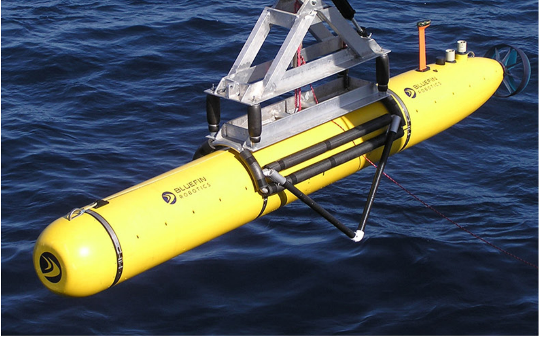
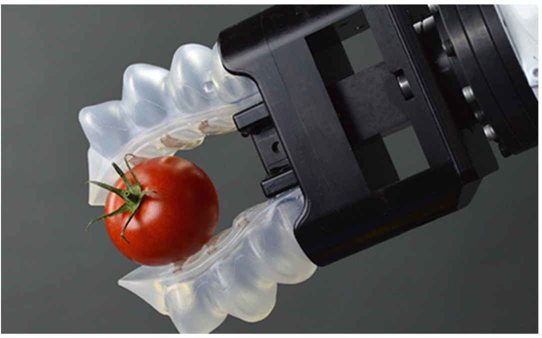
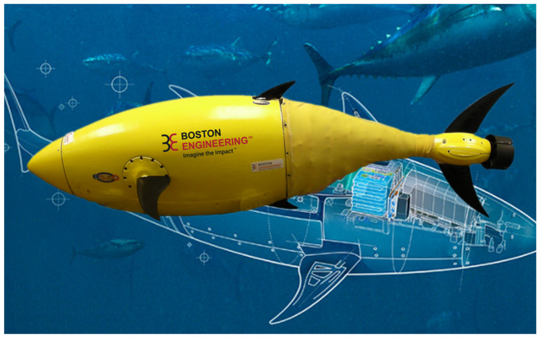


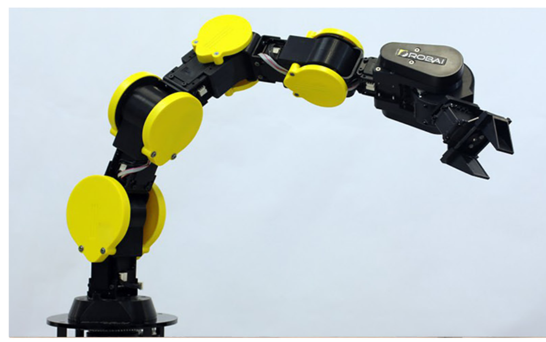




ABIresearch®
www.abiresearch.com

THE MASSACHUSETTS
ROBOTICS CLUSTER

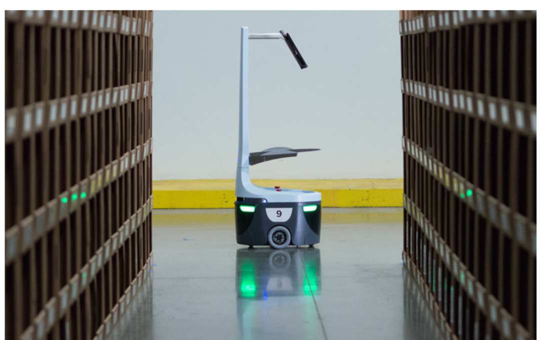
MASSACHUSETTS
TECHNOLOGY
COLLABORATIVE












THE MASSACHUSETTS ROBOTICS CLUSTER

Dan Kara
Research Director, Robotics
ABI Research

Phil Solis
Research Director
ABI Research

Photo Credits: Amazon Robotics: www.amazonrobotics.com, Aquabotix Technology: www.aquabotix.com, Bluefin Robotics: www.bluefinrobotics.com, Boston Engineering: www.boston-engineering.com, Corindus Vascular Robotics: www.corindus.com, Endeavor Robotics: www.endeavorrobotics.com, iRobot: www.irobot.com, Jibo: www.jibo.com, Locus Robotics: www.locusrobotics.com, Neurala: www.neurala.com, Rethink Robotics: www.rethinkrobotics.com, ReWalk Robotics: www.rewalk.com, Robai: www.robai.com, Softrobotics: www.softroboticsinc.com, Vecna Technologies: www.vecna.com

TABLE OF CONTENTS

1. CONTRIBUTORS 1

2. EXECUTIVE SUMMARY 2

3. INTRODUCTION 7

3.1. INNOVATION ECONOMY 7

3.2. STRATEGIC APPROACH 7

4. ROBOTS AND ROBOTICS TECHNOLOGIES 9

4.1. AUTONOMY 9

4.2. AUTONOMOUS, INTELLIGENT SYSTEMS 10

5. ROBOTICS AS AN INNOVATION DRIVER 11

5.1. UNIQUENESS OF ROBOTICS 11

5.2. MULTIPLIER EFFECT X2 12

6. THE GLOBAL ROBOTICS AND INTELLIGENT SYSTEMS SECTOR 13

6.1. A FRAMEWORK FOR UNDERSTANDING AND EVALUATION 13

6.1.1. Taxonomizing the Sector 13

6.2. INDUSTRIAL ROBOTICS 15

6.2.1. Dramatic Growth 15

6.2.2. Driving Growth 16

6.3. PROFESSIONAL SERVICES SECTOR 19
6.3.1. Healthcare Robotics 20
6.3.1.1. Healthcare Robotics Drivers 21
6.3.2. Defense 26
6.3.2.1. Unmanned Aerial Systems 27
6.3.2.2. Unmanned Ground Systems 28
6.3.2.3. Unmanned Maritime Systems 29
6.3.3. Field Robotics 30
6.4. LOGISTICS ROBOTICS 34
6.4.1. Total Automation 34
6.4.2. Multiple Classes 34
6.5. THE CONSUMER SECTOR 37
6.5.1. Strong Growth 39
6.6. THE EDUCATIONAL/RESEARCH SECTOR 41
6.6.1. Educational Robotics 41
6.6.2. Research Robotics 42
6.7. EMERGING MARKETS 43
6.7.1. Unmanned Underwater Vehicles 43
6.7.1.1. Remotely Operated Vehicles 44
6.7.1.2. Autonomous Underwater Vehicles 44
6.7.1.3. Massachusetts Leads 45
6.7.2. Advanced Manipulation 46
6.7.2.1. The Past 46
6.7.2.2. Manipulation Complexity 47
6.7.2.3. The Next Generation 47
6.7.3. Automated and Autonomous Vehicles 48
6.8. EMERGING ROBOTICS ENABLERS 51
6.8.1. The IoT and Industrial Internet Architectures and Services 52
6.8.1.1. Connected Things 52
6.8.2. Cloud Robotics/Distributed Robotics 53
6.8.3. AI, Machine Learning, and Deep Learning 53
6.8.3.1. Machine Learning 53
6.8.3.2. Deep Learning 54

6.8.3.3. Research and Investment 54
6.8.3.4. Cloud and Local 54
6.8.3.5. Deep Learning and Robotics 54
6.8.4. Robot Operating System and Open Source Solutions 54

7. THE MASSACHUSETTS ROBOTICS CLUSTER 56
7.1. NUMBER AND TYPES OF COMPANIES 56
7.1.1. Funding Sources 57
7.1.2. Key Industries and Application Areas 58
7.2. KEY TECHNOLOGIES, PRODUCTS, AND SERVICES 58
7.2.1. Technologies and Services for Developing Robotics Systems 59
7.3. REVENUE, EMPLOYMENT, AND NEW BUSINESS FORMATION 60
7.4. SALARIES FOR ROBOTICS ENGINEERS 61
7.5. OFFICE LOCATION/RELOCATION OF NON-STATE-BASED ROBOTICS FIRMS 62
7.6. INVESTMENT IN ROBOTICS 62
7.7. PRIVATE INVESTMENT IN MASSACHUSETTS-BASED ROBOTICS FIRMS 66
7.8. MASSACHUSETTS INCUBATORS, ACCELERATORS, AND WORKSPACES 67
7.8.1. Accelerators 68
7.8.2. Corporate Accelerators 69
7.8.3. Incubators 69
7.8.4. Co-working Spaces and Makerspaces 70
7.9. EDUCATION AND RESEARCH 70
7.9.1. Degree Programs 70
7.9.2. University Research Laboratories 70
7.9.3. Private, Non-profit Research Facilities 71
7.9.4. Robotics Research at Medical Centers 72

