6. THE GLOBAL ROBOTICS AND INTELLIGENT SYSTEMS SECTOR

One limitation of regional business development initiatives is that they often focus on a single geographic area to the exclusion of others. In today's current business climate, competition, as well as investment, partnerships, and more, is just as likely to come by way of international sources as it is from state or national sources. In addition, critical robotics technologies, along with business and research trends, emerge throughout the world. As a consequence, a critical first step in the examination of the Massachusetts robotics sector begins with a description of the overall market.

6.1. A FRAMEWORK FOR UNDERSTANDING AND EVALUATION

The word "robotics" can refer to a wide swath of technologies, applications, markets, and even industries. As such, describing the totality of the robotics sector, a critical first step in the evaluation of the Massachusetts robotics ecosystem, can be problematic and inexact. Ongoing, rapid technological churn only makes the process more difficult.

6.1.1. Taxonomizing the Sector

For this study, the robotics ecosystem is classified into four distinct robotics sectors based on the intersection of the payment/funding sources for robotics technologies, products, and services rendered, and the markets and industries they support (Figure 1):

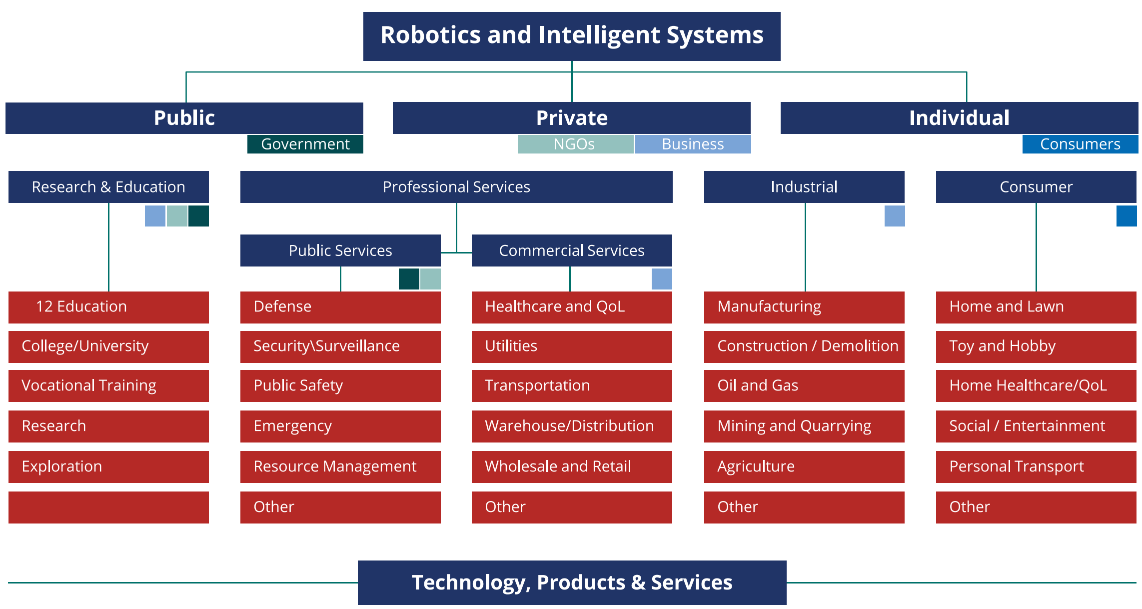
- **Consumer Sector:** The consumer sector is characterized by markets where products are purchased by individuals for their own use to assist, educate, and entertain. These products are referred to as consumer robots.
- **Industrial Sector:** The term "industrial" often equates strictly to manufacturing, but it can also be used in the broader sense to characterize industries that produce some type of tangible product or asset. In this sense, the industrial sector is a goods-producing sector. Markets consisting of the industrial sector include manufacturing (discrete and process), construction, and mining. Not unexpectedly, robotic systems employed by companies in the industrial sector are called industrial robots.
- **Professional Services Sector:** At one time the robotics sector was limited to systems employed for industrial manufacturing, and almost exclusively by the automotive industry. Over time, systems designed for purposes outside of industrial automation entered the market, forming the professional services sector, which itself is further broken down into the public services sector and the commercial services sector:

- **Public Services Sector:** As its name implies, the constituents making up the public services sector are funded through public, "soft-money" sources. They include industries and markets that deliver solutions supporting the common good or provide for security and public welfare. The defense industry serves as the best example.
- **Commercial Services Sector:** Industries in the commercial services sector consist of for-profit companies whose principal activity is to provide some type of beneficial service to businesses or individuals. The healthcare, retail, and utilities industries provide examples.

- **Research and Education Sector:** The markets in this sector draw revenue and funding from multiple sources, both public and private. Many companies develop products used as education enablers for groups ranging from preschoolers through the university-level students (educational systems). Others provide robotic systems targeted to PhD-level researchers at universities and research centers (investigatory/research systems).

Figure 1: Robotics Sector Taxonomy by Funding Source and Supported Markets and Industries

(Source: ABI Research)



6.2. INDUSTRIAL ROBOTICS

The definition as to what constitutes an industrial robot has varied over time. Initially, standard definitions from the International Organization for Standardization (ISO), the IFR, the Robotics Industries Association (RIA), and other national and international robotics groups differed slightly on particular issues, such as how the major robot design configurations are classified (selective compliance assembly robot arm (SCARA) robot, gantry robot, articulated robot, ***etc.***). Still, these groups were in agreement on where industrial robots are generally employed and what they are used for: in industry, functioning in a manufacturing or factory automation role.

As their name implies, industrial robots are used in industry, largely in a manufacturing or factory automation role.

Initially, the technology of the time limited the industrial robotics segment to immobile, inflexible, single-task robots that had little interaction with humans or the world around them as they performed their tasks. As capabilities increased over time, the formal definition of an industrial robot was broadened to include mobile systems, as well as autonomous operation. As it stands today, the formal definition of an industrial robot given by ISO-Standard 8373:2012 is:

> *An automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications.*

Advancements in robotics and control technology have made it possible for industrial robots to expand their range of applications within their traditional market sectors of large automobile, electronics, and semiconductor manufacturers (and their Tier One suppliers), and to perform more complex tasks. Other classes of manufacturers, including smaller firms, are also now automating industrial processes using robots, and at an increasing rate.

6.2.1. Dramatic Growth

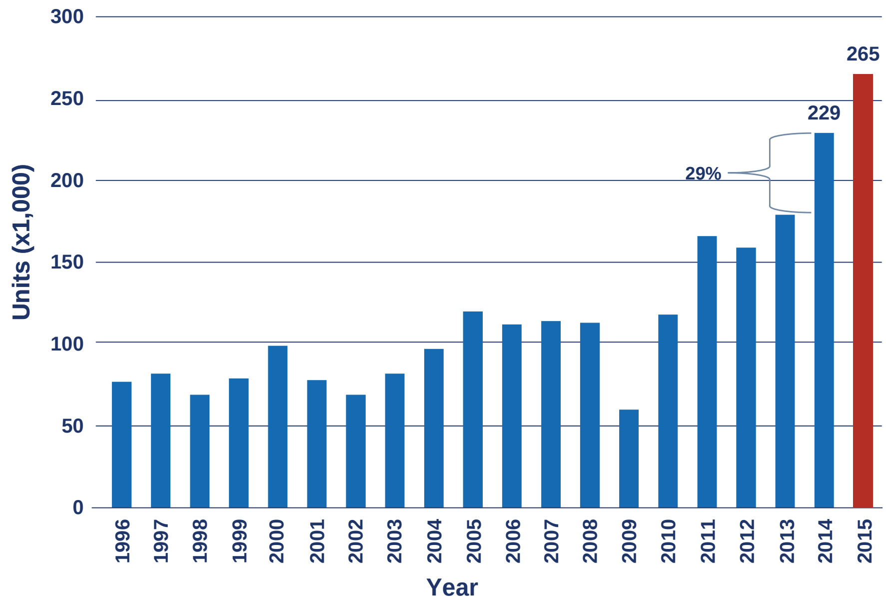
According to the IFR, and as described in Figure 2, the total number of industrial robotics installations has increased dramatically year-over-year beginning in 2010, which was up sharply as the industry rebounded following the economic downturn in North America and Europe. In 2014, the most recent figures available, 229,000 industrial robot systems were sold worldwide, up 29% over 2013, accounting for approximately US$32 billion in revenue when services are included (IFR, 2015-1). The IFR estimates this figure will jump to 400,000 units by 2018.

Sales of industrial robots are up sharply following the worldwide economic downturn of 2007 to 2009.

The recent levels of high growth are unprecedented. Prior to 2010, the number of shipped systems was basically flat year-over-year, with any fluctuations the result of normal business cycles in key geographic areas, as well as the industry's overdependence on the automotive sector with whom its fortunes were tightly bound.

Figure 2: Annual Worldwide Installations of Industrial Robots

(Source: International Federation of Robotics)



Additional Insight: *The industrial robotics sector is undergoing rapid change and market growth. This expansion will continue to accelerate and usher in a new age of industrial robotics systems that will radically transform businesses, and thereby, societies. As with change of any consequence, the growth of the industrial robotics sector will open up opportunities for all members in the industrial robotics value chain, as well as other robotics technology providers and the investment community.*

6.2.2. Driving Growth

Today, business drivers and political/social drivers, in combination with technological advancements, have greatly accelerated the expanded use of industrial robots beyond their traditional industries and traditional roles. Stakeholders promoting industrial robotics expansion—robotics suppliers, general industry, and economic development groups—do so for a variety of reasons depending on circumstance, but the overarching goals are relatively few and are summarized in Figure 3, below.

Figure 3: Drivers for Industrial Robotics Growth

(Source: ABI Research)

Political / Social Drivers	Business Drivers	
	Supply Side	Demand Side
• Back reshoring initiatives • Address shrinking labor pools • Improve national competitiveness • Maintain / increase high wage jobs • Increase manufacturing productivity • Increase exports of manufactured goods • Increase levels of high value manufacturing	• Enter new markets • Drive revenue and growth • Reduce dependence on few industries • Build sustainable competitive advantage	• Reduce costs • Improve quality • Increase productivity • Introduce new products • Meet customer demands • Offset increase labor costs • Increase automation levels • Support variable production • Support mass customization • Overcome labor pool variability • Increase manufacturing flexibility

Actuators & Actuation   Human-Machine Interfacing   Control and Control Systems   Perception & Sensor Integration
Sensor Technology & Sensing Systems

Technological Advancement

Key Market: Collaborative Robotics

Industrial robots have been engineered to serve multiple purposes and, as a group, they have found great success. Yet for all their accomplishments, the usefulness of these same systems has been limited by their high costs, complex programming, inflexibility, and inability to work in close association with humans.

Rethink Robotics is located in the Boston area, as is Teradyne, the parent company to Universal Robots.

As a result, the market for collaborative robots—human-scale systems that are easy to set up and program, are capable of being used by workers with a wide range of qualification levels, can support multiple types of automation, and can work safely in close proximity to human workers, often collaboratively—is very active at this time. Both large, established robotics suppliers, as well as new, smaller firms, have released or are developing innovative collaborative robotics technologies into the market. Larger firms are actively acquiring smaller companies with proven technology. Examples of collaborative robots include ABB's YuMi and Roberta platforms, Rethink Robotics' Baxter and Sawyer, Universal Robots's (Teradyne) UR family of robots, KUKA's LBR iiwa, and Kawada Industries's Nextage.

The collaborative robotics sector is expected to increase roughly tenfold between 2015 and 2020.

The collaborative robotics sector is expected to increase roughly tenfold between 2015 and 2020, reaching more than US$1 billion from approximately US$95 million in 2015 (Figure 4). This growth will be fueled by three key markets: electronics manufacturers and electronics manufacturing services companies, small-to-medium manufacturers, and manufacturers seeking robotics solutions optimized to support agile production methodologies.

While demand side/supply side dynamics has played a significant role in the expansion of the collaborative robotics sector, much of early development of the technologies incorporated into the systems was the result of early, and formal, academic-business-government partnerships. These efforts went beyond funding for pure and applied research. Eventually, the resultant technologies were transferred to the private sector. The development of ABB's YuMi and Kawada Industries's Nextage provide examples.

Figure 4: Collaborative Robots, Total Worldwide Revenue by Year

(Source: ABI Research)

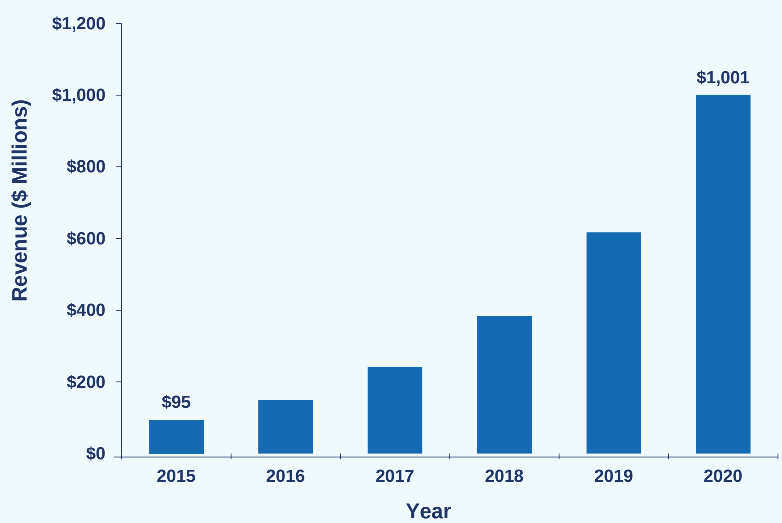


Table 3: Representative Massachusetts Industrial Robotics Companies
Rethink Robotics, Universal Robots, RightHand Robotics, Soft Robotics, Empire Robotics, Vaccon

(Source: ABI Research)

Company Spotlight: Soft Robotics

Soft Robotics, a spinoff from Harvard University's Whitesides Research Group, is a developer of novel robotic gripping technology for material-handling applications. The company, founded in 2013, closed its first investment round—a US$5 million Series A—in December 2015.

