Jinks, Beth. "IBM's Watson Gets Wall Street Job After 'Jeopardy' Win." *Bloomberg*, 6 Mar 2012. http://www.bloomberg.com/news/2012-03-05/ibm-s-watson-computer-gets-wall-street-job-one-year-after-jeopardy-win.html (accessed 19 Mar 2012).

Johnsson, Magnus and Christian Balkenius. "Sense of Touch in Robots with Self-Organizing Maps." *IEEE Transactions on Robotics*, Vol. 27, No. 3 (June 2011): 498-507.

Jones, Daniel, Andrew Lewis, and Gregory S. Fischer. "Development of a StandAlone Surgical Haptic Arm." *33rd Annual International Conference of the IEEE EMBS*, Boston, MA (August 30-September 3, 2011): 2136-2139.

Katayama, Lisa. "How Robotics Master Masahiro Mori Dreamed Up the 'Uncanny Valley'." *Wired Magazine*, December 2011. http://www.wired.com/magazine/2011/11/pl_mori/ (accessed 20 March 2012).

Keller, John. "DOD Plans to Spend $5.78 Billion for Unmanned Vehicles Procurement and Research in 2013," *Military and Aerospace Electronics*, February 14, 2012, http://www.militaryaerospace.com/articles/2012/02/dod-unmanned-vehicle-spending-requiest-for-2013-announced.html.

Kemp, Geoffrey. "The Continuing Debate Over U.S. Arms Sales: Strategic Needs and the Quest for Arms Limitations." *Annals of the American Academy of Political and Social Scienc*e 535, no. 00027162 (2008): 146-146.

Kucera, Danielle. "Amazon Acquires Kiva Systems in Second-Biggest Takeover," *Bloomberg News*, March 19, 2012, http://www.bloomberg.com/news/2012-03-19/amazon-acquires-kiva-systems-in-second-biggest-takeover.htmlKurzweil, Ray. *The Singularity is Near.* New York: Viking, 2005.

Kyrki, Ville "Computer and Robot Vision." *IEEE Robotics & Autonomous Magazine*, June 2011, 121.

Lardinois, Frederick. "Report: Wearable Computing Will Soon Intensify the Platform Wars," *TechCrunch*, 17 April 2012, http://techcrunch.com/2012/04/17/report-wearable-computing-will-soon-intensify-the-platform-wars/.

Leed, Maren and Brittany Gregerson. "Keeping Faith: A Sustainable Path for Military Compensation." Washington DC: Center for Strategic & International Studies, October 2011.

Magnusun, Stew. "Defense Department to Donate Hundreds of Surplus Robots to Law Engorcement." National Defense Industries Association, accessed April/19, 2012, http://nationaldefensemagazine.org/blog/lists/posts/posts.aspx?ID=736.

Mazzara, Mark. "RS JPO Interoperability Profiles," briefing slides, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA548099, accessed March 20, 2012.

Medical Robotics Company Representative Interview, March 16, 2012.

Ministry of Knowledge Education, "Policy for Korean Robot Industry," presentation to the 2012 ICAF RAS Industry Study group, Seoul, South Korea, May 2, 2012.

Ministry of Economy, Trade, and Industry, presentation to the ICAF RAS Industry Study group, Tokyo, Japan, May 7, 2012.

National Cancer Institute, "DNA Nanorobot Targets Therapeutic Responses," April 2012. http://nano.cancer.gov/action/news/2012/apr/nanotech_news_2012-4-2e.asp, accessed April 20, 2012.

Nusca, Andrew. "Texas Instruments, iRobot partner on 'intelligent' robots." *SmartPlanet*, March 13, 2012, http://www.smartplanet.com/blog/smart-takes/texas-instruments-irobot-partner-on-8216intelligent-robots/24173.

Nurmikko, A. V., et al.. "Listening to Brain Microcircuits for Interfacing With External World—Progress in Wireless Implantable Microelectronic Neuroengineering Devices." *Proceedings of the IEEE*, Vol. 98, Issue: 3 (2010): 375-388.

OECD, Programme for International Student Assessment (PISA) 2009 Results; What Students Know and Can Do – Student performance in Reading, Mathematics and Science (Volume 1), 2010.

Official, Government, interview by Timothy O'Hara. *DARPA expert* (March 9, 2012).

Olive, David. "Predator UAV Costs – An Analysis of Alternatives that Needs Further Analysis." *Security Debrief*, George Washington University Homeland Security Policy Institute. http://securitydebrief.com/2011/02/02/predator-uav-costs-an-analysis-of-alternatives-that-needs-further-analysis/ (accessed 20 March 2012).