7.10. NATIONAL LABORATORIES....72
7.11. MASSACHUSETTS MILITARY INSTALLATIONS....73
7.11.1. U.S. Army Natick Soldier Systems Center....73
7.11.2. Joint Base Cape Cod....73
7.11.3. Fort Devens....74
7.11.3.1. Devens Interoperability Playground....74
8. GUIDANCE AND RECOMMENDATIONS....75
8.1. MASSACHUSETTS ROBOTICS CLUSTER....75
8.2. CLUSTER STRATEGIES....76
8.2.1. Talent Development....76
8.2.2. Encourage Entrepreneurship as a Part of STEM Education....76
8.2.3. Expand Internship and Co-op Opportunities....76
8.2.4. Develop Workforce Training and Retraining Initiatives....77
8.2.5. Technology Implementation: Facilitate Development, Testing, and Validation....77
8.2.6. Ensure Sustained Accelerator and Incubator Activity....78
8.2.7. Ensure Continued Support for Testing Centers....78
8.2.8. Offer Low-cost Loans for Development, Prototyping, and Testing Tools....79
8.2.9. Leverage State Procurement for Validation....79
8.2.10. Maintain a Simple, Stable Regulatory Environment....79
8.3. BRAND BUILDING: BRAND AND MARKET THE CLUSTER....79
8.4. STRENGTHEN AND ENHANCE CLUSTER DYNAMICS....80
8.4.1. Strengthen Cluster Ties....81
8.4.2. Increase Local Demand....81
8.4.3. Strategically Support Nascent and Emerging Submarkets....81
8.4.4. Support New Business Formation....81

9. EVALUATION AND IMPLEMENTATION METHODOLOGY 83

9.1. EVALUATION METHODOLOGY 83

9.1.1. Develop a Commercial Class Database 84

9.1.2. Formally Define Cluster Members 84

9.1.3. Utilize a Modernized Taxonomic Framework 84

9.1.4. Standardize Company Descriptors 84

9.1.5. Simplify, Limit, and Standardize Cluster Indicators 85

9.2. THE IMPLEMENTATION METHODOLOGY 86

9.2.1. Phase 1: Develop the Tools 87

9.2.2. Phase 2: Implement Recommendations 87

9.2.3. Phase 3: Measure and Assess Performance 88

9.2.4. Phase 4: Gauge Effectiveness 88

9.2.5. Phase 5: Report and Evaluation 89

9.2.6. Phase 6: Iterate the Process 89

10. REFERENCES 90

11. APPENDIX A: LIST OF FIGURES 92

12. APPENDIX B: LIST OF TABLES 93

13. APPENDIX C: RESEARCH LABORATORIES 94

13.1. MASSACHUSETTS UNIVERSITY RESEARCH LABORATORIES 94

13.2. NEW ENGLAND UNIVERSITY LABORATORIES/WORKING GROUPS 96

14. APPENDIX D: WAGES FOR ROBOTICS ENGINEERS 97

14.1. ELECTRICAL ENGINEERS* 97

14.2. MECHANICAL ENGINEERS* 98

14.3. SOFTWARE DEVELOPERS, SYSTEMS SOFTWARE* 99

14.4. SOFTWARE DEVELOPERS, APPLICATIONS* 100

14.5. COMPUTER HARDWARE ENGINEERS* 101

15. APPENDIX E: COMPANY DESCRIPTORS 102

16. APPENDIX F: PRIORITIZED RECOMMENDATIONS 104

17. APPENDIX G: ACRONYMS USED IN THIS REPORT 105

18. APPENDIX H: MASSACHUSETTS ROBOTICS CLUSTER COMPANIES 108

1. CONTRIBUTORS

ABI Research would like to thank the following individuals, organizations, and other contributors for their assistance in the development and preparation of this report:

Massachusetts Robotics Innovation Advisory Board

- Ted Acworth, Founder and CEO, Artaic
- David Askey, Co-founder and CEO, Ascend Robotics
- James G. Bellingham, Director, Center for Marine Robotics, Woods Hole Oceanographic Institution
- Tye Brady, Chief Technologist, Amazon Robotics
- Cynthia Breazeal, Founder and Chief Scientist, Jibo, and Professor, MIT Media Lab
- Dan Deguire, Director of Land Systems, QinetiQ North America
- Scott Eckert, CEO, Rethink Robotics
- Michael Gennert, Director, Robotics Engineering, and Professor, Computer Science, Worcester Polytechnic Institute
- Chris Jones, Strategic Technology Director, iRobot
- Waseem Naqvi, Director, Advanced Technology Programs, Raytheon
- Robert Playter, Director, Google Robotics
- Andre Sharon, Professor of Mechanical Engineering, Boston University, and Director, Fraunhofer CMI
- Mark Smithers, CTO and Co-founder, Boston Engineering
- Neil Tardella, CEO, Energid Technologies
- Eric Truebenbach, Director of Corporate/Business Development, Teradyne
- Massimiliano Versace, CEO, Neurala
- Holly Yanco, Professor, Computer Science, University of Massachusetts, Lowell, and Director, New England Robotics Validation and Experimentation (NERVE) Center

List of Interviewees

- Bob Anderson, President, OceanServer Technology
- Conny Breuning, Chair, Computer Science Department, Framingham State University
- Rod Grupen, Director, Laboratory for Perceptual Robotics, University of Massachusetts, Amherst
- Jonathan Pale, Vice President, Global Engineering and Technology, Hasbro
- Stan Reiss, General Partner, Matrix Partners
- Thomas Ryden, Executive Director, MassRobotics
- Carl Vause, CEO, Soft Robotics
- Loren Walker, Director, Research Development, University of Massachusetts, Amherst

2. EXECUTIVE SUMMARY

2.1. ROBOTS AND ROBOTICS TECHNOLOGIES ARE FOUNDATIONAL

Robots are mechanical devices that sense, think, and act in the physical world, often autonomously. It is the physicality inherent in robotics systems that differentiates the technology from software, although it is increasingly powerful software that allows robots to physically interact with, move through, and modify their environments. These capabilities set robots apart from most other computerized or automated systems, allowing them to take on a wide range of functional roles in the workplace, public places, the home, and more, with an operational sphere that includes air, sea, and land, and even deep space.

Robotics is a foundational, technology-based capability that can be applied across many industries and markets.

Robots and robotics technologies are increasingly characterized as the physical instantiation of artificial intelligence (AI). In terms of an innovation driver, it might better serve to think of robotics as a foundational, technology-based capability that can be applied across many industries and markets.

2.2. ROBOTS AND ROBOTICS TECHNOLOGIES ARE TRANSFORMATIVE

For advanced economies, innovation is the most critical determinant of long-term competitiveness, and is responsible for the majority of productivity an*d per capita inc*ome growth in regions, states, and nations. But it has been technological innovation that has proven to be the most transformative, creating entirely new products, services, and industries, and as a result, generating increasing levels of economic activity for extended periods of time. Robotics is no exception, particularly as systems become increasingly interconnected to each other and the world around them, using and sharing a broad spectrum of intelligence, and becoming increasingly more capable and autonomous in the process. The sectoral multiplier effect of robotics is substantial.

Technological innovation, robotics technologies included, is transformative, and capable of generating increasing levels of economic activity for extended periods of time.

2.3. STRONG, CONTINUED GROWTH FOR INDUSTRIAL ROBOTS

Business drivers and political/social drivers, in combination with technological advancements, have greatly accelerated the use of industrial robots. In 2014, 229,000 industrial robot systems were sold worldwide, up 29% over 2013 and accounting for approximately US$32 billion in revenue when services are included (International Federation of Robotics (IFR), 2015-1). It is estimated that in 2018, 400,000 industrial robots will be sold worldwide.

More than US$30 billion was spent on industrial robots in 2014.

2.4. MASSACHUSETTS COLLABORATIVE ROBOTICS MARKET LEADERSHIP

One recently developed industrial robotics sub-segment, collaborative robots, is very active at this time, with Massachusetts-based firms acting as market share and mindshare leaders. Collaborative systems are human scale, easy to set up and program, and capable of being used by workers with a wide range of qualification levels. 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. Universal Robots, a subsidiary of North Reading, Massachusetts-based Automated Test Equipment (ATE) supplier Teradyne, is the collaborative robotics market leader. Boston's own Rethink Robotics is also a key collaborative robotics supplier.

Massachusetts companies are strongly positioned in the rapidly growing collaborative robotics space.

2.5. IROBOT LEADS IN CONSUMER ROBOTICS

Consumer robotics, robots, or robotics technologies purchased by individuals that educate, entertain, or assist, often in the home, have sold in the millions and continue to exhibit strong growth, yet have only begun to scratch the surface in terms of market penetration. In 2015, the consumer robotics sector was responsible for shipments reaching approximately 33 million units, resulting in revenue of US$3.5 billion. By 2025, total shipments are forecast to increase to 165 million and total revenue to more than quadruple, reaching US$17 billion.

iRobot is the market leader for the consumer robotics sector with more than 15 million of its Roomba robotic vacuums sold. The Bedford-based firm has over 475 employees working in the State. Another Massachusetts-based consumer robotics firm, early-stage startup Jibo, has attracted more than US$38 million in investment. Jibo's primary offering, also named Jibo and based on years of Massachusetts Institute of Technology (MIT) research, exemplifies an entirely new class of consumer product and one with high expectations: social robots. Jibo will become available for sale in 2016.

Massachusetts-based iRobot (14 million Roombas sold) dominates the consumer robotics sector with more than 60% market share of robotic floor cleaners.