Soft Robotics produces compliant, force-limiting, adaptable end-of-arm tooling (grippers), along with control technology. A single gripper, using the same programming, can undergo elastic deformation, allowing it to grasp and hold objects of varying size, weight, and shape. "Deformation," a term borrowed from materials science, describes the change in shape of an object when some type of force or action is applied—mechanical, electrical, chemical, temperature, and so on. "Elastic deformation" implies that the object will return to its original shape once the force is removed.

Many types of robotics automation applications require highly dexterous, precise grasping and fine manipulation of objects in an accurate, delicate, yet firm manner. In the past, these applications required the use of expensive, complex grippers only suitable for a limited number of tasks, and complex programming. Soft Robotics' gripping approach overcomes these limitations. More importantly, the company's deformable and pliant gripping technology can grasp and manipulate objects that are ill-suited for traditional grippers and grasping, such as foodstuff, glassware, and cloth.

Why Soft Robotics Matters

Soft Robotics' gripping technology supports new classes of automation tasks, and can introduce robotics automation in many industries that previously have missed out on the benefits of robotics industrial automation. In many instances, new opportunities and innovative applications will emerge with the development of new technology.

6.3. PROFESSIONAL SERVICES SECTOR

In the past, the majority of robots were used in a manufacturing capacity. Today, robotics systems are employed in a variety of non-manufacturing industries. These professional "service robots" are purchased by corporate entities for business purposes, or by governmental agencies.

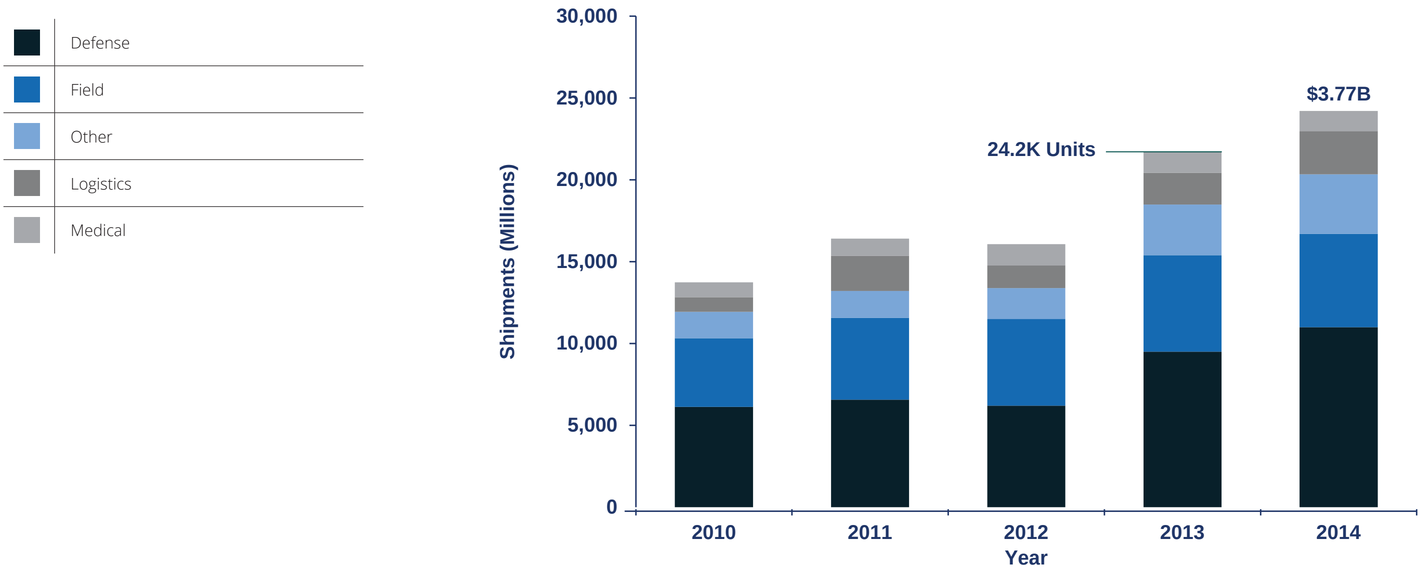
Service robots have found great success in the defense sector, where technologies like UASes have mainstreamed completely. The same holds for the healthcare industry where robotic surgical and therapeutic technologies, along with pharmacy automation and autonomous hospital delivery systems, are common. Mobile robots for e-commerce fulfillment operations in warehouses, in agriculture performing field work, or below ground inspecting sewers are also common. Service robots have applications in almost every industry—anywhere tasks require continuously high levels of concentration and fine control, or conversely, are repetitive, physically demanding, or take place in dangerous environments.

Service robots are being used in a variety of different industries and markets, with funding coming from both public and private sources.

The market for professional service robots is sizable and growing. According to the latest figures from the IFR, more than 24,000 service robots were sold in 2014 (Figure 5), attracting approximately US$3.77 billion in sales (IFR, 2015-2).

Figure 5: Annual Worldwide Installations of Professional Service Robots

(Source: International Federation of Robotics)



6.3.1. Healthcare Robotics

Healthcare robotics is the application of robotics technology to diagnose and treat disease, or to correct, restore, or modify a body function or a body part.

Healthcare providers are under enormous pressure to reduce costs and improve the quality of their services. Robotics technology can act as a cost-reduction enabler, as a means to improve the efficiency and efficacy of healthcare services, or both. For example, robotically assisted minimally invasive surgical procedures have been shown to reduce the length of patient hospital stays, while robotic-assistive technology allows disabled individuals to stay in their homes and live more independent lives. Similarly, robotic pharmacy automation systems have been shown to increase operational efficiency and enhance patient safety, which equates to higher quality patient care.

While the most recent figures for the number of shipped field and defense service robots were larger, healthcare systems were accountable for more revenue, approximately US$1.3 billion, according to the IFR (IFR, 2014-2). Healthcare robotics technologies and products can be costly and they provide for high margins. The market itself can be taxonomized according to the target group that the technology supports (Figure 6, below).

Figure 6: The Healthcare Robotics Sector

(Source: ABI Research)

Robotics Technologies		
Supports Doctors and Staff	**Supports Patients**	**Supports Infrastructure**
• Interventional/Surgical Systems • Training Systems • Diagnostic Systems • Other	• Rehabilitation / Therapeutic Systems • Assistive Technology Systems • Prosthetic and Orthotic Systems • Lifestyle Enhancement Systems • Other	• Hospital Automation Systems • Laboratory Automation • Smart Living Spaces • Other
Technological Advancements		
Business Drivers		
Social Imperatives		

6.3.1.1. Healthcare Robotics Drivers

Continuing technological advancements and economic and demographic trends, as well as the psychographic profile of the West's aging population, create a perfect storm of demand for products and services that make use of robotics technologies.

Business Drivers

The healthcare industry is massive and growing, yet it struggles from the combination of skyrocketing costs and a shortage of qualified workers. At the same time, healthcare institutions are under pressure to continuously improve the quality of their services, even in the face of limited budgets. Robotics and automation technology can be employed to address these contradictory imperatives.

Business drivers for healthcare robotics can best be summed up by the payer, employer, and government mandate to "do more with less."

- **Costs:** Healthcare providers are under enormous pressure from payers, employers, and governments to reduce costs. Robotics is seen as a cost-reduction enabler, supporting a shift to less costly outpatient and ambulatory services. Some techniques, such as robotically assisted minimally invasive surgical procedures, have been shown to reduce the length of hospital stays. Robotic assistive technology that allows disabled individuals to stay in their homes and live more independently provides another example.

- **Quality, Consistency, and Safety of Treatments:** Robotics systems are able to perform extremely precise, repetitive motions without fatigue, with the result that they are more accurate and consistent than their manual counterparts. Using sensors and feedback, they constrain movement during surgery or rehabilitation, for example, increasing the quality and safety of procedures.

- **Labor Shortages:** The healthcare industry struggles with a labor shortage in many occupations, particularly those that are physically or mentally demanding. Robotics technology holds the promise of reducing the physical demands and monotony associated with some healthcare jobs, making them more appealing, as well as increasing staff productivity.

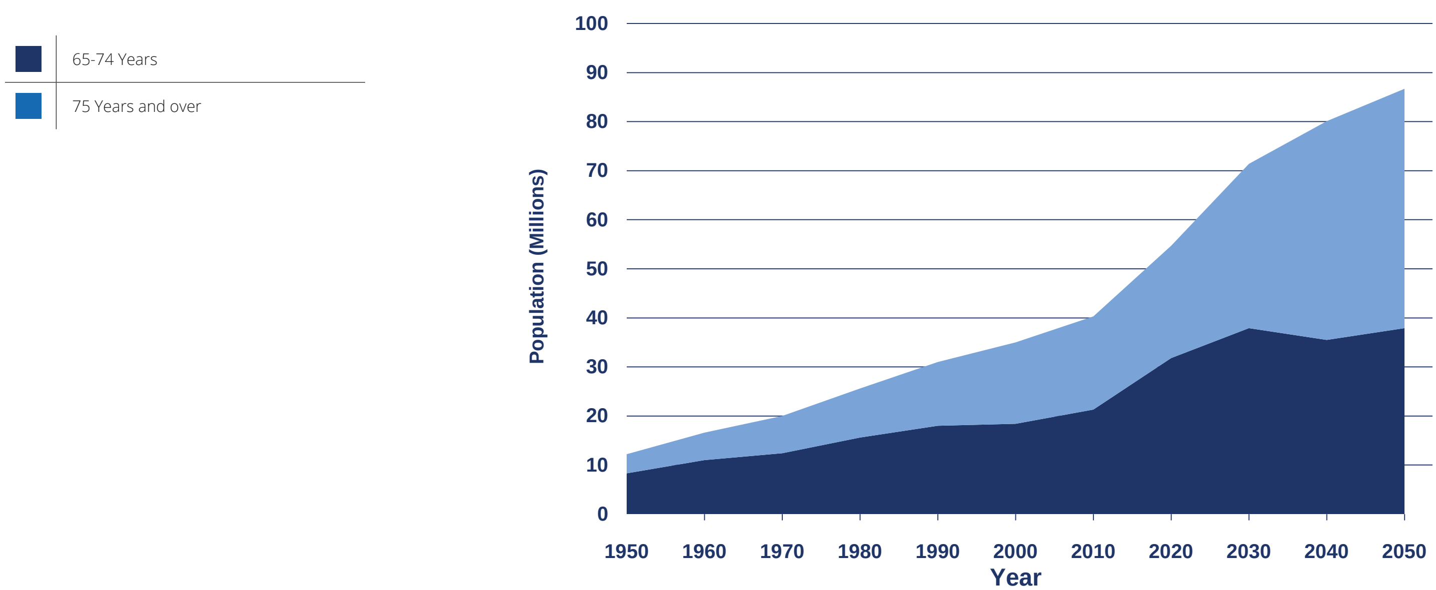
- **Aging Populations:** Life expectancies in most of the world, and particularly in industrialized states, have been increasing since 1900. Due to advances in healthcare, the average age of the older population is increasing. In addition, as the "baby boom" generation reaches retirement age, the percentage of the population above age 65 in industrialized countries is also increasing (Figure 7). The result is that many countries will be severely challenged by what epidemiologists refer to as "double aging." Unfortunately, life's golden years are often filled with illness and physical disability that require costly and ongoing medical care. Government healthcare agencies have acknowledged research showing that it is more cost-effective to support the independence of the elderly in as many aspects of their lives as possible, rather than ignore that need until it becomes critical.

- **Increased Numbers of Disabled:** According to the United Nations, approximately 650 million people, about 10% of the world's population, live with some type of disability, and with a growing population and advances in healthcare, this number is increasing rapidly. Also, despite efforts by many governments, the disabled are chronically underemployed. Robotics technology can be used to increase the independence of the disabled, and make their lives more productive. It can also make it easier for the disabled to support their continued employment, independent living, and self-sufficiency when their ability to move is restricted but they are otherwise in good health.

Robotics technology can increase the independence of the disabled population, make their lives more productive, and reduce costs for governments, health services, and insurance providers.

Figure 7: Aging Populations in the United States

(Source: National Center for Health Statistics, United States, 2012)



- **Increased Expectations:** With the certainty of aging comes the equal certainty of eventual disability. Older adults, who have higher expectations than previous generations and will not age in the same way, will increasingly choose to continue to live at home rather than be in assisted living facilities or in nursing homes. They will demand that advances in technology be leveraged to overcome the disabilities associated with aging.

- **Money and Political Power:** According to the insurance industry's MetLife Mature Market Institute, when the last baby boomer turns 65 in 2029, the generation will control more than 40% of the nation's disposable income. In addition, the huge number of baby boomers will guarantee that their political voice will be heard. The result will be that boomers, which represent a population that has historically been disinclined to compromise on lifestyle issues, unwilling to age gracefully, and backed by large amounts of disposable income, will demand greater independence than their parents and grandparents.

A wealthy, politically connected elderly population will drive the market for technology that increases independence and enhances their lifestyle in old age.

***More Insight:** Healthcare robotics share many areas of technical commonality with electrically powered medical devices. Because they both serve the healthcare industry, they hold in commonality issues relating to funding, investment, testing, and approval, not to mention the mutual goals of improving patient care, and the social and business requirements to create new and innovative product offerings. Healthcare robotics business development and commercialization activities will be more successful when examined in light of the well-understood, mature (and highly profitable) medical devices industry.*

Hospital and healthcare centers are increasingly using autonomous, mobile robots to transport food, drugs, and medical supplies.

The use of autonomous, mobile robots for transportation and delivery in healthcare environments has proven to deliver a quick ROI.

Key Market: Mobile Service Robots for Hospital Logistics

A significant cost driver for the healthcare sector is the complexity of its supply chain. When applied correctly, automation can increase supply chain operational efficiency, improve the quality of supply chain operations, and allow the redeployment of human resources, all of which contribute to improved patient care, as well as overall cost reduction.