Oswald, Ed. "Cadillac Self-Driving Cars: Out By 2015?" *PC World*, April 20, 2012, http://www.pcworld.com/article/254192/cadillac_selfdriving_cars_out_by_2015.html#tk.rss_news, Pedersen, Jorgen, Vice Admiral Dyer USN (Ret), Joe, and Dauth, Michael. *Interoperability Standards Analysis (ISA)*, (Washington, DC: National Defense Industry Association Robotics Division, November 2007), http://www.ndia.org/Divisions/Divisions/Robotics/Documents/Content/ContentGroups/Divisions1/Robotics/Interoperability%20Standards%20Analysis%20(ISA).pdf, accessed March 14, 2011.

Porter, Michael E. *Competitive Strategy: Techniques for Analyzing Industries and Competitors*. New York: The Free Press, 1998.

President's Council of Advisors on Science and Technology (PCAST), "Prepare and Inspire: K-12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future," Executive Office of the President, September 2010, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-stemed-report.pdf,.

President's Council of Advisors on Science and Technology. *Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology*, Report to the President and Congress, December 2010. http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nitrd-report-2010.pdf (accessed 19 March 2012).

Robotic Systems Joint Project Office. *Unmanned Ground Systems Roadmap*, July 2011, http://www.rsjpo.army.mil/images/UGS_Roadmap_Jul11_r1.pdf.

Rusu, Radu Bogdan and Steve Cousins. "3D is here: Point Cloud Library (PCL)." http://www.pointclouds.org/assets/pdf/pcl_icra2011.pdf (accessed 18 March 2012).

Saenz, Aaron. "The Era of Robotic Warfare Has Arrived – 30% of All US Military Aircraft are Drones," http://singularityhub.com/2012/02/09/the-era-of-robotic-warfare-has-arrived-30-of-all-us-military-aircraft-are-drones/, February 9, 2012.

Schacht, Wendy H. *Industrial Competitiveness and Technological Advancement: Debate Over Government Polic*y. Washington DC: Congressional Research Service, 2011.

Schmitz, Alexander, Perla Maiolino, Marco Maggiali, Lorenzo Natale, Giorgio Cannata, and Giorgio Metta. "Methods and Technologies for the Implementation of Large-Scale Robot Tactile Sensors." *IEEE Transactions on Robotics*, Vol. 27, No. 3 (3 June 2011): 389-400.

Schwartz, Ariel. "Using Big Data to Predict Your Potential Heart Problems," Co.Exist Blog, *Fast Company*, http://www.fastcoexist.com/1679654/using-big-data-to-predict-your-potential-heart-problems, accessed April 20, 2012.

Simon, Catherine. "From Industrial Maturity to the "Robolution" Industrial and Service Robotics in Europe," Presentation for INNOROBO (August 2011), Business Resonance, Innovation Robotic Summit 2011, http://www.slideshare.net/bizresonance/robotique-industrielle-et-de-service-europe-aout-2011-8839337 ,accessed April 16, 2012.

Sofronia, R. E., G. Savii, and A. Davidescu. “Haptic Devices in Engineering and Medicine.” *IEEE International Joint Conferences on Computational Cybernetics and Technical Informatics*, Timisora, Romania (May 27-29 2010): 373-378.

SRI International, “Medical Robots and Telepresence,” http://www.sri.com/robotics/telemedicine.html, accessed April 20, 2012.

Stalk Jr, George. *White Paper: Creating a Distribution Powerhouse: Why Rapid Deployment Matter*s. Boston, MA: Boston Consulting Group, 2011.

Talasaz, A., R.V. Patel, and M.D. Naish. “Haptis-enabled Teleoperation for Robot-assisted Tumor Localization.” *IEEE International Conference on Robotics and Automation*, Anchorage, Alaska (May 3-8, 2010): 5340-5345.

Tathireddy, P., L. Rieth, A. Sharma, and F. Solzbacher. "Implantable microsystems and neuro electronic interfaces." *Bionic Health: Next Generation Implants, Prosthetics and Devices* (Oct. 2009): 1-22.

Taylor, Trevor. “Kinect for Robotics.” http://blogs.msdn.com/b/msroboticsstudio/archive/2011/11/29/kinect-for-robotics.aspx (accessed 19 March 2012).

Teal Group, "Teal Group Predicts Worldwide UAV Market Will Total $89 Billion in its 2012 UAV Market Profile and Forecast," April 11, 2012, http://tealgroup.com/index.php?option=com_content&view=article&id=79:teal-group-predicts-worldwide-uav-market-will-total-89-billion-in-its-2012-uav-market-profile-and-forecast&catid=3&Itemid=16.

Visiongain. "Military Video Surveillance Systems Market Worth &8.b1Bn in 2012." PR.com, , www.pr.com/press-release/406134, accessed April 19, 2012

Yuang Zheng, George Bekey, Arthur Sanderson. *Assessment of International Research and Development in Robotics.* Baltimore: World Technology Evaluation Center, 2006.