2.6. MASSACHUSETTS STRONG IN KEY SERVICE ROBOTICS MARKETS SEGMENTS

Massachusetts robotics cluster member companies are recognized internationally as leaders in key service robotics markets. For example, 90% of the mobile ground robotics supplied to the U.S. military were developed by Massachusetts-based companies QinetiQ North America and iRobot (now Endeavor Robotics). The State also leads the world as a source of mobile robots for retail e-commerce logistics, critical technologies in support of the US$1.2 trillion worldwide retail e-commerce market. Amazon Robotics alone has fielded more than 30,000 mobile robots for e-commerce logistics work.

Amazon Robotics alone has fielded more than 30,000 mobile robots for e-commerce logistics work.

Massachusetts is widely acknowledged as a leading, if not the foremost, international center for the development of unmanned underwater vehicles (UUVs), a market expected to reach US$4.6 billion by

2020, up from US$2.2 billion in 2015. The same holds for advanced manipulation technologies and healthcare robotics solutions. CyPhy Works and other firms produce commercial small unmanned aerial systems (UAS), a market that will surpass US$8.4 billion by 2018, up from US$2.8 billion in 2014, according to ABI Research.

Massachusetts is the leading center for UUV development.

More than 2,100 workers in Massachusetts develop service robotics products and technologies, which resulted in US$576 million in revenue attributed to the companies employing them.

2.7. SKYROCKETING INVESTMENT

Private sector investment in robotics companies increased dramatically in 2015. Approximately US$1.5 billion was invested in companies producing robotics technologies and products, or offering services, a dramatic increase over the previous year. Massachusetts-based companies received US$190 million in private investment in 2015, representing 23% of the total funding to U.S. firms, exceeded only by California, a state with a population more than five times that of Massachusetts. The Commonwealth can also boast of a venture capital (VC) community second only to Silicon Valley/San Francisco for technology investments. The City of Boston itself is one of the top three VC investment hubs in the world overall, accounting for more than US$3.1 billion in outlays (Florida and King, 2015).

Massachusetts-based robotics firms attracted approximately US$190 million in private investment in 2015. Both on a per capita basis and in terms of real dollars, Massachusetts attracts a disproportionally larger amount of private robotics investment than other regions.

2.8. ROBOTICS CLUSTER SUBSTANTIAL AND GROWING

To eliminate ambiguity, reduce subjectivity, and increase the accuracy of both the current and future cluster assessments, it is necessary to define cluster membership as formally as possible. To do otherwise reduces the value of the current exercise, making cluster monitoring and analysis, as well as comparisons to other regional robotics clusters, more difficult, costly, and error prone. For this study, cluster membership was limited to those entities that met the following requirements:

- **Headquarters:** Commercial cluster members should be headquartered in the Commonwealth, or have an office in the State that is a major subsidiary or regional division office.
- **Primary Robotics Cluster:** The focus of this report is the primary robotics cluster which consists of over 97% of all robotics companies in the State (see Appendix H). Formally defined, the primary robotics cluster consists of the concentration of localized, mutually supportive businesses found within 50-mile radius of Boston and Cape Cod. The robotics companies outside this area lack the critical mass and concentration to form another regional robotics cluster.
- **Revenue or Support:** Commercial cluster companies must derive approximately 35% or more of their revenue from robotics products, enabling technologies, or services, or a robotics division or subsidiary within a larger firm must do the same. Exceptions are made for startups without revenue, as well as larger firms evaluating robotics opportunities or supporting the cluster in other ways.

- **Universities and Labs:** Massachusetts-based private and public university research laboratories; national laboratories, and testing centers; or private, non-profit laboratories with currently active robotics research programs or initiatives are cluster members.

The Massachusetts robotics cluster is mature, substantial, and growing. Using the formal cluster definition given above, the cluster includes 122 commercial companies, which employ approximately 4,716 individuals. The average yearly salary for the various classes of engineers employed for robotics development in the Massachusetts robotics cluster region is substantial, and higher than for the United States as a whole (see Appendix D). These commercial firms generated US$1.6 billion in revenue for robotics products, technologies, and services in 2015.

It should be noted that a significant number of businesses do not qualify using this formal definition. Some are not geographically proximal to the Boston robotics hub, including companies in Western Massachusetts, New Hampshire, and Rhode Island. Others do not develop robotics products or technologies per se, but support the cluster indirectly with a variety of business services. Examples include design firms, public relations companies, marketing and engineering services providers, and more.

The Massachusetts robotics cluster is not reliant on a single, large industry.

As a whole, the Massachusetts robotics cluster is not reliant on a single, large industry, and therefore is at a reduced risk from the effects of a sector downturn. Manufacturing was the largest single target industry for Massachusetts robotics cluster members' products and services, followed by the healthcare and warehouse/distribution sectors. The State is also strong in the defense and consumer sectors.

2.9. NEW ROBOTICS BUSINESS FORMATION

Approximately 61% of robotics cluster member companies were formed since 2000.

New robotics businesses are being created in the State at a steady rate, especially over the last decade. Between 2011 and 2015, 33 new robotics businesses were created, up 57% from the previous 5 years, which itself was an increase of 31% over the preceding 5 years. Approximately 61% of robotics cluster member companies were formed since 2000.

Table 1: The Massachusetts Robotics Cluster at a Glance

Number of Commercial Companies	122
Number of Company Employees	4,716
2015 Revenue	US$1.6 billion
2015 Private Equity Investment	US$190 million
New Business Formation 2011 to 2015	33 companies
Research Laboratories and Testing Centers	17

(Source: ABI Research)

2.10. EXITS AND ACQUISITIONS

The approximately 122 robotics firms located in Massachusetts speak to a booming Bay State robotics sector, as does the 33 robotics companies formed within the last 5 years alone. So, too, do the number of mergers and acquisitions of robotics companies. For example, in April 2015, North Reading, Massachusetts-based ATE supplier Teradyne acquired Universal Robots for US$285 million. The Denmark-based and privately held Universal Robots is far and away the leading seller of the new generation of collaborative robots, advanced systems that can work safely and efficiently in close proximity to human co-workers. Conversely, in March 2012, Amazon acquired North Reading-based Kiva Systems, for US$775 million in cash, a 7X plus multiple on Kiva revenue and Amazon's second-largest acquisition at the time. Kiva Systems is joined by suppliers of UUVs, such as Bluefin Robotics and Hydroid, both of which were acquired and now operate as subsidiaries to General Dynamics Mission Systems and Kongsberg Maritime, respectively.

In March 2012, Amazon acquired North Reading-based Kiva Systems, for US$775 million in cash, a 7X plus multiple on Kiva revenue and Amazon's second largest acquisition at the time. Amazon Robotics currently employs over 600 workers in Massachusetts and is actively hiring at this time.

2.11. EDUCATION AND RESEARCH ARE KEY ASSETS

Massachusetts is home to a collection of leading, world-class universities and research centers, such as MIT, Harvard University, Worcester Polytechnic Institute, the University of Massachusetts, Boston University, Northeastern University, and many more. With respect to robotics, this collective asset is unequaled in the world. These institutions and others are the primary source for the Commonwealth's greatest asset: its educated workforce. They are also home to cutting-edge pure and applied research, which is the basis for robotics innovation (see Appendix C). The State is also home to the New England Robotics Validation and Experimentation (NERVE) Center at the University of Massachusetts Lowell, one of only three robotics test facilities sanctioned by the National Institute of Standards and Technology (NIST).

The State's universities and research centers are the source of its educated workforce, as well as the pure and applied research that undergirds robotics innovation and commercialization.

3. INTRODUCTION

Although substantial gains can be obtained by improving institutions, building infrastructure, reducing macroeconomic instability, or improving human capital, all these factors eventually run into diminishing returns. The same is true for the efficiency of the labor, financial, and goods markets. In the long run, standards of living can be largely enhanced by technological innovation.

—Klaus Schwab, World Economic Forum, and Xavier Sala-i-Martín, Columbia University

Massachusetts is uniquely positioned as a global robotics innovation hub.

Advances in hardware and software technologies, ongoing academic research, and dramatic increases in robotics investment have had the collective effect of enabling the development of practical, robust, commercial-class robotics products, technologies, and services in support of applications in a great number of industries. Their consumer equivalents have also come to market and found success. These trends will continue and are accelerating. As such, the robotics sector provides for a vast number of business and investment opportunities for Massachusetts, along with other states, regions, and countries. Massachusetts, however, can boast of a number of distinct and, collectively, unique advantages as a global robotics innovation hub.

3.1. INNOVATION ECONOMY

The state's long-term economic expansion is dependent on its innovation economy.

The Massachusetts robotics sector is supported by a state government that recognizes that the Commonwealth's greatest natural resource can be found "between the ears" of its highly educated workforce. The Massachusetts state government also understands that economic expansion in the long term is dependent on its innovation economy; a complex, dynamic, supportive web of knowledge, technology, entrepreneurship, investment, and smart public-private partnerships.