Logistics is a major component of the overall healthcare supply chain, and includes many indoor logistics services that directly impact patients and health workers. Examples include the transport of food, drugs, medical supplies, and other items. Companies are now providing autonomous, self-navigating mobile robots to automate these logistics operations. Notable examples include Massachusetts-based Vecna Technologies, along with Swisslog (KUKA), Omron Adept Technology, and Aethon. Common healthcare facility delivery tasks automated using mobile service robots include:

- **Dietary/Food Delivery Services:** Autonomous mobile robots are used to deliver meals from the preparation area to the appropriate patient room or stationing zone where a healthcare worker will remove the meals from the cart for final delivery to a patient. They also are used to return the dirty dishes.
- **Environmental Transportation Services:** Mobile systems transport trash, recyclables, and other material, including "red bag" biohazardous waste, using specialized containers.
- **Pharmacy Delivery Services:** Secured mobile robots that require the use of passcodes and fingerprint scanners for access deliver medicines and other drugs from hospital pharmacies to nursing stations and other sites.
- **Laundry Delivery Services:** Mobile systems convey cleaned and soiled linens to and from hospital laundry services.
- **Laboratory Delivery Services:** Robots cart lab specimens and other similar material throughout hospital environments.

Hospital and healthcare centers report a quick return on investment (ROI) using these systems, but labor cost reduction is not the key measure of success. Staffing typically remains at previous levels. The mobile robots deliver substantial cost savings outside of labor, such as improving efficiency, increasing productivity among hospital staff, and enhancing levels of patient care. Greater job satisfaction and reduced turnover rates among workers have also been reported.

Mobile service robots for internal healthcare logistics work remain a greenfield opportunity. However, the acquired material transport expertise and experience allows the suppliers of autonomous delivery solutions to pursue the many additional commercial opportunities outside the healthcare industry. For these companies, the manufacturing and warehouse/distribution sectors, both of which are adopting novel robotics automation solutions at a rapid rate, are prime targets.

Table 4: Representative Massachusetts Healthcare Robotics Companies

Solution	Company
Surgical/Interventional Systems	OMNIlife science
Rehabilitation/Therapeutic Systems	Myomo, Hocoma, Interactive Motion Technologies, AndrosRobotics
Prosthetic/Orthotic Systems	BionX Medical Technologies
Hospital Logistics Automation	Vecna Technologies
Exoskeletons	ReWalk Robotics, Rise Robotics

(Source: ABI Research)

Company Spotlight: Healthcare Robotics: Myomo

Orthotic systems augment, correct, or support weakened or malfunctioning joints and limbs due to neuromuscular disorders or stroke, multiple sclerosis (MS), and other forms of neurological injury. Robotic orthotic systems differ from traditional orthotic products in that they are not passive, but instead include sensors and embedded microprocessors to control device functionality and movement.

Cambridge, Massachusetts-based Myomo produces the MyoPro Motion-G and MyoPro Motion W, FDA-approved, robotic, upper limb orthoses. The Myomo technology was developed at MIT in collaboration with Harvard Medical School and other Boston-area medical centers. MIT's Deshpande Center for Technological Innovation, a commercialization accelerator for transitioning technologies from the MIT laboratories to the marketplace, assisted in the commercialization of the Myomo technology. The privately held Myomo has received more than US$13 million in funding.

Myomo's MyoPro orthoses act as powered, functional arm braces. The custom-fit devices are under user control by way of non-invasive, skin-mounted electrodes that pick up electromyography (EMG) signals emitted during the contraction of specific muscle groups, amplify, and then transmit them as control signals to motorized joints, which assist in the movement of the arm. When the user is not engaging the targeted muscle groups, the MyoPro is inactive.

Myomo's initial myoelectric technology targeted the rehabilitation market for use in clinical settings. But the lightweight systems had the distinct advantages of portability and usability compared to other rehabilitation technologies, allowing the devices to be used outside rehabilitation centers. The current MyoPro systems are meant to be used in the home and other nonclinical settings for rehabilitation, but also for use performing daily living tasks. This aids in rehabilitation, as well as provides other therapeutic benefits.

Why Myomo Matters

Myomo has incorporated into its MyoPro orthotic solutions microprocessors, miniaturized mechatronics, and myoelectric technology, all controlled using smart software. It has, in effect, added intelligence and patient-controlled, powered actuation to a product class that formerly relied on mechanical action and reaction, which provided only rudimentary control, thus limiting rehabilitation efficacy. Myomo's MyoPro orthoses are revolutionary and indicative of the future course of orthotic products.

6.3.2. Defense

Many countries are embracing robots and robotics technology as a means to increase the efficacy of their militaries and to reduce casualties. Robust, practical military robots are now deployed in the field in multiple theaters, and new technologies and systems are under development (and in test). Cost reduction is not a driver at this time, but could be realized as systems become more autonomous, functional, and durable.

The defense robotics sector can be broken down into three basic categories based on the operational environment: unmanned ground systems (UGS), unmanned maritime systems (UMS), and of course, UAS. A smattering of other robotics types—nanorobots, micro-aerial vehicles, and more—are also used by militaries.

U.S. military funding can be used to roughly gauge global unmanned systems markets and highlight trends.

More than 11,000 robotic systems for defense were sold in 2014 according to the IFR, the last year for which data is available (IFR, 2015-2). The IFR states that these systems were responsible for approximately US$1 billion in revenue, a 4.7% increase over 2013, but also admits, "The value of defense robots can only roughly be estimated." This is an understatement, as well as the consensus option of those who study the defense robotics sector where austerity budgets are a global phenomenon and some markets are still developing. In other cases, procurements are not made public, or long-term defense programs are cancelled.

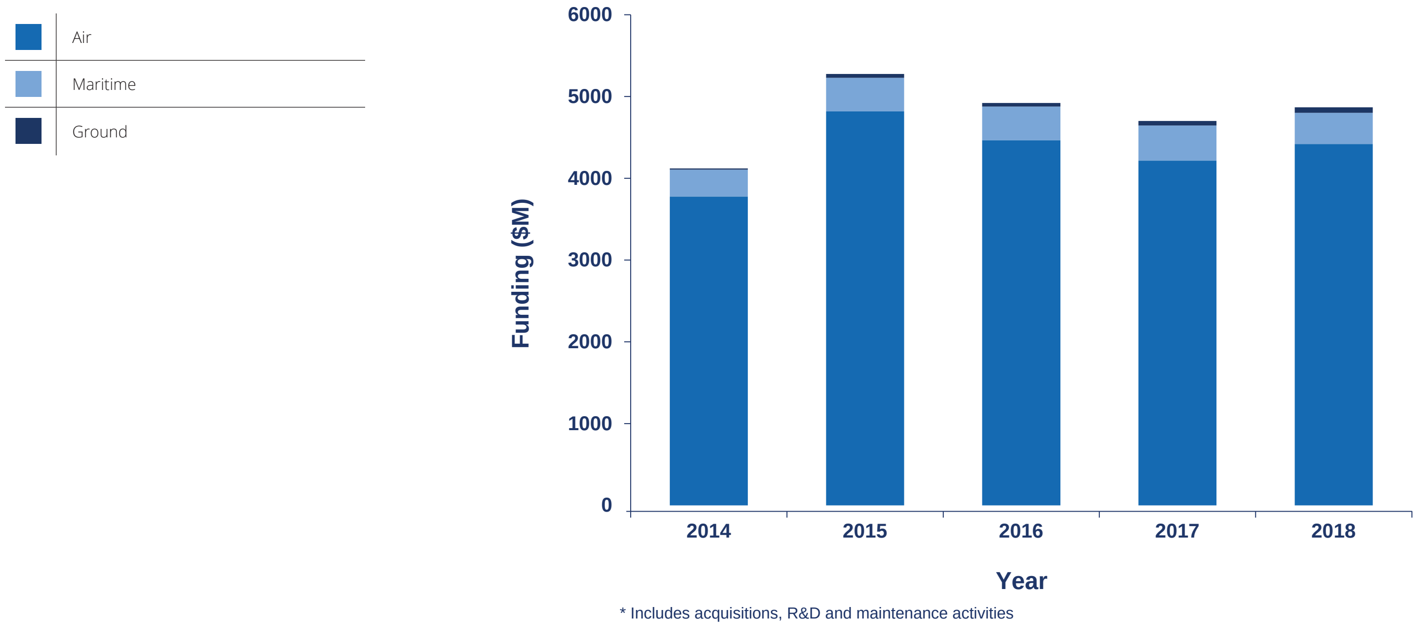
Defense funding levels for unmanned systems are expected to remain largely flat, with spending on UAS dominating.

The United States has the largest military budget by far, so it can be used to model global markets, as well as highlight trends. Baseline unmanned systems funding expectations can be gleaned from the U.S. Department of Defense (DoD)'s Unmanned Systems Integrated Roadmap, a biannual technological vision statement looking out over 25 years last published in February 2014 (U.S. DoD, 2013). Figures given in this document approximate those in the actual budgets. For example, 2014 unmanned systems expenditure estimates for fiscal year (FY) 2016 were given as US$4.9 billion, while the actual 2016 budget calls for spending levels of US$4.6 billion (Gettinger, 2016).

As seen in Figure 8, absent a significant military intervention, the DoD expects funding levels for unmanned systems to remain largely flat, with spending on UAS dominating.

Figure 8: Projected U.S. DoD Unmanned Systems Funding

(Source: U.S. Department of Defense)



6.3.2.1. Unmanned Aerial Systems

UAS for defense operations have been under development for more than 40 years, at the cost of billions in research and development (R&D) spending. They have found great success, primarily as a capabilities multiplier, and as a result, the technology has now reached a point where it has completely mainstreamed. UAS are in active service in all branches—army, air force, and navy—of militaries worldwide. These groups understand the value of applying robotics technologies to military requirements and are willing to spend time and money to deliver operational systems.

UAS for defense operations have completely mainstreamed.

The U.S. UAS inventory is the largest in the world. Small UASes exceed 10,000 in number, while there are approximately 1,000 larger platforms, according to DoD sources.

DoD funding for UAS is ongoing, with the 2017 budget request for acquisitions equaling US$2.4 billion (U.S. Undersecretary of Defense, 2016). This figure, while substantial, is much less than the US$4.5 billion figure given in the DoD's Unmanned Systems Integrated Roadmap (U.S. DoD, 2013), but the figure does not include spending for research, development, test, and evaluation (RDT&E) or maintenance programs. In fact, the 2017 UAS acquisition budget is somewhat greater than that predicted in the roadmap. Still, the 2017 UAS acquisition budget is roughly in accordance with the FY 2016 DoD budget of US$2.3 billion (U.S. Undersecretary of Defense, 2015), and therefore does not signal strong growth.

Defense funding for UAS is sizable and ongoing, but remains largely flat.

The 2016 and 2017 budget "ask" calls for the development and acquisition of all manner of UAS. Systems range from Northrop Grumman's high-flying RQ-4 Global Hawk and MQ-4C Triton surveillance aircraft, to more tactical systems, such as AeroVironment's RQ-14 Dragon Eye and AAI Corporation's RQ-7 Shadow (AAI Corporation is a subsidiary of Providence, Rhode Island-based Textron). Funding levels for system types are not comparable, however. For example, the FY 2016 DoD budget calls for approximately US$2 billion to be spent for the largest UAS, while only US$286 million is to be spent on smaller, tactical systems.

U.S. defense spending for UAS favors large, strategic platforms.

***More Insight:** Military UAS solution providers, especially those offering smaller, tactical aerial systems are actively targeting non-defense markets. To date, the emphasis for these vendors was the civil market for applications, such as infrastructure monitoring, search and rescue, and border surveillance. ABI Research estimates the overall military/civil market for small UAS (<25 lbs.) to reach US$2.3 billion in 2019, up from US$1.7 billion in 2014. These same small UAS suppliers are now focused on the commercial UAS sector where strong, long-term growth is expected.*

6.3.2.2. Unmanned Ground Systems

Robust UGS are now deployed in the field by advanced militaries throughout the world, and new technologies and systems are under development (and test). Initially, casualty reduction was the primary reason for interest in battlefield UGS. But the same robots were found to be able to accomplish some operations better than their human counterparts, or undertake tasks that humans simply cannot perform. That is, robotics systems increase battlefield operational effectiveness, in addition to saving lives. At this time, cost reduction is not a driver for military UGS, but savings can be realized as robots become more autonomous, functional, and durable.

Robotics in the form of unmanned ground vehicles (UGVs) can also be used to completely change the way in which military force is applied. The army's current transformation from a slow-moving, heavily armored force to a highly flexible, responsive, and agile entity provides an additional driver for the increased use of mobile ground robots. As it is now envisioned, advanced militaries will eventually rely on UGS to both extend perception (reconnaissance, surveillance, and target acquisition) and affect action (counter-mine operations, transport, as well as weapons platforms, extraction of the wounded, etc.) on the battlefield (U.S. DoD, 2013). Accordingly, the U.S. Army's FY 2017 RDT&E budget calls for programs to develop advanced capabilities for UGVs (U.S. DoD, 2016-2).

With further development, UGS will transform the ways that militaries operate in the field.

Key Market: Small Unmanned Ground Vehicles

Small unmanned ground vehicles (sUGVs) for military missions came to the fore during the 2000s in Iraq, Afghanistan, and elsewhere for improvised explosive device (IED) detection and explosive ordnance disposal (EOD), as well as to provide situational awareness. More than 10,000 remote-controlled sUGVs have been deployed by the U.S. military, up from fewer than 100 in 2001. Most of these systems (90%) were supplied by the Massachusetts-based companies QinetiQ North America and iRobot. iRobot's Defense and Security Business Unit, which produced the company's sUGS, was recently sold to Massachusetts-based Endeavor Robotics.

The wars in Iraq and Afghanistan were a substantial demand driver for military sUGS.

Casualty reduction during the wars in Iraq and Afghanistan—both a social and political driver—was the primary reason for the U.S. military's dramatic increase in sUGV acquisitions and deployments. In this regard, sUGV were wildly successful, much more than other UGV programs.

The market for UGVs for defense applications slowed considerably after the United States and other countries reduced troop levels in Iraq and Afghanistan. But sUGVs have proven robust and able to address many requirements for countering irregular warfare, and therefore deployments will continue. Also, the sUGV market is expected to increase again as militaries replace, as opposed to upgrade, their fleets of small UGS. For example, the DoD estimates that spending on sUGVs will increase from US$45 million in 2016 to US$54 million in 2017 (U.S. DoD, 2013). Much of this funding is for research into expanding mission capabilities, with military officials requesting that research in sUGV functionality focus on what robots can do better than humans, as opposed to what humans already do well.

6.3.2.3. Unmanned Maritime Systems

UMS include both surface vehicles and subsurface systems, and include both remote-controlled and autonomous systems. UMS are currently in active military use for missions ranging from hull inspection, search operations, intelligence, surveillance, and reconnaissance (ISR), environmental monitoring, anti-submarine warfare, and particularly mine counter measures. Perhaps more importantly, UMS research is very active at this time, and is a precursor to active deployment. Basically, militaries are seeking to bring the same capabilities found in UAS to marine environments, including weaponized platforms.

Militaries are seeking to bring the same capabilities found in unmanned aerial systems to marine environments.

The market for UMS for military is dependent on defense funding trends, especially for the U.S. military, with Europe and Israel contributing in some measure. In 2014, the DoD projected unmanned maritime expenditures to roughly equal US$400 million per year until 2018 (U.S. DoD, 2013). This is in rough agreement with the FY 2017 DoD budget for UMS funding, which reaches approximately US$442 million. Of that, approximately US$91 million is dedicated to procurement, while roughly US$351 million is dedicated to research, development, and testing activities. Further out, defense spending for UMS is expected to increase, driven by greater capabilities and the ability of UMS to perform many of the same functions of other, much more expensive naval vessels.

DoD UMS funding is averaging US$400 million per year, with most dedicated to research, development, and testing activities, a precursor to full deployment.

Table 5: Representative Massachusetts Defense Robotics Companies	
Solution	**Company**
Unmanned Ground Systems	QinetiQ North America, Endeavor Robotics
Unmanned Aerial Systems	CyPhy Works, Textron Systems, Aurora Flight Sciences
Unmanned Maritime Systems	Hydroid (Kongsberg Maritime), Boston Engineering, Bluefin Robotics (General Dynamics Mission Systems),Teledyne Marine Systems

(Source: ABI Research)

Foster-Miller was founded by MIT graduate students, and later acquired by QinetiQ North America.

More than 4,000 of QinetiQ North America TALON systems have been deployed throughout the world.

Company Spotlight: QinetiQ North America

QinetiQ North America (QNA) is a subsidiary of QinetiQ, the United Kingdom's largest technology research and design company. The group was formed following the acquisition of Waltham, Massachusetts-based Foster-Miller by QinetiQ's Technology Solutions Group in 2004 (US$164 million), along with Westar Aerospace & Defense Group (US$130 million) and assorted other small technology R&D firms. Foster-Miller, a research and technology development firm, was founded by MIT graduate students.

QinetiQ North America produces solutions for the transportation, utilities, aerospace, security, and defense sectors. Among the company's many product and service offerings are unmanned systems technologies. The company is particularly noted for its UGV offerings, with much UGV technology originally developed by Foster-Miller or acquired by them. Foremost among these are the company's TALON and Dragon Runner platforms.

Over the course of 15 years, QNA's mid-sized, teleoperated TALON systems have been used for hundreds of thousands military missions, ranging from explosive ordnance disposal, to reconnaissance, remote sensing, and more. With each new generation, the TALON platform added new capabilities, making it more functional, capable, and autonomous. The systems are also increasingly being employed by North American and international police forces and SWAT teams for public safety and security applications. More than 4,000 TALONs have been deployed throughout the world.

QNA's Dragon Runner is a man-portable (15 lbs.), very durable, sUGV designed for surveillance, reconnaissance, and light manipulation work in urban environments. As befitting its role, the Dragon Runner boasts of multiple cameras, along with motion detectors, infrared sensors, listening devices, and more.

Why QinetiQ North America Matters

QNA's sUGVs have operated in some of the most demanding environments in the world, and have been validated in the field as being both capable and robust. Many of the military applications for QNA's sUGVs have equivalents in the civil, and even commercial, sphere. As a result, QNA, like other providers of military-grade sUGVs, are targeting non-military markets and optimizing their platforms for security, public safety, and emergency response applications.

6.3.3. Field Robotics

Field robotics pertains to mobile robotics systems—aerial, ground, and maritime—designed for operation in outdoor, unstructured, and dynamic environments, such as construction worksites, open mines, and farm fields. Field robotics systems share many characteristics with other classes of robotics technologies, but they tend to be larger and more ruggedized than systems designed for indoor use. In 2014, approximately 6,000 field robotics systems were sold worldwide, which accounted for nearly US$1 billion in revenue (IFR, 2015-2).

Field robotics initiatives are often undertaken by countries or industries that are heavily dependent on natural resources for revenue. It is for this reason that Canada and Australia established field robotics centers that study the application of robotics technology to mining and oil/gas exploration. Commercial efforts are underway as well. For example, international mining firm Rio Tinto's Mine of the Future program, a plan for automating mining processes in Western Australia, is the world's largest privately funded robotics initiative. As part of its Mine of the Future program, Rio Tinto is spending US$7.2 billion to expand operations targeted at the US$300 billion iron ore market, which is a subset of US$1 trillion global mining sector.

Field robotics research is also common in agricultural areas, resulting in both new prototype systems for applications, such as weeding and pest control, as well as picking and harvesting. Commercial products are also available. For example, in 2014, more than 5,000 robotic cow milkers were sold, accounting for more than 90% of service robotics systems sold in that year (IFR, 2015).

Robotics systems in support of aquaculture also fall under the aegis of field robotics. According to the U.S. National Oceanic and Atmospheric Administration (NOAA), aquaculture supplies more that 50% of all seafood produced for human consumption, and that figure is expected to increase significantly as traditional fisheries reach capacity. The United Nations Food and Agriculture Organization estimates that by 2030, an additional 40 million tons of seafood worldwide per year will be required to meet current consumption rates. As a result, efforts are underway to increase the efficiencies of both traditional and farmed fishing through automation, including robotics. As a maritime robotics leader with a long commercial fishing history, Massachusetts is well placed to lead aquaculture automation efforts. Woods Hole Oceanographic Institution (WHOI), along with commercial maritime robotics suppliers, such as Sea Machines and InnovaSea, are currently developing solutions for automating aquaculture.

Field robotics, while still nascent, is linked to some of the world's largest industries, including mining, agriculture, aquaculture, and more.

Key Market: Commercial Drones

The small unmanned system (sUAS) market is the fastest-growing and most dynamic UAS sector. Compared to larger systems, sUAS, those systems weighing less than 25 pounds, are much lower in cost to purchase and operate, offering young companies the opportunity to create novel solutions based on UAS technologies that deliver real value.

At this time, the consumer UAS is currently engaged in a race to the bottom in terms of pricing, a process that will continue as technology becomes commoditized and new companies enter the market. At the same time, defense funding for sUAS technologies remains flat. As a result, providers of both consumer and defense sUAS are reengineering their offerings and amending their business plans to quickly provide commercial sUAS solutions. In doing so, they are joining a large number of young, entrepreneurial firms focused on the same markets, many who have recently received sizable sums of early-round investment funding for commercial drone technologies. Examples include Massachusetts-based CyPhy Works, as well as PrecisionHawk, Airware, and more. Funding rounds for these firms are given in expectation that the base hardware platform is only one component of a larger offering that can include:

Commercial sUAS ecosystem revenue will reach more than US$5 billion by 2019, up from US$651 million in 2014.

- **Platforms:** Base sUAS platform, plus customary technology required for system use. Includes airframes, standard sensor/camera payloads, control technology, battery chargers, etc.
- **Systems/Platforms Support and Services:** Ancillary hardware and software technologies provided by the platform supplier or services firms. Includes additional/custom payload options, redundant components, toolkits, training, technical support, service/repair, casing, launch or recovery equipment, hardware (HW)/software (SW) updates, etc.
- **Application Services:** Includes data services, modeling services, operator services, licensing/permitting services, legal/liability services, industry specific applications and services, etc.
- **Enabling Technologies:** Enabling technologies that replace, augment, improve, or extend the functionality of UAS. Includes specialized/custom payloads, motors, propellers and balancers, control systems, cameras and gimbals, batteries/power, communication HW/SW, navigation/monitoring HW/SW, airframe components, and more.

Commercial sUAS revenue will reach US$5 billion in 2019, up from US$651 million in 2014.

According to ABI Research, the total commercial sUAS ecosystem revenue will reach more than US$5 billion by 2019, up from US$651 million in 2014 for a CAGR of 51.4%. Perhaps more importantly, the bulk of 2019 revenue will be the result of application services (Figure 9).

Most commercial drone applications fall under "field robotics."

Most commercial sUAS applications fall under the aegis of "field robotics," with applications targeting some of the largest industries in the world. In 2015, approximately 25% of all commercial sUAS applications were for agriculture, followed by infrastructure/industrial inspection (15%), geology/mining (13%), and oil and gas (10%) (ABI Research, 2015).

Figure 9: Total Worldwide Commercial sUAS Ecosystem Annual Revenue

(Source: ABI Research)

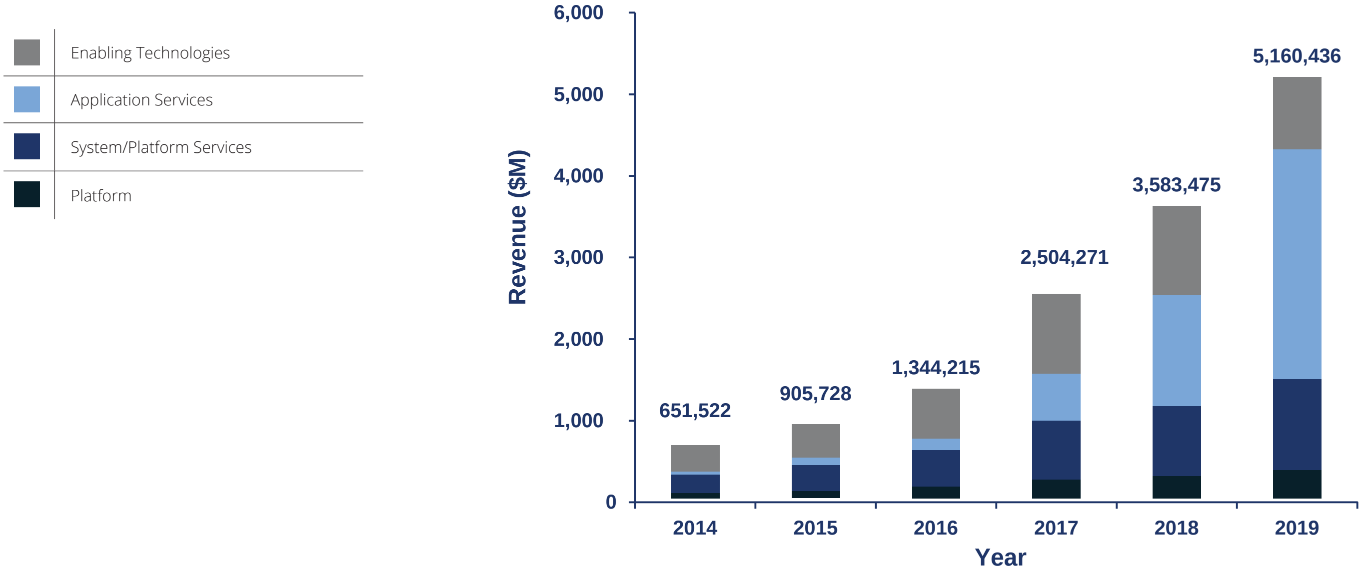


Table 6: Representative Massachusetts Field Robotics Companies
Harvest Automation, Iron Goat, Franklin Robotics, RailPod, Scanifly, CyPhy Works, Panoptes, XactSense

(Source: ABI Research)

CyPhy Works received a total of US$25 million of private equity funding in 2015.

CyPhy's drones are distinguished for their secure communications, ability to stream high-speed, high-definition video, and long operational flight time.

Company Spotlight: Commercial Systems: CyPhy Works

CyPhy Works is a Danvers, Massachusetts-based robotics firm founded by Helen Greiner, one of the founders of iRobot, which in turn was an MIT spinoff. In 2015, the company received two rounds of venture funding for a total of US$25 million.

CyPhy Works produces small unmanned aerial vehicles (UAVs or "drones"). CyPhy's drones are notable for their secure communications, ability to stream high-speed, high-definition video, and long operational flight time. Moreover, the communication link between drone and operator is fast (no lag), secure, and reliable, and cannot be intercepted, interrupted, or interfered with. This is accomplished using a combination of a very light platform; a remote, replaceable power source; and a microfilament tether that is spooled out from the bottom of the drones, keeping them constantly connected to communications and power. The tether, which is patented technology, is extremely thin and flexible, hangs slack from the sUAS, and does not restrict the vehicle's movement. It can be easily replaced once the mission is complete.

For commercial drones, increasing levels of autonomy is a capabilities multiplier. While navigation autonomy for sUAS is improving, the operational flight time of the vast majority of the sUAS is severely limited. That is, they do not provide for power autonomy, the ability to operate for a long period of time before a power source must be replenished or replaced. As a result, the effectiveness and reliability of the sUAS are less than optimal and make them unsuitable for many commercial applications.

Why CyPhy Works Matters

The CyPhy systems can operate much longer than the typical sUAS, and if constant power is supplied through tethering, then operational time, at least theoretically, is unlimited. For many applications, tethering is not only appropriate, it is ideal.

6.4. LOGISTICS ROBOTICS

The word "logistics" can refer to a wide range of operations for the movement of material, personnel, and products across an equally large number of sectors. The maritime international shipping of raw materials, the delivery of packages to the consumer, or even the movement of men and supplies for military operations are logistics processes. At this time, robotics support for logistics operations occurs indoors, largely at manufacturing sites, warehouses, and distribution centers.