3.2. STRATEGIC APPROACH

The Massachusetts robotics innovation economy has taken root and is expanding. To nurture and accelerate the growth of this important domain, the Massachusetts Technology Collaborative selected ABI Research to conduct an analysis of the Massachusetts robotics sector, including describing and quantifying the global robotics marketplace; highlighting dominant research, technical, business, and investment tends; and analyzing public and private robotics business development initiatives. The end result of the analysis is to generate statistically measurable qualities, attributes, and rankings that provide for meaningful interpretation and speak to robotics business development, particularly for new commercial launches—in essence, to produce an actionable roadmap for growing the State's robotics innovation economy.

This document is that analysis. It was developed in consultation with Massachusetts-based business, academic, and investment leaders, as well as with key contributors to the greater Massachusetts robotics ecosystem. This included one-on-one interviews conducted over the course of January and February 2016, as well as consultation with advisory board members at a formal meeting held in Boston on January 28, 2016, and in subsequent discussion held later. Other sources of information and insight included market research studies, along with other publicly available and private sources of information, including state and national governmental publications, financial statements, earnings reports, corporate briefings, government/academic funding announcements, association and industry publications, and more. The expectation is that the results of this study will be used to inform decision making regarding public and private robotics business development initiatives, so that businesses, academia, the investment community, and the Massachusetts state government can work collaboratively to improve the competitive position of the Commonwealth in the economically vital robotics sector.

The results of this study will be used to inform decision making regarding public and private robotics business development initiatives.

Additional Insight: *Due to the requirements for completeness and deep analysis, this report is fairly lengthy. Those policy makers and others who wish to first review the set of recommendations for public sector initiatives designed to drive Massachusetts robotics innovation are directed to the Guidance and Recommendations section. A methodology for assessing and monitoring cluster status, along with implementing the recommendations, is given in the Evaluation and Implementation Methodology section.*

4. ROBOTS AND ROBOTICS TECHNOLOGIES

Robots sense, think, and act in the physical world, often autonomously.

Definitions as to what constitutes a robot vary greatly, even among users and suppliers of robotics systems. However, a general consensus has been developed as to the essential features that distinguish robotics from other classes of technology. Robots must exhibit the following capabilities: sensing, intelligence, and motion, as described in Table 2, below.

Table 2: Features of Robots and Robotics Technology

Ability	Definition
Sensing	Robots employ sensing technology to acquire information about their environment.
Intelligence	Robots process information captured through sensor technology and produce outputs for decision making, coordination, and control.
Motion	Robots automatically follow instructions that are pre-programmed or generated in real-time based on sensor input to perform a deliberate, controlled, and often repeated, mechatronic action, including point-to-point mobility.

(Source: ABI Research)

4.1. AUTONOMY

Many would add "autonomy," the capacity of robotics systems to move or perform tasks responding to both environmental and internal stimuli without external control, to the classic "sense-think-act" definition of robotics. It is the combined ability to sense, think, and act with some degree of autonomy that differentiates robotics from other classes of technology and machinery.

Rising levels of autonomy in robotics systems is a capabilities multiplier, and can reduce costs as well.

Increasing levels of autonomy is an overarching trend within all segments of the robotics sector—consumer, industrial, commercial, civil, and defense. Greater autonomy in robotics systems can reduce application costs and increase system capabilities. In addition, the same technologies that support autonomous operation in robotics systems can be incorporated into products and services not necessarily deemed "robotic" by the general public, such as self-driving cars.

Autonomy is a transformational capability.

As technology improves and autonomous robots build on their successes to become commonplace, the number and scope of independent, self-directed systems and applications will increase substantially. As such, autonomy is a transformational capability, and therefore a massive opportunity.

4.2. AUTONOMOUS, INTELLIGENT SYSTEMS

The definition of the term "robotic" has evolved over time to reflect the change from fixed, programmable actuated devices to mobile systems that adjust their actions based on multimodal sensor feedback, becoming progressively more autonomous over time. These same autonomous systems have also benefited from advances in on-device hardware and software, as well as access to cloud-based, distributed computing resources, becoming much more intelligent with each passing day.

Robots and robotics technology are increasingly, and accurately, viewed as the physical instantiation of AI.

Robots also have a physicality that humans find greatly appealing and many other technologies lack. For this reason, robots have historically been employed by researchers and businesses to demonstrate advances in machine learning and AI, and as a result, they have become equated in the process. The entertainment industry, along with the media and business communities, has done the same. As a result, robots and robotics technologies are increasingly understood as the physical instantiation of AI. This is an accurate characterization for many robotics systems and will become more so over time.

5. ROBOTICS AS AN INNOVATION DRIVER

For advanced economies, innovation is the most critical determinant of long-term competitiveness, and is responsible for the majority of productivity and *per capita* income growth in regions, states, and nations. Innovation can take many forms, both technological and non-technological. But it has been technological innovation that has proven to be the most transformative, creating entirely new products, services, and industries, and as a result, generating increasing levels of economic activity for extended periods of time.

Historically, technological innovation has proven to be the most transformative and economically beneficial.

Technology is a key innovation driver, but some technologies are more impactful than others. The invention of the steam engine, widespread electrification, and the development of computer systems and digital networks have had wide-ranging and long-term beneficial economic effects, while impacting all aspects of society.

Robotics, too, is transformative in this way, particularly as systems become more interconnected to each other and the world around them, using and sharing a broad spectrum of intelligence, and becoming increasingly more capable and autonomous in the process. But even earlier generations of robotics technologies, largely limited to systems in a manufacturing automation role, have had an impact that goes beyond simple productivity increases and quality improvements. For example, in one recent study, researchers examining 17 countries estimated that between 1993 and 2007, the use of robots for manufacturing increased a country's gross domestic product (GDP) growth by 0.37 percentage points and labor productivity by 0.36 points (Graetz and Michaels, 2015).

It has been demonstrated that the use of robots for manufacturing increases a country's GDP growth.

5.1. UNIQUENESS OF ROBOTICS

The development of robots and robotics technology requires the mastery of multiple disciplines, including software development, along with mechanical and electrical engineering. The consequences of these dependencies produce unique technologies that function as a bridge between the physical and the virtual. Robotics technologies bridge the physical and virtual worlds.

Robotics technologies bridge the physical and virtual worlds.

It is the physicality inherent in robotic systems that differentiates the technology from software, although it is software that provides the "intelligence" that allows robots to physically interact with, move through, and modify their environments. These capabilities set robots apart from most other computerized or automated systems, allowing them to take on a wide range of functional roles in the workplace, public places, the home, and more, with an operational sphere that includes air, sea, and land, and even deep space.

5.2. MULTIPLIER EFFECT X2

Robotics should be considered a foundational, technological capability that has wide applicability.

It is somewhat misleading to describe robotics as an "industry" or "sector," which is often done for the sake of convenience. Some define robotics as the technologies and techniques used for the construction of robots, which are themselves robotic systems, another useful construct. As an innovation driver, it might better serve to think of robotics as a foundational, technology-based capability that can be applied widely. As such, the sectoral multiplier effect of robotics can be difficult to quantify, but is real nonetheless, and should include both the production of robotics technologies, as well as their contribution during use in industry and elsewhere.

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):

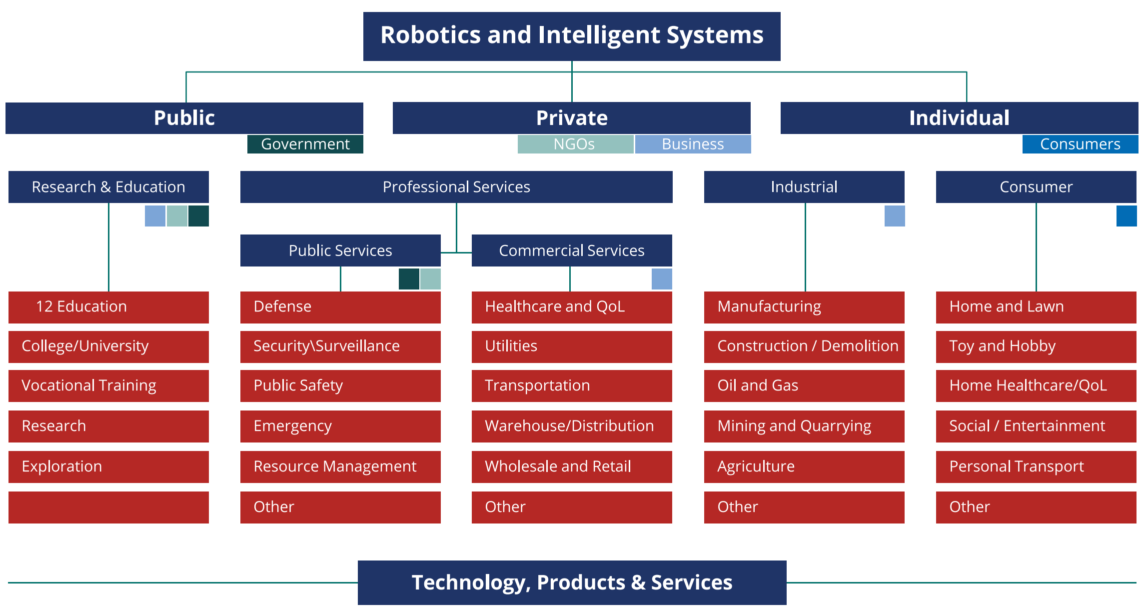
- **Consumer Sector:** The consumer sector is characterized by markets where products are purchased by individuals for their own use to assist, educate, and entertain. These products are referred to as consumer robots.
- **Industrial Sector:** The term "industrial" often equates strictly to manufacturing, 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