Corporate logistics and supply chain groups have adopted a wide range of automation technologies to improve the operational efficacy and efficiency in manufacturing sites, warehouses, and distribution centers. Robotics technologies can be employed in warehouses and distribution centers to automate costly, dangerous, and time-consuming activities. Moreover, these new robotics solutions provide companies with a high degree of flexibility, a capability lacking in many earlier forms of warehouse and distribution center automation, such as fixed conveyors and carousels.

6.4.1. Total Automation

Today's logistics and supply chain managers are faced with multiple sets of contradictory requirements. They must reduce the space they use, but increase the volume of goods they transport, as well as increase service levels while reducing costs. These same managers understand that automation is key for meeting these goals. As a result, all major manufacturing and warehouse/distribution center processes have been automated to some degree (see Figure 10), with the goal of achieving near total automation.

6.4.2. Multiple Classes

Many different classes of robotics systems are used to automate logistics operations. They Include:

- **Automated Guided Vehicles (AGVs):** AGVs are a common form of robotic assistance in warehouse and DC automation systems. They are also employed in manufacturing environments. AGVs range from enormous factory units designed to move multi-ton products from one stage of fabrication to another, to cart-sized units that navigate hallways carrying smaller amounts of materials. Many different classes of technologies and products fall under the definition of AGVs, including:
    - **Automatic or Automated Carts:** Simple carts capable of automated transportation
    - **Unit Load AGVs:** Individual AGVs that carry discrete unit loads onboard the vehicle
    - **Tugs or Towing Vehicles:** AGVs that pull one or a series of unpowered trailers
    - **Forklift AGVs:** Unmanned forklifts that pick up and deliver pallets, often when unloading or loading trucks
- **Articulated Robots:** Classic industrial robots with multiple rotary-jointed "arms." Articulated robots can range from simple two-joint robots to complex 10-joint robots. Articulated robots are commonly employed for palletizing and depalletizing work.

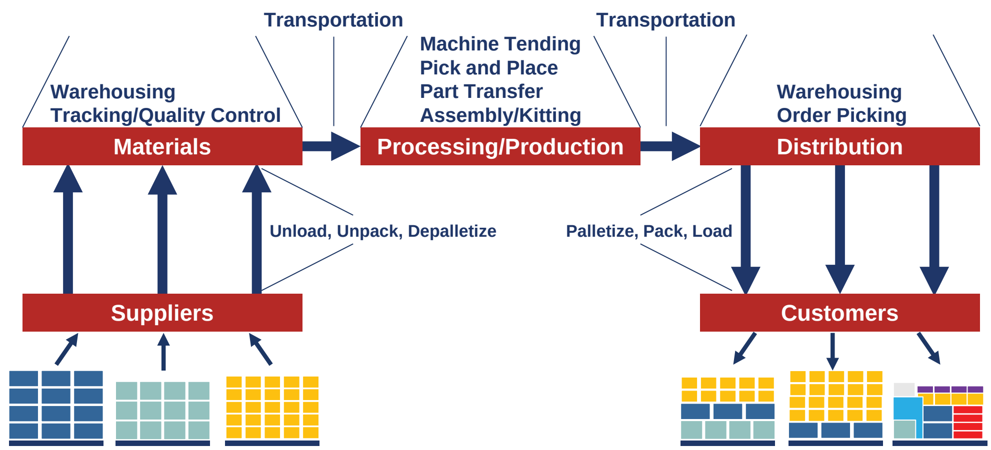
- **Linear Robots:** Also called gantry or cartesian robots, and largely used for lifting and carrying heavy objects over long distances.

- **Collaborative Robots:** Human-scale, articulated robots that work directly and safely with their human workers.

- **Mobile Robots:** Intelligent, mobile robots capable of autonomous navigation are increasingly being used for logistics in manufacturing and distribution centers.

Figure 10: Automating Manufacturing, Warehousing, and Distribution Center Logistics Operations

(Source: ABI Research)



The worldwide retail e-commerce market exceeds US$1.2 trillion.

Massachusetts leads the world as a source of mobile robots for retail e-commerce logistics.

Key Market: Mobile Robots for E-commerce Logistics

According to the United Nation's Organization for Economic Cooperation and Development, the worldwide retail e-commerce market exceeds US$1.2 trillion, and is growing faster than the business-to-business (B2B) e-commerce sector (United Nations Conference on Trade and Development (UNCTAD), 2015). In the United States alone, total retail e-commerce sales for 2015 exceeded US$341 billion, accounting for 7.3% of total retail sales and representing a 14% increase over 2014 figures, according to the U.S. Department of Commerce. Moreover, in the United States, online retail as a percentage of overall retail sales continues to increase year-over-year (see Figure 11). Asia and Europe are similar in this regard.

Efficient order fulfillment is key to the success of e-commerce retailers, especially given the rapidly increasing number of products offered for sale, along with promises of same-day and next-day deliveries. The same holds for third-party logistics (3PL) companies that offer fulfillment services to retailers.

All e-commerce retailers, as well as 3PL providers supporting them, understand that fulfillment operations are a major contributor to the burgeoning cost of online retail sales, with fulfillment costs as a percentage of sales revenue actually increasing. Profitability, to say nothing of the economic viability of retail e-commerce models, requires that fulfillment costs be reduced substantially.

Automation, and perhaps only automation, is the key to reducing online retail fulfillment costs. That is why public equity financing is pouring into companies developing mobile robots that support indoor logistics automation for retail e-commerce fulfillment operations. Recently funded companies providing mobile robots for retail e-commerce fulfillment include Massachusetts-based 6 River Systems and Locus Robotics, along with Fetch Robotics and GreyOrange Robotics. Locus Robotics and 6 River Systems join Massachusetts-based Amazon Robotics (see below), Vecna Technologies, and Symbotic in making the Commonwealth the leader in this critical and fast-growing robotics sector.

Figure 11: U.S. Retail E-commerce Sales as a Percent of Total Quarterly Retail Sales

(Source: U.S. Census Bureau, U.S. Department of Commerce)

Table 7: Representative Massachusetts Logistics Robotics Companies

Mobile Service Robots for Indoor Logistics	Amazon Robotics, Locus Robotics, Symbotic, 6 River Systems, Vecna Technologies

(Source: ABI Research)

Company Spotlight: Logistics Systems: Amazon Robotics

E-commerce retail giant Amazon has made massive investments in automation to cut the cost of fulfillment operations at its distribution centers. Amazon's ongoing fulfillment automation efforts take many forms: software, hardware, communications, and more. But the posterchild for Amazon's profitability through automation efforts is the Kiva mobile-robotic fulfillment system (MFS). In March 2012, Amazon announced that it had reached an agreement to acquire Kiva Systems, a Massachusetts-based provider of robotic material-handling technology for US$775 million in cash, a 7X plus multiple on Kiva's revenue. It was Amazon's second-largest acquisition up until that point. Kiva was originally founded in 2003 by Mick Mountz, an MIT-trained engineer with a Harvard MBA. The new subsidiary was renamed Amazon Robotics.

Amazon Robotics's Kiva MFS is an advanced goods-to-man picking solution using intelligent mobile service robots specifically optimized for retail e-commerce fulfillment operations in large warehouses. Specifically, mobile robots locate shelving containing storage bins with needed items, expand vertically to lift a shelf unit off the floor, and then deliver the material to a human worker at a workstation who "picks" the required number of items from the bin and then places them in another container for shipping. Compared to traditional methods, the Kiva approach is more productive, accurate, and flexible, and has proven to reduce the cost of pick-pack-ship operations and increase throughput.

Amazon produces its intelligent mobile service robots in Massachusetts and employs over 600. More than 30,000 of the systems are at work 24x7x365 in the company's fulfillment centers.

In August 2015, Amazon publicly stated that it had more than 30,000 of its mobile robots at work 24x7x365 in its fulfillment centers, a figure that is substantially higher at this time. Amazon officials also note that the Kiva solution has proven to reduce the cost of pick-pack-ship operations in its fulfillment centers.

Why Amazon Robotics Matters

The Amazon/Kiva acquisition raised the profile of robots and robotics technology in the eyes of the business and investment community, and validated robotics as an investment opportunity. The deal demonstrated a clean, quick exit strategy and software-like ROI to a financial community that is often hesitant to invest in far horizon, hardware-centric robotics startups.

Amazon's Kiva solution also represents a shift in the way that warehousing, distribution, and fulfillment operations are viewed. At one time, these back-end processes were considered as cost centers only, albeit ones where dollars could be saved and productivity increased through automation. This tactical attitude has given way to a more strategic viewpoint. E-commerce business models demand that fulfillment costs be reduced substantially. Thus automation, and perhaps only automation, including mobile service robots, is the key to online retail sustainability and success.

6.5. THE CONSUMER SECTOR

Consumer robotics are robots or robotics technologies purchased by individuals that educate, entertain, or assist, often in the home. These consumer systems have sold millions, yet have only begun to scratch the surface in terms of market penetration. As new technologies, architectures, and services come online, including cloud robotics and the global network of interconnected objects that is the Internet of Things (IoT), consumer robotics products will expand into other areas and create entirely new markets yet unimagined.

Consumer robots are purchased by individuals for their own personal use.

The products serve the consumer market in many diverse segments, including:

- **Home Care/Lawn Care Robots:** As their name implies, home care/lawn care robots are used in and around the home to perform household chores. Most of these products are single function, and relatively low cost. Examples include robotic vacuums from iRobot, Ecovacs Robotics, Neato Robotics, Infinuvo, and others, as well as robotic pool cleaners from Zodiac, Maytronics, iRobot, and more. Also included in this group are robotic lawn mowers from well-known global brands such as Husqvarna, Honda, Robert Bosch, and John Deere.

- **Robotic Toys/Entertainment:** Robotic smart toys are typically intelligent extensions of classical children's toys and come in a wide variety of form factors, although animals; animal-like creatures; cars, trucks, and other vehicles; and classical robotic form factors predominate. Many robotic smart toys can be networked to the Internet and include some combination of infrared, touch, and stereo sensors so that they can produce actions based upon receiving stimuli from people or their surroundings. Examples of robotic smart toys include Sphero's BB-8, Anki's Anki OVERDRIVE, WowWee Robotics's Robosapien, and Innvo Labs's Pleo.

- **Consumer Drones:** Consumer drones range from low-cost toys to more functional models featuring high-quality cameras and advanced navigational capabilities, costing more than US$1,000. Common applications for consumer drones include recreational photography and videography, first-person flying, and action sports. ABI Research predicts that more than 90 million consumer UAVs will ship during 2025, up from 4.9 million in 2014, at a 30.4% CAGR from 2014 to 2025. In addition, consumer drone revenue in 2025 will reach US$4.6 billion.

The consumer drone market is expected to reach US$4.6 billion by 2025.

- **Personal/Social Robots:** Social robots, often called "companion robots" or "personal robots," are technically advanced robots that interact directly with people and are designed to assist in the home, or to act as a companion, often to the elderly. Personal robots, web-enabled and usually humanoid in form, are designed to be the center of control for consumer devices and household appliances, and can monitor the home and respond as requirements dictate. Social robots are loaded with a variety of sensors, with some able to recognize faces and speech, and respond to verbal commands. Examples of personal robots include NEC's PaPeRo, Blue Frog Robotics' BUDDY, and Jibo's Jibo.

- **Other Consumer Robotics Products:** Home automation and security, pet care, and durable juvenile products are also becoming "robotized," adding the ability to sense, think, and act (impact or move through) in the physical world. These and other classes of consumer robotics products have begun to come to market, although most are only selling in small numbers to date.

Table 8: Representative Massachusetts Consumer Robotics Companies
iRobot, Mini-Mole, Jibo

(Source: ABI Research)

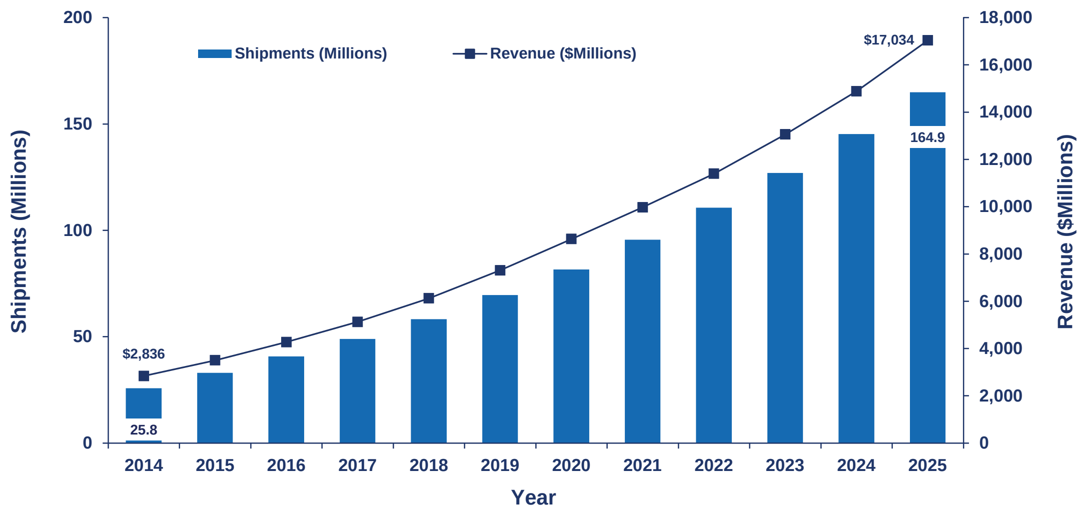
6.5.1. Strong Growth

In 2015, the consumer robotics sector was responsible for shipments reaching approximately 33 million units, resulting in revenue of US$3.5 billion, according to ABI Research (Figure 12). By 2025, both shipments and revenue are expected to dramatically increase, with total shipments forecast to increase to 165 million and total revenue to more than quadruple, reaching US$17 billion.

In 2015, 33 million consumer robotics products shipped.

Figure 12: Worldwide Consumer Robotics Product Shipments and Revenue

(Source: ABI Research)



Robotic floor cleaners have mainstreamed, yet a massive market opportunity remains.

iRobot is the leading producer of floor-cleaning robots with more than 60% market share.

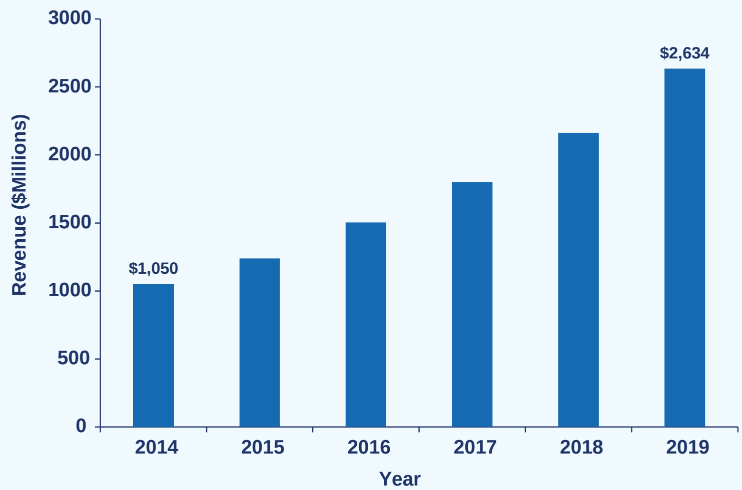
Key Market: Floor-cleaning Robots

Since the release of iRobot's Roomba in 2002, the robotic vacuum cleaner market has changed dramatically. First, the market has proven to be a new and growing opportunity. No longer an impulse purchase for technophiles, robotic vacuums have mainstreamed. The release of robotic cleaners by leading home appliance companies such as Hoover, Phillips, LG, Samsung, Miele, and Toshiba, along with industry leader iRobot (14 million sold) and others, is indicative of a robust, dynamic market.

The global market for robotic vacuum cleaners is exhibiting double-digit growth. ABI Research estimates that the robotic vacuum/floor cleaner market will reach more than US$2.6 billion in 2019, up from US$1 billion in 2014 for a CAGR from 2014 to 2019 of 20.2% (see Figure 13). More importantly, the remaining addressable market is very large. It is estimated that just 5% to 7% of vacuum cleaner owners currently own a robotic vacuum cleaner. Massachusetts-based iRobot is the leading producer of floor-cleaning robots with more than 60% market share.

Figure 13: Robotic Vacuums/Floor Cleaners, Worldwide Revenue

(Source: ABI Research)



Boston-based Jibo received US$50 million in investment funding in 2015.

Company Spotlight: Consumer Systems: Jibo

Jibo is a Boston-based robotics firm launched in 2012 by social robotics pioneer Cynthia Breazeal, the founder and director of the Personal Robots Group at the MIT Media Lab. Jibo's CEO, Steve Chambers, was formerly the president at Nuance Communications, the Burlington, Massachusetts-based producer of speech recognition and visioning software and other advanced technologies. Jibo received more than US$50 million in investments in 2015.

Jibo is developing Jibo, which the company describes as the world's first "family robot," and which is more typically referred to as a "social robot." The 11-inch-tall, 6-pound Jibo is designed to assist people with their daily life activities, acting as the nexus of control and interaction with other people and technology. Jibo is immobile, but can pitch and turn in a manner that makes it appear alive.

Jibo's social functions are based on years of research at MIT dedicated to social robots and robot-human interaction. Jibo is as much a platform as a product. While Jibo will ship with a core set of functions and social skills—facial recognition, speech recognition, natural language processing, touch, personalization, programmability, understanding and demonstration of social cues, etc.—the company intends to let third-party developers create Jibo-compliant applications. Examples might include Jibo for preschool teaching or storytelling, Jibo as elder assistant (reminders, technology interfaces, etc.), Jibo for active families (scheduling, reminders, messaging, etc.), and so on.

Commercial availability for Jibo is expected in 2016. Expectations are extremely high.

Why Jibo Matters
Jibo could usher in an entirely new consumer electronics market: social robots for the home.

6.6. THE EDUCATIONAL/RESEARCH SECTOR

This group of robotics technology includes software and hardware platforms that are used in academic or research institutions as the basis for conducting primary robotics R&D, as well as early commercialization work.

6.6.1. Educational Robotics

Robots and robotics technology have great emotional appeal for children and young adults. Educators have found that this fascination among young people can be leveraged to stimulate interest in science, technology, engineering, and mathematics (STEM), as well as robotics itself. Since robots represent a practical application of physics, computer science, engineering, and mathematics, robotics technology is often used to teach and physically demonstrate concepts within these disciplines.

Robotics can be employed successfully as a tool for education and learning facilitation, particularly as it applies to STEM.

It has been well established that robotics can be employed successfully as a tool for education and learning facilitation, particularly as it applies to STEM. This, of course, dovetails into larger social and political agendas operating at the national level in all industrialized counties, as well as at the state, province, and prefectural level, to develop an engineering workforce able to contribute to 21st-century economies. This sector is largely, although not exclusively, dependent on public funding; educational robotics products are also purchased by consumers as a type of smart toy.

6.6.2. Research Robotics

A number of robotics technology suppliers develop robot hardware and software systems specifically to sell to universities and private groups as research platforms. The deliverables are typically "open" both with regard to their ability to be physically accessed, as well as supporting open source software libraries such as OpenCV and Robot Operating System (ROS) (see Robot Operating System, below). Often, the provider companies also produce commercially hardened versions of the same systems. Companies offering research robot platforms include Aldebaran Robotics, Festo, CoroWare, Barrett Technology, ABB, Rethink Robotics, Universal Robots, ROBOTIS, and many others.

The suppliers of research robots receive feedback from investigators using their products, which helps them maintain their innovation edge.

The market for research robots is relatively small, and for many companies it is only a minor, supplementary revenue stream. Research programs are often publicly funded, which implies long, nonrecurring sales cycles subject to the vagaries of grant writing and political trends. Still, feedback from ongoing research allows provider companies to remain at the forefront of innovation, which is extremely critical.

Table 9: Representative Massachusetts Education and Research Robotics Companies

Solution	Company
Educational Robotics	KinderLab Robotics, Gears Educational Systems, Robotix USA
Research Robotics	Aldebaran Robotics, Rethink Robotics, Universal Robots, Barrett Technology, RightHand Robotics

(Source: ABI Research)

Massachusetts Spotlight: New England Robotics Validation and Experimentation Center

Established in 2013, the NERVE Center is an advanced robotics test facility located at the University of Massachusetts in Lowell. UMass Lowell also manages the installation. Funding for the NERVE Center has come from multiple sources including NIST, the DoD, UMass Lowell, and other sources.

The 9,000-square-foot NERVE Center was developed with the assistance of NIST, a division of the U.S. Department of Commerce chartered with developing measurement techniques, standards, and technologies, often working in partnership with industry and academia, with an eye to increasing U.S. industrial competitiveness. NIST also supervises robotics test centers at its headquarters in Maryland and in Texas.

The operating environment and testing methods employed at the NERVE Center are modeled after NIST test beds so that assessments are repeatable and results comparable. Formal, standardized protocols are used for measuring the performance attributes of mobile robots for tasks such as mobility on uneven surfaces and stairs; movement over dirt, gravel, and sand; and driving through water. Other methods test manipulation, human-robot interaction, power consumption, and more. NERVE also serves as a training center for robot operators.

NERVE Center facilities are made available to academics, government entities, and private industry.

NERVE Center facilities are made available to academics, government entities, and private industry on an hourly or daily basis, with reservations and training managed through UMass Lowell's Core Research Facilities program. Data collected during research testing is held in strictest confidence.

The NERVE Center itself has been host to a number of robotics events at the UMass Lowell facility. The center has also participated in other seminars, demonstrations, competitions, and conferences throughout the United States and elsewhere, often in partnership with other academic, industry, and government groups.

Why the NERVE Center Matters
The NERVE Center is one of only three NIST-sanctioned robotics testing centers in the United States.

6.7. EMERGING MARKETS

New markets emerge when viable products or services, often the result of technical evolution or innovation, are developed to meet a specific requirement—business, social, political, ***etc.*** In many cases, the young market is unsettled and not dominated by a few suppliers. In some cases, greenfield opportunities are present, but more typically, new solutions are inserted into existing market segments. In the robotics sector, two of the most promising emerging markets are UUVs and advanced systems for robotic manipulation. Both automated and autonomous vehicles, which make use of many types of robotics enabling technologies and techniques, but are typically considered separate, yet intersecting, disciplines, are entering the market rapidly, supported by traditional automakers and their suppliers, as well as a large number and wide range of new companies.

UUVs and systems supporting robotic manipulation are two of the most promising emerging robotics markets. They are joined by automated and autonomous vehicles systems, which employ many robotics technologies.

6.7.1. Unmanned Underwater Vehicles

The blanket term "unmanned underwater vehicles" refers to two classes of underwater robots, which are further differentiated by their method of control. The first, remotely operated vehicles (ROVs) are teleoperated by human operators on surface vessels using umbilical cables for communication and control. As their name implies, the second type of UUVs, autonomous underwater vehicles (AUVs), dive and navigate and surface autonomously based on preprogrammed instructions, often over great distances, augmented by real-time sensor feedback. A third class of hybrid AUV/ROV has recently emerged that employs thin fiber optic tethers for real-time data transfer to and from the platform, allowing direct manual control to be exerted if necessary.

UUVs mirror terrestrial mobile robots: some are teleoperated, while others move and navigate autonomously.

In many ways, UUVs mirror terrestrial mobile robots: some are teleoperated, while others move and navigate autonomously. Similarly, both the ground- and underwater-based robots were first developed and used for military applications (and subsidized by the defense sector), and in the case of UUVs, for scientific purposes as well. At this time, UUVs are increasingly being employed by commercial entities.

6.7.1.1. Remotely Operated Vehicles

ROVs have been in use since the 1960s. Systems range in size from small, man-portable, "observational class" devices to "heavy class" systems weighing many tons and sporting advanced manipulators and other equipment. Approximately 70% of all ROVs in use today are produced in the United States or United Kingdom (Brun, 2012).

Most ROVs are used for commercial purposes, primarily in the oil and gas industry for applications such as underwater inspection and repair of oil platforms and pipelines, the installation and maintenance of underwater cables, and diver support. ROVs are also used commercially for search and recovery operations, water tank inspection, aquaculture, and much more.

Militaries and other governmental entities across the world employ ROVs for missions including underwater mine detection, hull inspection, dam assessment, and harbor security. The scientific community has also made use of ROVs for oceanographic and ecological studies, exploration and observation, sampling, and a host of other work.

6.7.1.2. Autonomous Underwater Vehicles

Lacking the tether required for remotely operated vehicles, AUVs can accomplish tasks such as long-range data collection that are impractical for ROVs, or too costly to address using manned platforms. AUVs have not been in operation for the same length of time as ROVs. But following advancements in sensors, power management, and other enabling technologies, and after proving themselves as suitable, practical, and cost efficient for many types of underwater tasks, they slowly gained acceptance among military and commercial groups, as well as the scientific community, for a wide range of applications requiring unconstrained movement and data sampling over large distances. Like the ROV sector, military spending, along with the oil and gas sector, will drive the AUV market growth in the near term.

Table 10: Representative Massachusetts Unmanned Underwater Vehicles Companies
Hydroid (Kongsberg Maritime), Boston Engineering, Bluefin Robotics (General Dynamics Mission Systems), Riptide Autonomous Solutions, Teledyne Marine Systems, OceanServer Technology

(Source: ABI Research)

6.7.1.3. Massachusetts Leads

In 2015, the worldwide UUV market was US$2.2 billion, increasing to US$4.6 billion in 2020.

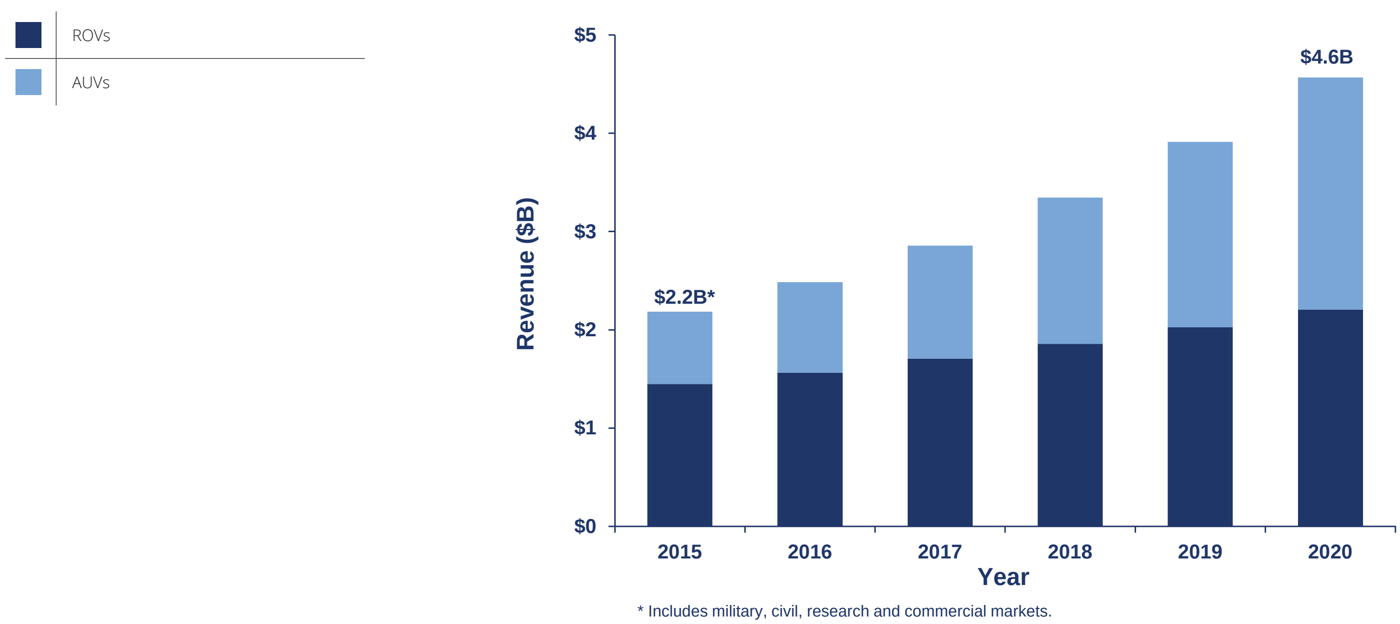
More than 144 different UUV platforms are currently available worldwide, according to the Autonomous Undersea Vehicle Applications Center, a non-profit UUV industry group. Revenue for the sector was US$2.2 billion in 2015, and this figure is expected to reach US$4.6 billion by 2020 for a CAGR of 15.9% (Figure 14).