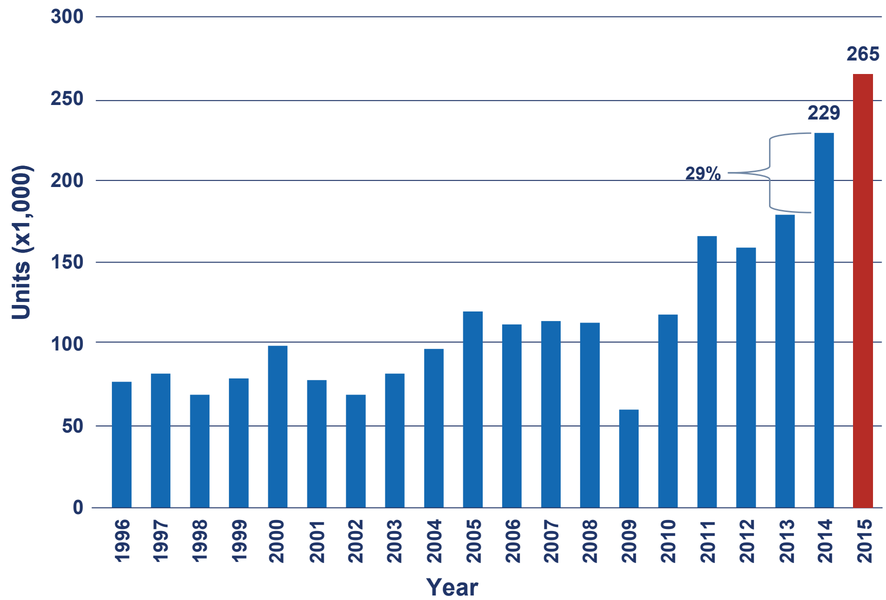
According to the IFR, and as described in Figure 2, the total number of industrial robotics installations has increased dramatically year-over-year beginning in 2010, which was up sharply as the industry rebounded following the economic downturn in North America and Europe. In 2014, the most recent figures 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

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

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

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.

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, 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)

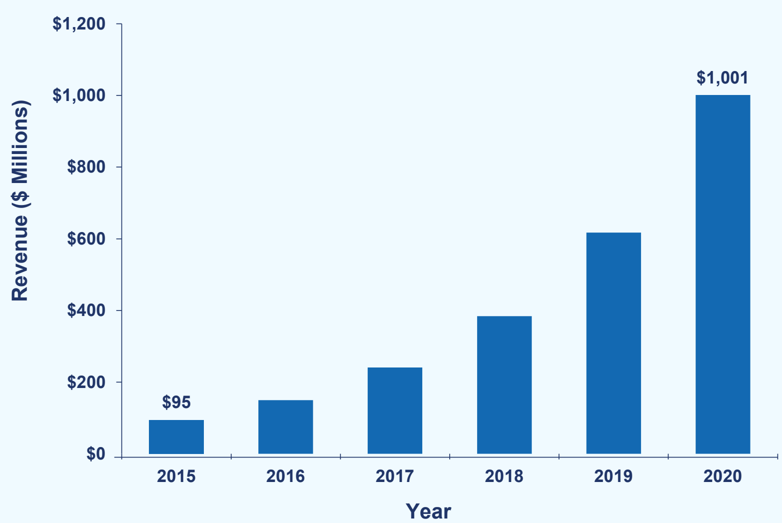


Table 3: Representative Massachusetts Industrial Robotics Companies
Rethink Robotics, Universal Robots, RightHand Robotics, Soft Robotics, Empire Robotics, Vaccon

(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.

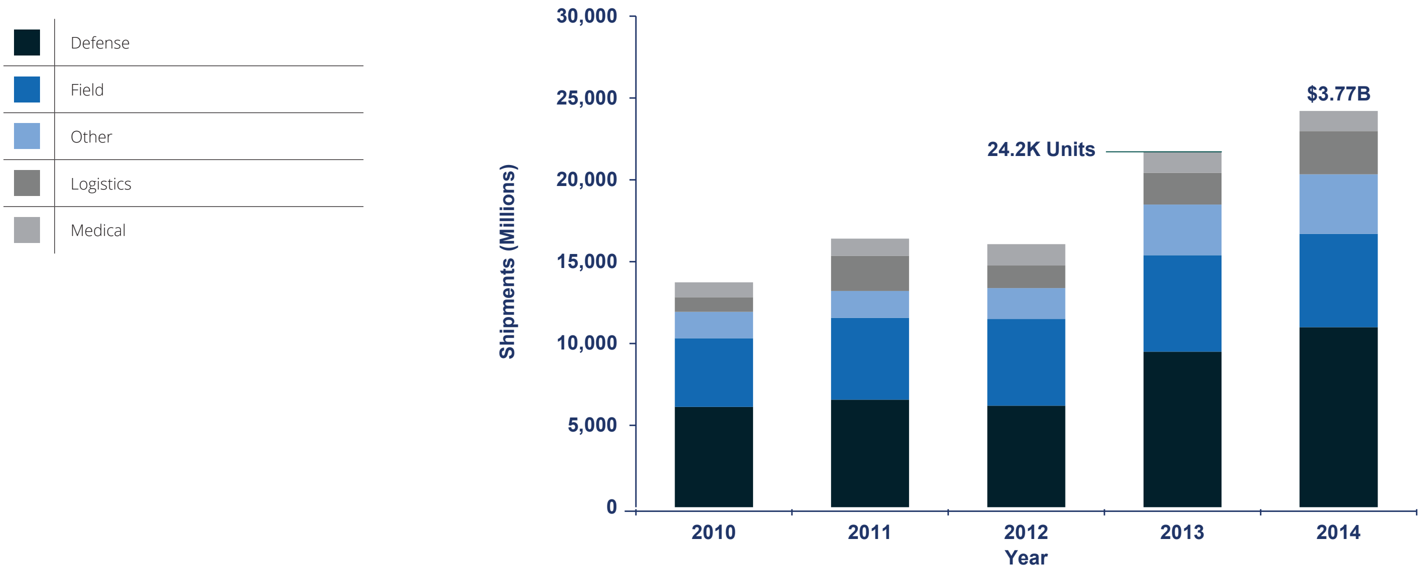
Service robots have found great success in the defense sector, where technologies like UASes have mainstreamed completely. The same holds for the healthcare industry where robotic surgical and therapeutic technologies, along with pharmacy automation and autonomous hospital delivery systems, are common. 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 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.

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.

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.

- **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.

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

- **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.

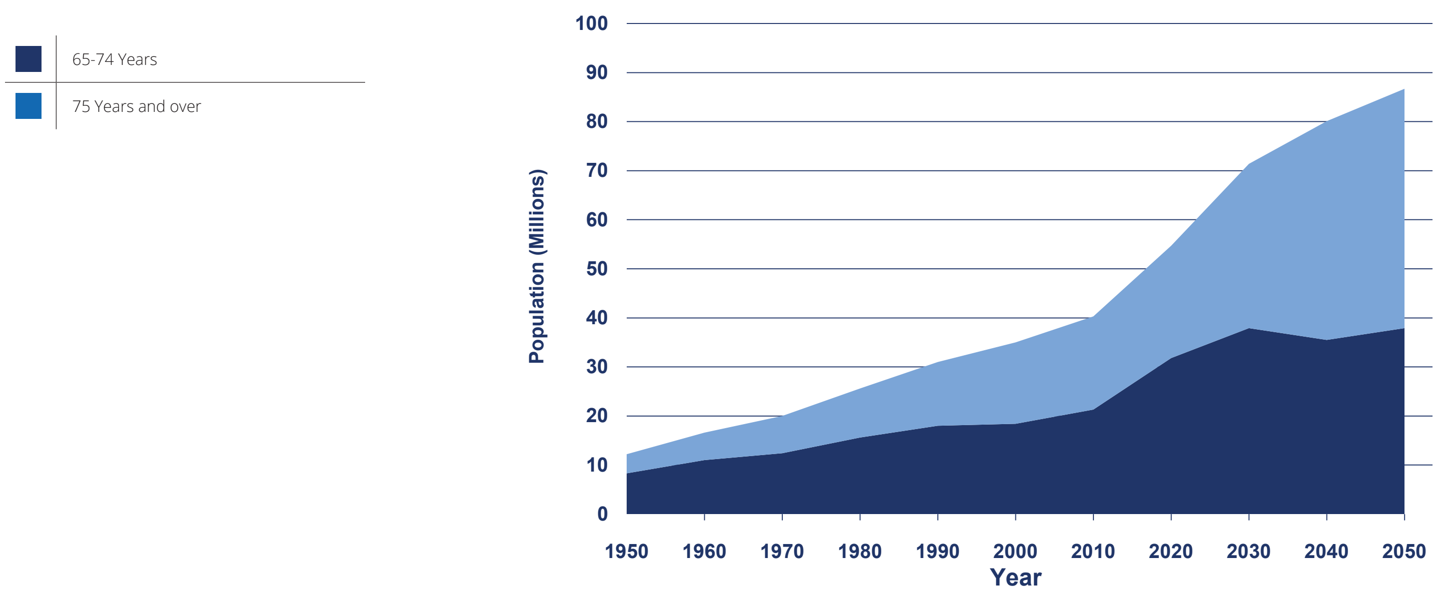
- **Aging Populations:** Life expectancies in most of the world, and particularly in industrialized states, have been increasing since 1900. Due to advances in healthcare, the average age of the older population is increasing. In addition, as the "baby boom" generation reaches retirement age, the percentage 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.