Massachusetts is home to many of the leading producers of UUVs and supporting technologies.

Massachusetts is widely acknowledged as a leading, if not the foremost, international UUV cluster. AUV technologies for commercial use were first developed in the State beginning in 1991 at MIT's Sea Grant AUV laboratory, and work on other forms of UUVs predated that work. Commercial companies sprung up based on the Sea Grant efforts, resulting in a UUV ecosystem that has developed over time. Today, many of the leading suppliers of UUVs and supporting technologies are based in Massachusetts, including Hydroid (a subsidiary of Kongsberg Maritime), Bluefin Robotics (a division of General Dynamics Mission Systems), Boston Engineering, Riptide Autonomous Solutions, OceanServer Technology, and more.

Figure 14: UUV Worldwide Revenue, 2015 to 2020

(Source: ABI Research)



Massachusetts Company Spotlight: Hydroid

Hydroid is a Massachusetts marine robotics company that was founded in 2001 by a team of engineers who developed AUV technology in the late 1990s at the Woods Hole Oceanographic Institution in Falmouth, Massachusetts. That technology is the Remote Environmental Monitoring Unit System (REMUS) AUV. Hydroid was established to commercialize and further develop the REMUS platform.

Acquisition and Growth

In 2008, Kongsberg Maritime, a division of Norwegian conglomerate Kongsberg, acquired Hydroid for approximately US$80 million, a 4X multiple on 2007 revenue, adding the REMUS platform to its existing family of deep-diving HUGIN AUVs. Hydroid now operates as a subsidiary of Kongsberg Maritime.

Hydroid has a staff of more than 155 full- and part-time employees, and is aggressively hiring for engineering positions.

Since the acquisition, Hydroid has exhibited double-digit growth, increased the number of employees working there, and opened a new 40,000-square-foot headquarters in Pocasset, Massachusetts. At this time, Hydroid has a staff of more than 155 full- and part-time employees, and has approximately 20 openings for additional workers.

Multiple Models

Hydroid offers three different models of AUV based on the REMUS platform: REMUS 100, REMUS 600, and REMUS 6000. The numerical designations indicate the maximum operational depths each platform is designed to operate at, although each platform can be configured to go deeper if necessary. The systems also share a common interface to REMUS platforms, and each system is designed to accommodate a number of different sensor packages depending on the mission or application.

Hydroid's REMUS systems have logged tens of thousands of hours underwater for use in a wide range of applications.

Hydroid's REMUS systems have logged tens of thousands of hours underwater for applications ranging from search, classify, and mapping missions, to mine countermeasures, wreckage location, environmental monitoring, and more. The REMUS platforms continue to be improved, including the incorporation of technology developed separately by Kongsberg Maritime (and vice versa).

Why Hydroid Matters

Sales of the REMUS platform continue apace and Hydroid's business continues to expand. These trends, as well as the Kongsberg Maritime acquisition in 2008, not only demonstrate the value of the REMUS platform for the defense, research, and commercial markets, but also validate the AUV sector as a whole, along with Hydroid's leadership position in it.

6.7.2. Advanced Manipulation

Many robotic systems have the ability to directly interact with and manipulate objects in the physical world. This capability differentiates them from most other types of computerized or automated systems. Robotic manipulators come in all shapes and sizes, and typically consist of both an articulated robotic arm and an end effector. End effectors, also known as end-of-arm (EOA) tooling or EOA devices, are any object attached to the robot flange (wrist) that serves a function. End effectors are of two types: non-prehensile tools, such as grinders and spot welders, and prehensile grippers.

Physical manipulation differentiates robotic systems from most other types of computerized or automated systems.

6.7.2.1. The Past

In the past, robotic manipulators largely consisted of articulated robot arms, with tools or simple grippers as end effectors. They were designed to work in highly structured, enclosed work areas. The placement of the end effectors was preprogrammed, with little regard for the movement of the arms. Forces applied to the end effector, or any other place on the arm, did not affect the movement of other sections of the arm, making them inherently unsafe for applications that require close contact with humans.

6.7.2.2. Manipulation Complexity

Manipulation technology complexity and capability is measured in degrees of freedom (DOF), or the number of axes in which the gripper and arm can move. A 1-DOF example is a gripper whose opening and closing jaws may be able to pick up an object in a variety of orientations. By adding a second DOF, such as a rotating "wrist," a gripper can reorient an object before it is set down or rotate knobs.

With the addition of extra DOF, robotic manipulators rapidly become much more capable, allowing them to accomplish actions such as pushing or throwing. Increased DOF in finger, wrist, and arm joints directly correlate to increased dexterity, to the point that advanced end effectors can match or even exceed the capabilities of the 24-DOF human hand.

6.7.2.3. The Next Generation

At this time, much of the research and commercialization work underway is directed at improving the capabilities of grippers, or producing new classes of gripping technology, as well as the next generation of advanced arms, and Massachusetts firms are leading in many of these efforts. Examples include:

Massachusetts-based Soft Robotics and Empire Robots make use of soft, compliant materials for their advanced grippers.

- **Compliant Grippers:** For grippers, adding active DOF increases part counts, which in turn increases costs and diminishes reliability. A new generation of grippers from companies such as Massachusetts-based Soft Robotics and Empire Robots take advantage of soft, compliant materials and new structural designs so that grippers form around an object without maintaining a potentially dangerous actuated grip. This approach also decreases the number of motors and drive elements required to actuate the robotic hand.

Companies such as Rethink Robotics, Barrett Technology, and Universal Robots have introduced backdrivablity and compliance into robotic arms.

- **Compliant Arms:** Companies such as Rethink Robotics, Barrett Technology, and Universal Robots have introduced backdrivablity and compliance into robotic arms. Sensors in the arms are used to determine the amount of force being exerted at each joint. This feedback can be used to maintain safe levels of actuation, allowing the arm to respond appropriately when it comes into contact with other objects. Increasing the complexity of the arm this way improves the system's overall functionality and reduces costs. By allowing bulky actuation hardware to be limited to the arm, lightweight, inexpensive grippers can be used as the end effector without diminishing controllability.
- **Additional Sensors:** Force and pressure sensors are now embedded in grippers to measure the strength or quality of a grip, or help a control loop determine the best way to manipulate irregularly shaped objects. Others may have encoders on each joint to precisely position the manipulator in a certain way. Vision systems that interface to the manipulator's controller are also commonly used to reorient or reposition a manipulator to better interact with an object.

- **Generalization:** Robotic arms with specialized end effectors are common throughout the manufacturing industry. They have found much success, but have limited applicability. The industry is now moving beyond task-specific end effectors in favor of grippers that are suited for a range of applications, including multi-fingered grippers and autonomous grasping with human capability as a goal.

- **Mobile Manipulation:** At this time, autonomous, indoor navigation for mobile robots has largely been solved, and manipulators are becoming increasingly functional. Currently, much effort is being exerted on the addition of advanced manipulation capabilities to mobile platforms.

Table 11: Representative Massachusetts Advanced Manipulation Companies
Barrett Technology, Robai, Energid Technologies, Rethink Robotics, Soft Robotics, Empire Robotics, RightHand Robotics

(Source: ABI Research)

Massachusetts Company Spotlight: Energid Technologies

Energid Technologies was founded in 2001 as a robotics products and services firm. The Cambridge, Massachusetts-based company focuses on four areas: machine vision, robotics control software, visualization/simulation, and custom robot solutions. Energid's flagship product, Actin, is a visual programming environment and simulation toolset that reduces the complexity and increases the speed of developing and deploying robot motion control and coordination software.

Actin is based on patented software that Energid developed following the awarding of a Small Business Innovation Research (SBIR) grant for designing robot control software for NASA's Robonaut, an innovative humanoid robot designed to assist astronauts during work in space. Since that time, Energid has employed the Actin technology on a wide range of projects for both governmental agencies and private industry, including more than 35 SBIR and Small Business Technology Transfer (STTR) grants alone. Example applications include citrus harvesting, oil drilling, surgical systems, and satellite maintenance and repair. In each case, the work called for advanced control and complex, often very complex, movement and manipulation.

Why Energid Matters

The complexity of developing control systems for robots is so great that it has limited innovation, becoming a gating factor for the production of new classes of useful robotics applications. That is, demand for robotics automation exceeds the ability of companies to deliver applications. Accordingly, tools and techniques that simplify and speed robot control programming are in very high demand. Actin's ability to reduce the complexity of developing advanced manipulation control software supports the development of novel applications and the possibility of entering new markets.

6.7.3. Automated and Autonomous Vehicles

"Automated vehicles" and "autonomous vehicles" are considered and treated separately from traditional robotics systems, even though they employ robotics enabling technologies and techniques to function. According to common usage, automated vehicles and autonomous vehicles refer almost exclusively to transportation systems such as cars and trucks. It is for this reason that autonomous cars are not considered a type of robotic UGV, and why autonomous mobile robots are not regarded as autonomous vehicles unless there is an additional qualifier, such as in AGVs.

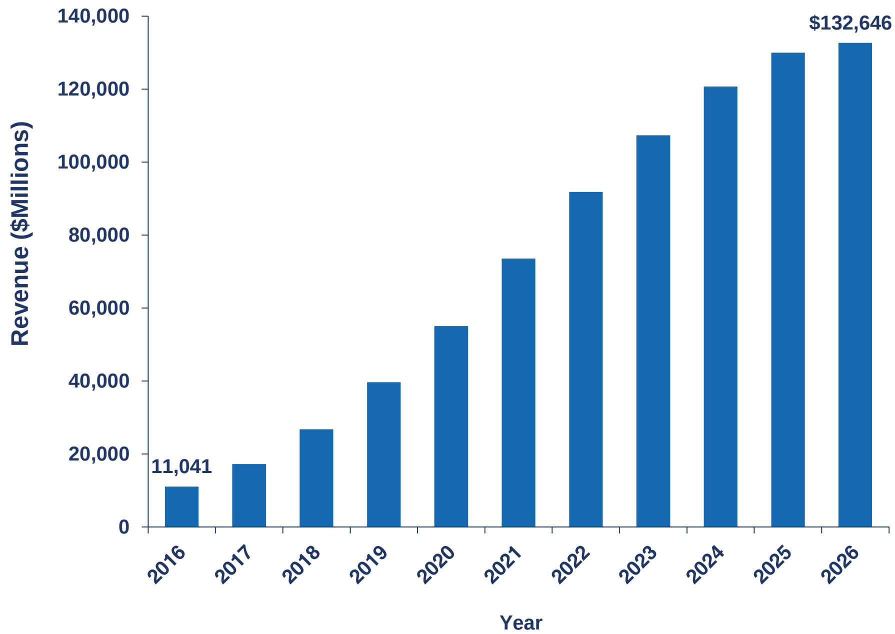
After decades of primary research, technological advancements, and the progressive addition of increasing levels of automation, the eventual commercial introduction of fully autonomous vehicles is nearing. While fully autonomous vehicles are currently not available to the public, Advanced Driver Assistance Systems (ADAS), those automation technologies that assist motorists and reduce driver errors such as blind-spot and lane-departure warning systems, lane-change assistance, adaptive cruise control, self-parking, and automatic braking, are currently offered in mid-priced vehicles.

Even at this early stage, advanced ADAS systems are available for mid-priced vehicles. Fully autonomous vehicles are nearing commercial introduction.

The market for automated and autonomous vehicles and the technologies that support them is substantial and growing. For example, the ADAS market alone will be worth US$132 billion by 2026, up from US$11 billion in 2016 for a CAGR of approximately 29% according to ABI Research (Figure 15). The growth will be fueled by new ADAS technologies coming to market, such as pedestrian and cyclist detection.

Figure 15: Global ADAS Market, 2016 to 2026

(Source: ABI Research)



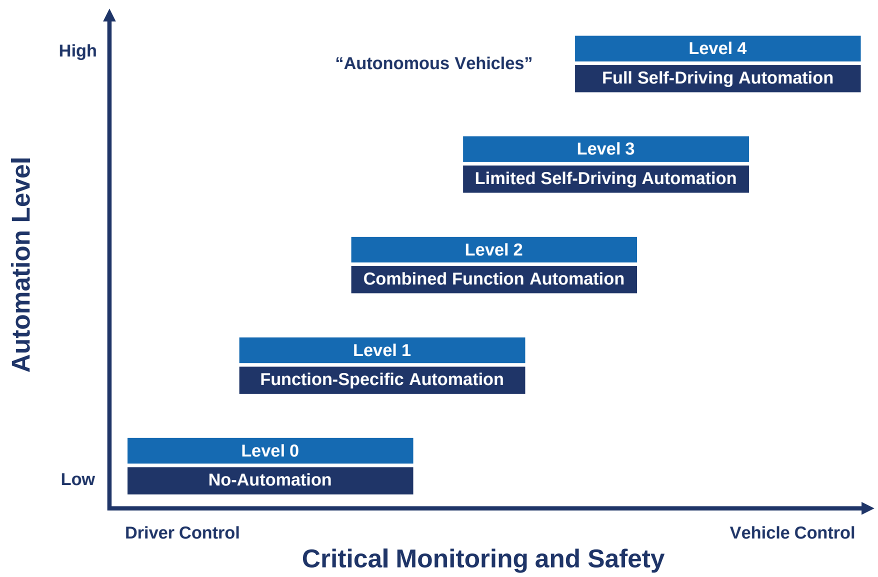
ADAS Systems have mainstreamed. There is now much demand for new technologies that go beyond simply supporting drivers. This is especially true for systems such as autonomous collision avoidance and navigation that can increase vehicle automation beyond Level 2 as defined by the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA):

- **Level 0:** The driver is in complete and sole control of the primary vehicle controls—brakes, steering, throttle, and motive power—at all times.
- **Level 1:** One or more control functions automatically assist with controls.