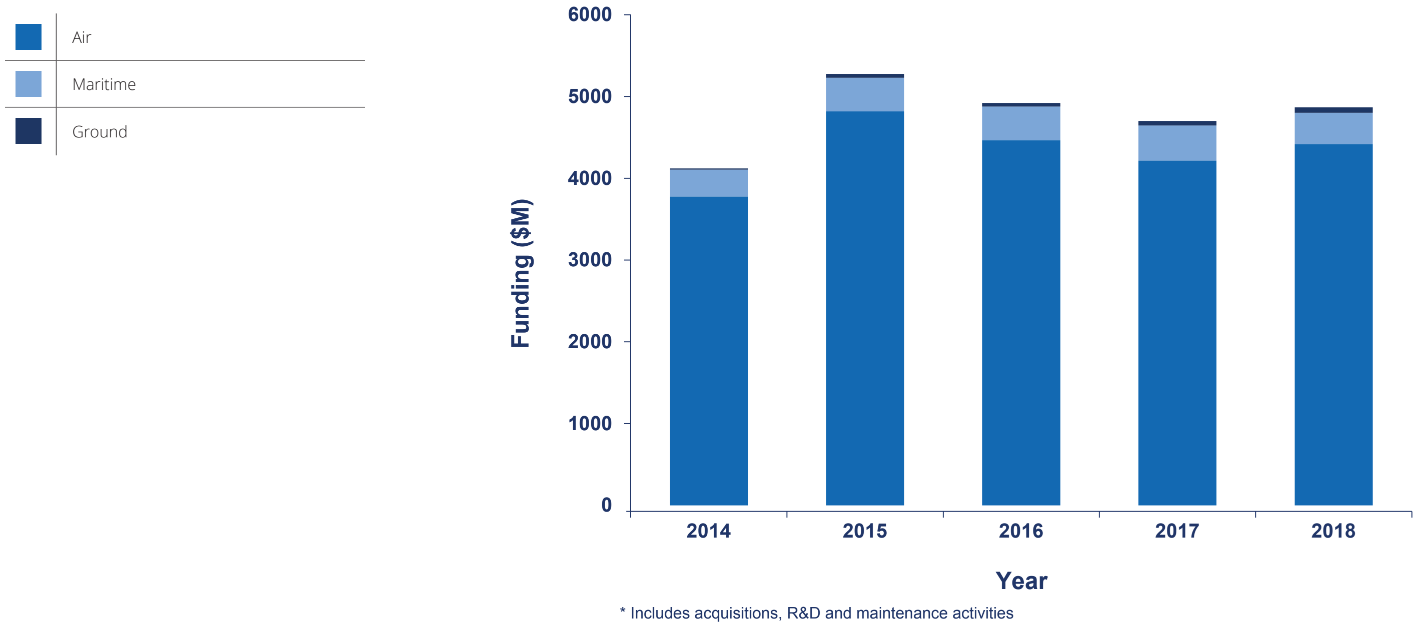
Defense funding levels for unmanned systems are expected to remain largely flat, with spending on UAS dominating.

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

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

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.

***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.

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

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).

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)

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.

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

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.

More than 4,000 of QinetiQ North America TALON systems 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)

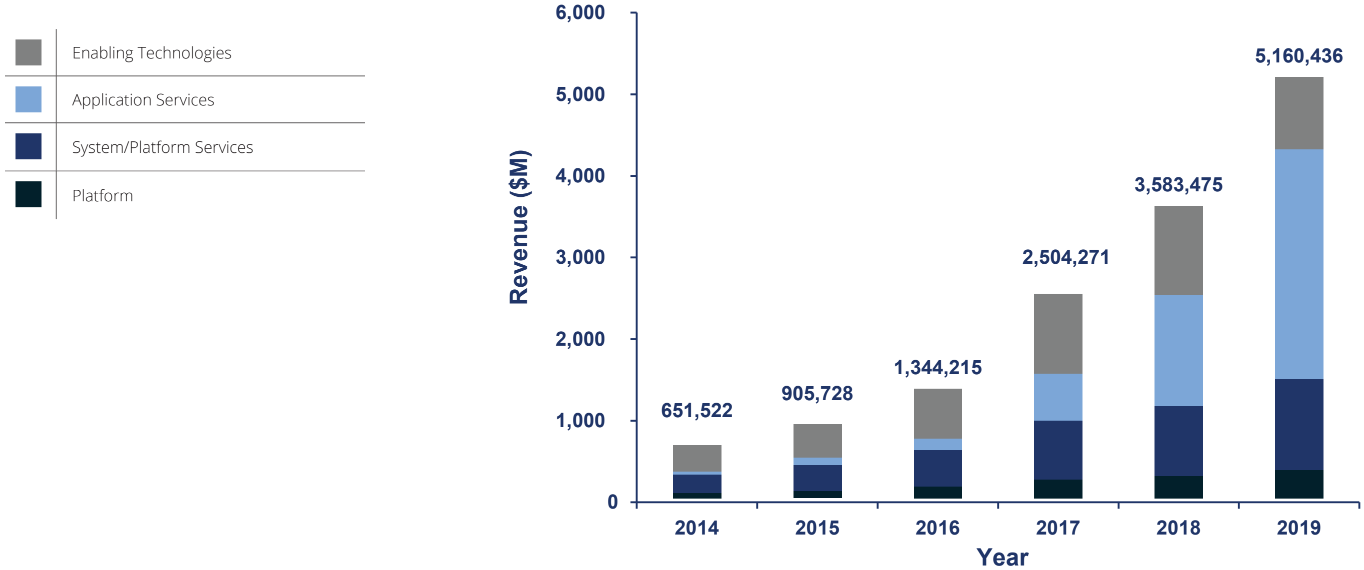


Table 6: Representative Massachusetts Field Robotics Companies
Harvest Automation, Iron Goat, Franklin Robotics, RailPod, Scanifly, CyPhy Works, Panoptes, XactSense

(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

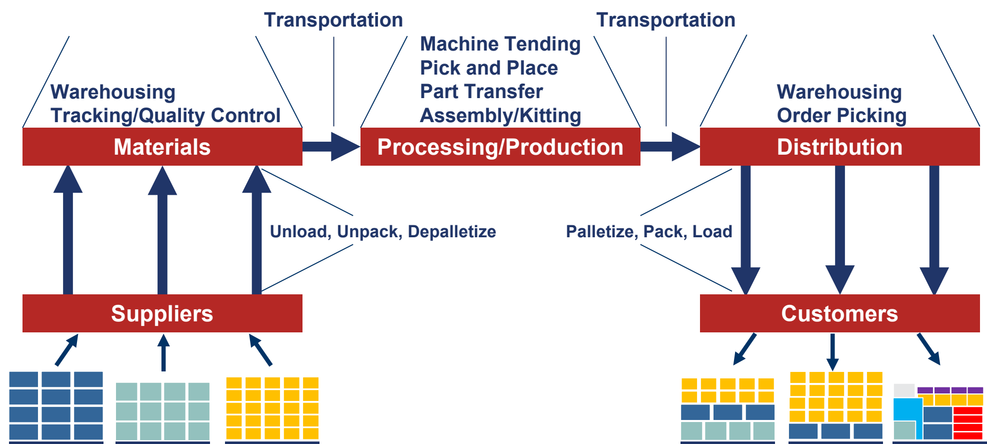
Many different classes of robotics systems are used to automate logistics operations. They Include:

- **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)



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.

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

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.

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

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)

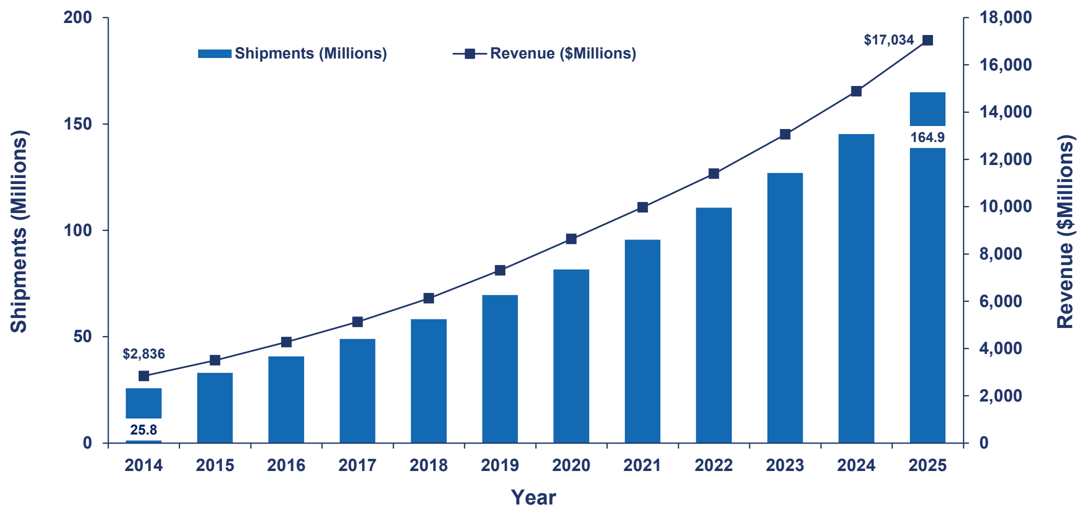
6.5.1. Strong Growth

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.

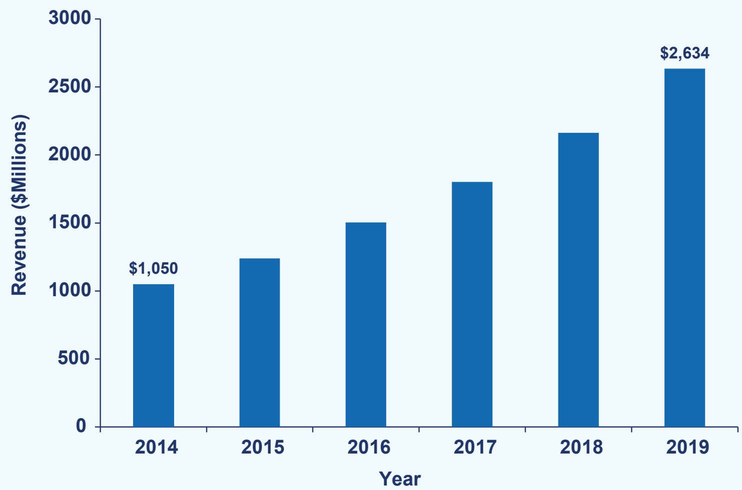
Key Market: Floor-cleaning Robots

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.

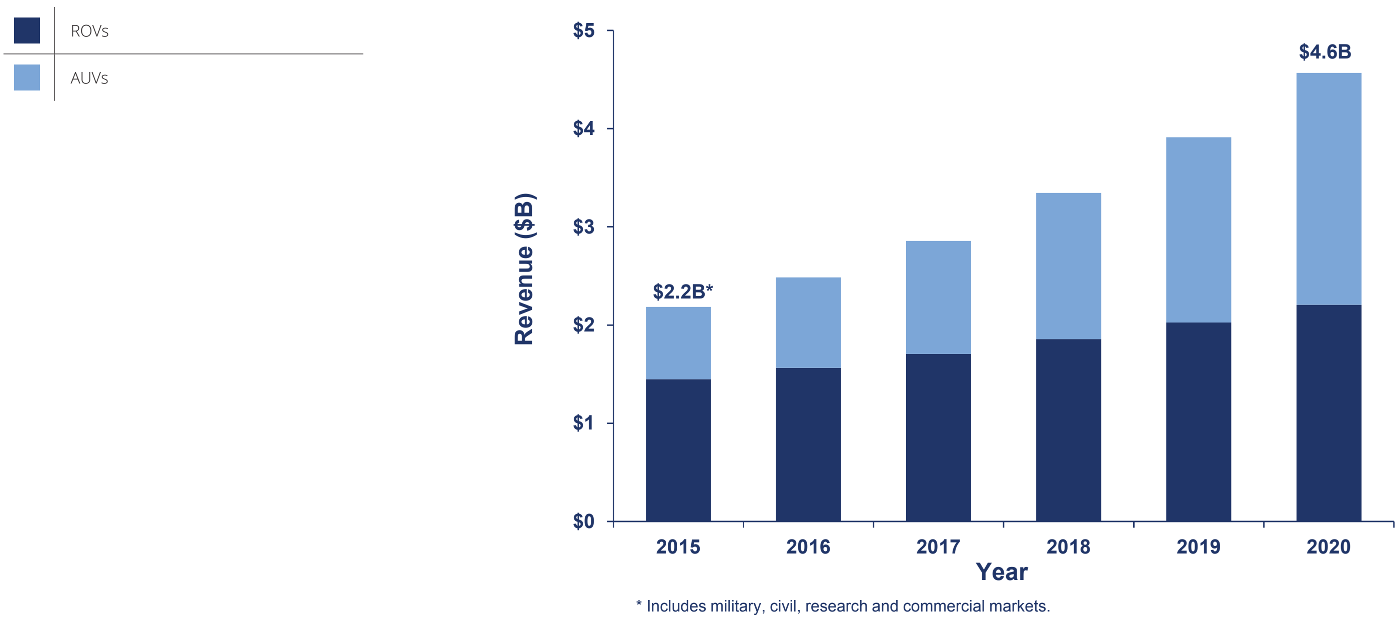
More than 144 different UUV platforms are currently available worldwide, according to the Autonomous Undersea Vehicle Applications Center, a non-profit UUV industry group. Revenue for the sector was US$2.2 billion in 2015, and this figure is expected to reach US$4.6 billion by 2020 for a CAGR of 15.9%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

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

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.

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.

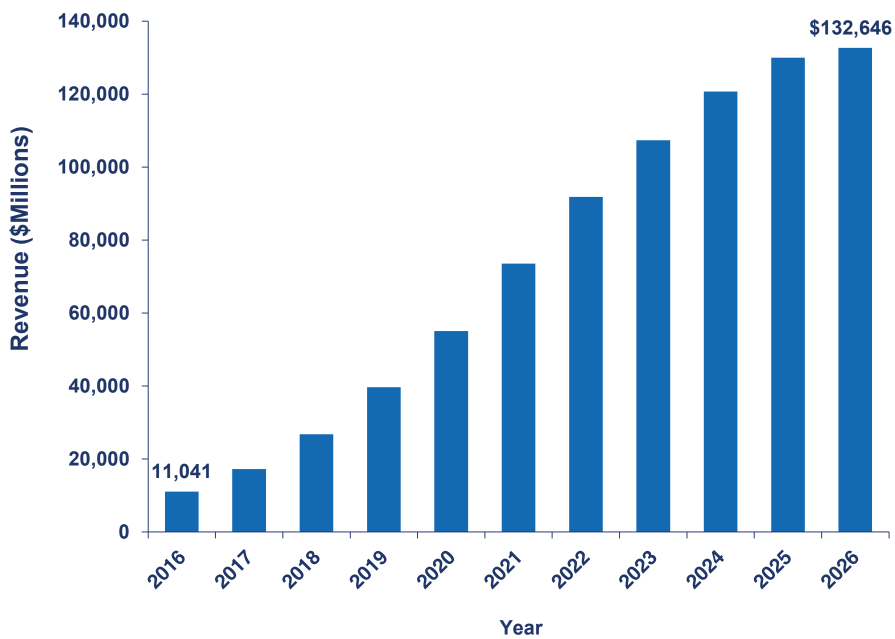
Even at this early stage, advanced ADAS systems are available for mid-priced vehicles. Fully autonomous vehicles are nearing commercial introduction.

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.

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)



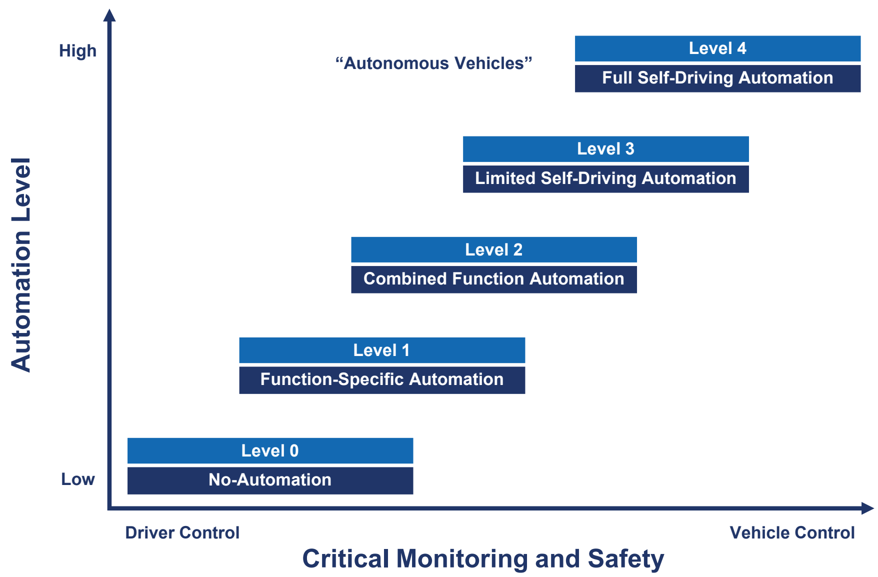
ADAS Systems have mainstreamed. There is now much demand for new technologies that go beyond simply supporting drivers. This is especially true for systems such as autonomous collision avoidance and navigation that can increase vehicle automation beyond Level 2 as defined by the U.S. Department of Transportation's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



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

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.