- **Level 2:** At least two key control functions work in unison to relieve the driver of control of those tasks.
- **Level 3:** The driver cedes full control of all safety-critical functions under certain conditions, but is expected to be available for occasional control.
- **Level 4:** After being provided destination or navigation input, the vehicle monitors roadway conditions for an entire trip and performs safety-critical driving functions. Level 4 vehicles are considered fully autonomous.

Figure 16: NHTSA Vehicle Automation Levels

(Source: ABI Research)



As illustrated in Figure 16, Level 3 and 4 systems provide the highest levels of automation for the most critical functions. At this time, only Level 2 capabilities are available to the public. But it has been estimated that in excess of 100 different types of autonomous vehicles from all the major automotive OEMs, such as Ford, General Motors, Toyota, and their Tier One suppliers, working in conjunction with national governments and others, are currently developing and testing Level 3 and Level 4 automation systems on public roadways, covering hundreds of thousands of miles each year. In the United States, Michigan, California, Florida, and Nevada have passed legislation allowing Level 3 and 4 automated vehicles to operate on public roads.

All of the major automotive OEMs are testing Level 3 and Level 4 vehicle automation systems on public roadways.

Testing on public roadways under "real-world," dynamic conditions offers a number of advantages. For the most part, however, testing is limited to the function of onboard systems, and the opportunity for rigorous, deep, and highly structured research is lost. Conversely, testing on closed tracks or other small, highly controlled roadways does not reflect normal driving conditions. As a result, automotive firms are also testing vehicles in tightly controlled test facilities that simulate city centers and public roadways, such as Mcity in Ann Arbor, Michigan, and GoMentum Station in Concord, California, which provide for formal, rigorous investigation, yet under real-world operational conditions (albeit simulated).

Automotive firms are also testing vehicles in tightly controlled test facilities that simulate city centers and public roadways.

Error-free, real-time mapping, navigation, object detection and recognition, distance measurement, and other functions required for Level 4 vehicular automation require the availability of powerful, yet low-cost hardware technologies such as sensors, but also advanced software systems. Massachusetts-based nuTonomy and Optimus Ride, along with Toyota Research Institute (TRI), are developing these systems. TRI, which has offices in Cambridge, Massachusetts, and Silicon Valley, was launched in November 2015 and funded with an initial 5-year, US$1 billion investment to develop AI and machine learning technologies in support of autonomous driving. In March 2016, TRI announced that the entire software engineering team of Somerville, Massachusetts-based Jaybridge Robotics would join TRI.

Table 12: Representative Massachusetts Automated and Autonomous Vehicle Companies
nuTonomy, Autoliv, Optimus Ride, Toyota Research Institute

(Source: ABI Research)

Massachusetts Company Spotlight: nuTonomy

Cambridge, Massachusetts-based nuTonomy develops software for autonomous vehicles. The company is an MIT spinoff, and nuTonomy's nuCore motion-planning and decision-making software technology is based on more than 10 years of MIT research. In May 2016, nuTonomy received a US$16 million Series A round from Highland Capital Partners, Samsung Venture Investment, Singapore Economic Development Board, and others. Earlier in 2016, the company attracted US$3.4 million in seed funding from Fontinalis Partners and Signal Ventures.

The Singapore investment in the May Series A round, which came through EDBI, the corporate investment arm of the Singapore Economic Development Board, is notable. In March 2016, nuTonomy announced that it was developing a fleet of driverless taxis for public transit in Singapore. The commercial launch of the autonomous taxi service systems is expected in 2018, which according to nuTonomy officials will be the first of its kind in the world.

At present, nuTonomy is actively operating a fleet of autonomous vehicles in Singapore as part of its R&D. According to nuTonomy, it was the first private company to win approval from the government of Singapore for testing autonomous vehicles on public roads.

Why nuTonomy Matters

nuTonomy is focused on the commercial autonomous vehicle. The price sensitivity of commercial customers is lower than that of consumers, which provides nuTonomy with the freedom to use advanced technologies that might not be economically feasible for consumer class vehicles.

6.8. EMERGING ROBOTICS ENABLERS

A number of emerging technologies, services, and techniques are increasing the capabilities of robotics systems, in much the same way as the availability of low-cost personal computers (PCs), the emergence of the global Internet, and the rapid growth of the mobile communications industry did. In each case, an expanding market contributed to rapid innovation, while the design and manufacture of consumer class products led to commodity pricing for advanced technology whose functionality increased considerably year after year.

6.8.1. The IoT and Industrial Internet Architectures and Services

The IoT, the technologies, architectures, and services that allow massive numbers of sensor-enabled, uniquely addressable "things" to communicate with each other and transfer data over pervasive networks using Internet protocols, is expected to be the next great technological innovation and business opportunity, exceeding in size and importance both the PC and mobile communications markets, and even the development of the Internet itself.

6.8.1.1. Connected Things

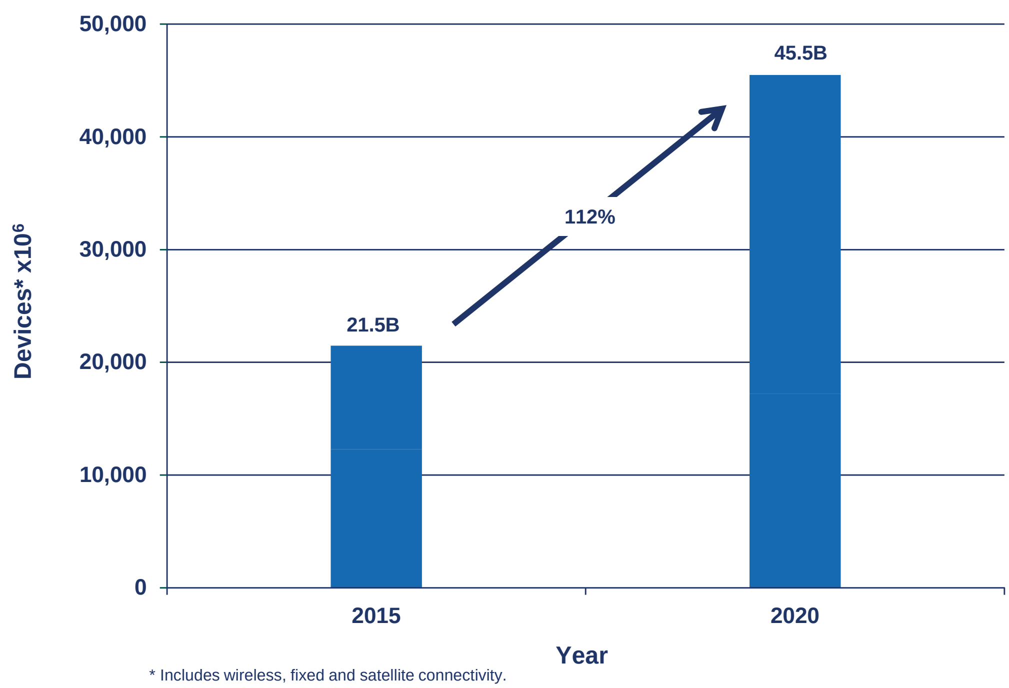
The number of connected "things" is expected to increase dramatically (Figure 17, below). Indeed, the number of device endpoints is so large that IPv6, the latest version of the Internet Protocol, is required. With IPv6, the number of Internet protocol (IP) addresses balloons from IPv4's approximately 4.3 billion addresses to 3.4x1038 addresses. This ensures that there will be enough unique Internet addresses for an unimaginable number of devices of every conceivable type far into the future.

IoT business drivers will spur technological innovation, and in doing so significantly advance the robotics market.

As IoT implementations and initiatives progress, a large number of technologies, standards, and other enablers will be enhanced or newly developed from scratch. Moore's Law (transistors per microprocessor) and Metcalf's Law (the network effect), of course, will contribute hugely to the growth of the IoT, as will the technological tailwinds generated by rapidly expanding consumer and B2B IoT markets. For example, sensors will surely be reduced in size and power consumption, while resolution, signal quality, and robustness are increased.

Figure 17: IoT Connected Objects

(Source: ABI Research)



Robotic edge products are fundamentally different from the vast majority of edge devices that will contribute to the IoT. All robots can actively move in the physical world, with some supporting point-to-point mobility or advanced manipulation (or both). They also support various levels of autonomy, eventually including full autonomy, as well as exhibit high levels of intelligence. As such, robotics systems have the ability to move through, interact with, alter, and manipulate the physical world (including interacting directly with humans). The combination of sensing, communication, processing, and actuation takes the original vision for the IoT to an entirely different level, and one that holds a great deal of promise and opportunity for providers of both IoT and robotics technologies, as well as users of the same.

Robotics technology takes the original vision for the IoT to an entirely different level, and offers many opportunities for solution providers and end users.

6.8.2. Cloud Robotics/Distributed Robotics

At this time, the "intelligence" of most robotics technologies resides with the systems themselves. That is, the totality of their instruction set is located onboard. In addition, robotics systems typically do not communicate with other robots. Many efforts are underway, however, to increase the performance, functionality, and communications capabilities of robotics systems by using the Internet to connect them to distributed processing, storage, and application services in the cloud. At the most basic level, the aptly named "cloud robotics" approach is, in effect, the intersection of cloud computing (Mell and Grance, 2011) with robotics.

Cloud robotics exploits global Internet connectivity, along with the computational capabilities and storage capacity of banks of distributed servers in the cloud. Using cloud robotics techniques, the robotics community can take advantage of standards-based, cloud infrastructure, products, and services developed and supported by some of the largest technology companies in the world, and utilized by countless others. With cloud robotics, processing can be distributed between robots and backend servers based on computational requirements, real-time constraints, and connectivity to improve performance and expand functional capabilities. In addition, robotics systems can connect with each other using the Internet as an intermediary "pipe" to communicate, as well as share data, images, specifications, behaviors, and other information. The result is lowered costs, significantly increased capabilities, and greater value.

The robotics community can exploit cloud infrastructure, products, and services developed and supported by some of the largest technology companies in the world

6.8.3. AI, Machine Learning, and Deep Learning

AI is the subfield of computer science that is focused on the development of computer systems that mimic learning and decision making in humans. Any Internet search for the term "artificial intelligence" with the word "robotics" will return a slew of research and commercial initiatives focused on the intersection of the technologies. Many of these are focused on using robotics to further the understanding of the brain, while others emphasize these technologies as an enabler for many robotic tasks.

6.8.3.1. Machine Learning

One discipline within the broader field of AI, machine learning, has demonstrated a tremendous potential to advance robotics. Using statistical computing techniques that are the basis of machine learning, patterns in data are identified and used as the basis for robotic decision making. These data-driven techniques have

AI and machine learning technologies and techniques are being used to make robotic systems more intelligent

been used in support of decision making, object identification, vision processing, speech translation, navigation, motor control, sensor integration, and other functions, as well as facial and emotion recognition.

6.8.3.2. Deep Learning

Deep learning, a class of machine learning techniques, has received much coverage from the technology and business media as of late, and for good reason. The technology, which employs multi-level ("deep") neural networks to create inferencing systems for pattern and feature detection in large datasets, has proven critical for commercial applications ranging from speech and music recognition, to industrial process control and product recommendation. Deep learning techniques continue to improve, as do results.

6.8.3.3. Research and Investment

Deep learning research is robust and ongoing, and investment in the technology is strong. Some of the world's leading technology firms are now invested in the technology. Google's purchase of U.K. AI startup DeepMind Technologies in 2014 for an estimated US$400 million exemplifies this. So, too, does Facebook's launch of its own AI laboratory in 2014, and IBM's launch of its Watson Group (also in 2014). Both research groups are focused on deep learning methods (among other research topics). IBM also purchased AlchemyAPI, a provider of AI-based text analysis and computer vision cloud services, in March 2015, and has other cognitive computing and deep learning initiatives underway. Microsoft's Project Adam, the goal of which is to enable software to visually recognize any object, also exploits deep learning techniques.

6.8.3.4. Cloud and Local

Deep learning methods are computationally intensive, requiring a great deal of computing resources. Software typically executes on powerful processors running on banks of highly optimized servers. As a result, devices running applications that use deep learning methods must typically access services residing in the cloud. Many efforts are currently underway to provide deep learning capabilities without the necessity of off-device processing in the cloud.

6.8.3.5. Deep Learning and Robotics

AI and machine learning technologies and techniques are being used to make robotic systems more intelligent.

Many of the capabilities enabled by deep learning methods are critical for robotics systems. Examples include computer vision, facial recognition, and natural language processing. Object recognition is especially important. A number of techniques have been employed to assist robots in recognizing objects, with deep learning methods central to many of them. Commercial companies are now coming to market with deep learning solutions designed specifically for robotics systems.

6.8.4. Robot Operating System (ROS) and Open Source Solutions

Developing and deploying robotics systems are difficult, time-consuming, and error-prone, and as a result, robotics innovation and commercialization efforts have been slowed or stalled. To address the problem, ROS, open source system software for robotics, was developed (Quigley et al., 2009). ROS includes software libraries, tools, and a run-time environment specifically designed to ease the burden of creating advanced robotics applications.

ROS usage among robotics researchers is widespread and increasing rapidly. ROS is now considered standard technology among robotics researchers, but equally important, the next generation of robotics engineers will be versed in ROS.

Robot Operating System is becoming foundational software for commercial robotics systems.

Industry support for ROS is also gaining, with a commercial robots and automation products based on ROS entering, and succeeding, in the market. By 2015, more than 70 commercial robotic systems used ROS (see Figure 18, below), including many produced by Massachusetts robotics cluster companies. ROS is becoming foundational software for all manner of actuated devices, ranging from service robots to industrial manipulators, and on to consumer systems, autonomous vehicles, and more.

Figure 18: Commercial Robots Supporting ROS

(Sources: Open Source Robotics Foundation, ABI Research)