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

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

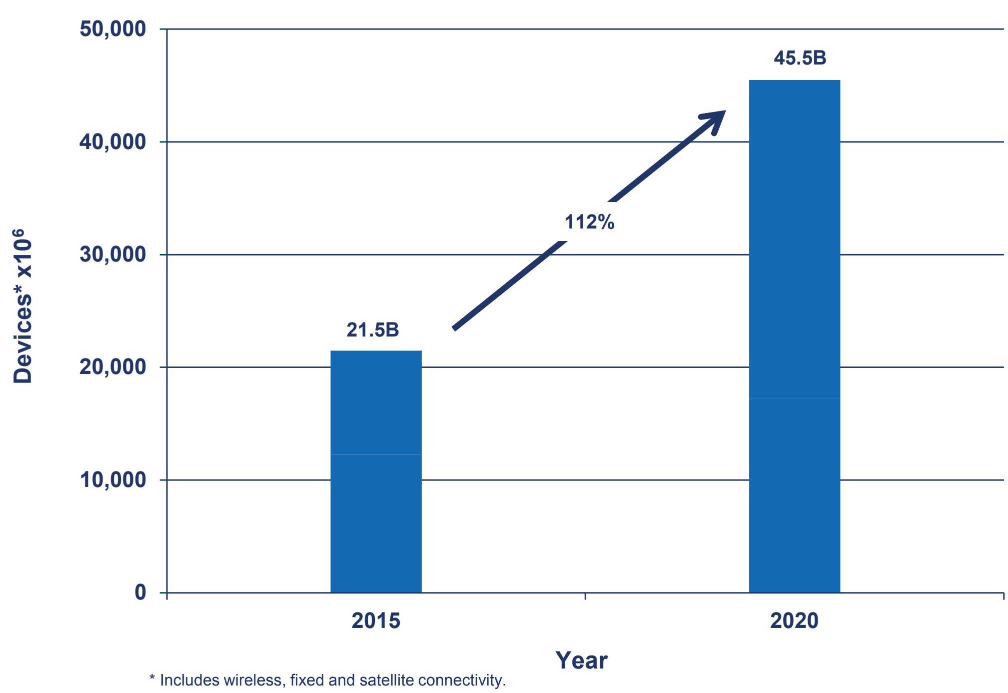
The number of connected "things" is expected to increase dramatically (Figure 17, below). Indeed, the number of device endpoints is so large that IPv6, the latest version of the Internet Protocol, is required. With IPv6, the number of Internet protocol (IP) addresses balloons from IPv4's approximately 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.

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.

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

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.

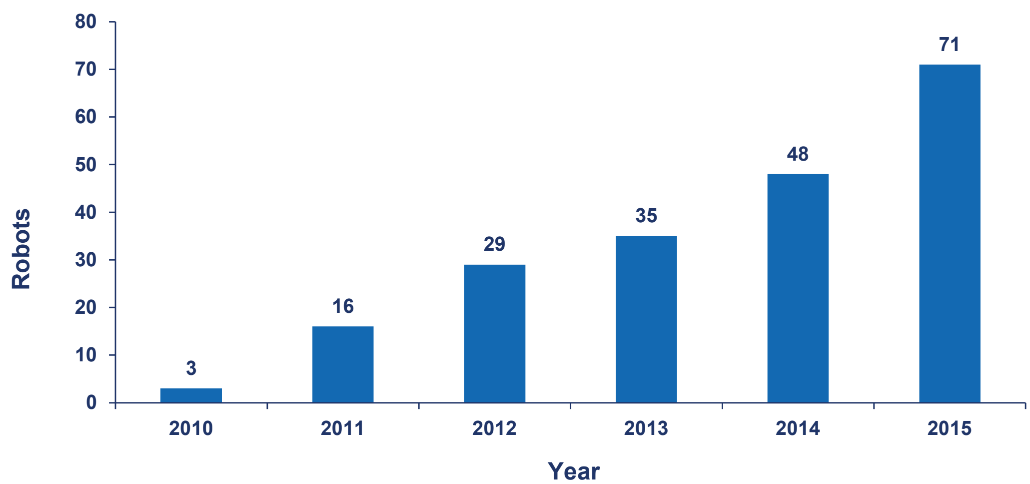
ROS usage among robotics researchers is widespread and increasing rapidly. ROS is now considered standard technology among robotics researchers, but equally important, the next generation of robotics engineers will be versed in ROS.

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)



7. THE MASSACHUSETTS ROBOTICS CLUSTER

> *Greater Boston is home to 55 colleges and universities. Massachusetts spends more on research and development than any other region in the world, and Boston attracts a diverse, technologically fluent workforce.*
>
> *—Jeff Immelt, CEO, GE*

The robotics cluster in Massachusetts is substantial and growing. As with other technology clusters, the Massachusetts robotics sector includes a localized concentration of core companies, of various sizes and levels of maturity, providing robotics technologies and products, as well as a range of services. These companies are themselves sustained by an array of supplier and services firms.

The Massachusetts robotics cluster benefits greatly from the many world-class educational and research institutions residing in the State. They are a leading source for an educated, skilled workforce, as well as the development of new capabilities and technologies resulting from fundamental and applied research undertaken in local laboratories. Universities and research institutions also support the cluster through technology transfer activities, facilities sharing, and networking events.

Other groups supporting the Commonwealth's robotics cluster include Massachusetts economic development groups, the investment community, industry associations, end-user companies, business and technology media, and much more. The resulting dynamic creates a self-reinforcing, beneficial web of innovation, reciprocality, and promotion, whose total impact greatly exceeds the sum of its individual parts.

7.1. NUMBER AND TYPES OF COMPANIES

It can be difficult to ascertain what defines a Massachusetts robotics cluster participant. For some entities, such as commercial firms iRobot and Boston Engineering, which are headquartered in the State and derive the majority of their revenue by providing robotics-related technologies, products, or services, the definition is clear, but for many other robotics firms, it is not. Although a wide variety of entities can contribute to the cluster's value chain, to eliminate ambiguity, reduce subjectivity, and increase the accuracy of both the current and future cluster assessments, it was necessary to define cluster members as formally as possible. For this study, cluster membership was limited by the following requirements:

- **Headquarters:** Commercial cluster members should be headquartered in the Commonwealth, or have an office in the State that is a major subsidiary or regional division office.

- **Primary Robotics Cluster:** The focus of this report is the primary robotics cluster which consists of over 95% of all robotics companies in the State (see Appendix H). Formally defined, the primary robotics cluster consists of the concentration of geographically bounded, localized, mutually supportive businesses found within 50-mile radius of Boston and Cape Cod. The robotics companies outside this area lack the critical mass and concentration to form another regional robotics cluster.

- **Revenue or Support:** Commercial cluster companies must derive approximately 35% or more of their revenue from robotics products, enabling technologies, or services, or a "robotics" division or subsidiary within a larger firm must do the same. Exceptions are made for startups without revenue, as well as larger firms evaluating robotics opportunities or supporting the cluster in other ways.

- **Universities and Labs:** Massachusetts-based private and public university research laboratories; national laboratories and testing centers; or private, non-profit laboratories with currently active robotics research programs or initiatives are cluster members.

Using the criteria above, the Massachusetts robotics cluster includes a total of 122 commercial companies (see Appendix H). A significant number of businesses do not qualify using this formal definition. Some are not geographically proximal to the Boston robotics hub, including companies in Western Massachusetts, New Hampshire, and Rhode Island. Others do not develop robotics products or technologies per se, but support the cluster indirectly with a variety of business services. Examples include design firms, public relations companies, marketing and engineering services providers, and more.

Most Massachusetts robotics cluster members are located within 50 miles of the Boston city center.

7.1.1. Funding Sources

When the companies in the greater Massachusetts robotics cluster were classified based on the primary payment/funding sources for their products, technologies, or services, it was found that most rely on commercial and industrial sources (see Figure 19). A sizable number of companies also depend on public sources for funding for research and defense work (the DoD, Defense Advanced Research Projects Agency (DARPA), National Science Foundation (NSF), etc.). A relatively fewer number of firms look to monies targeted for public services and education, as well as consumer dollars. Many companies had multiple sources for revenue.

The Massachusetts robotics cluster is well balanced with regard to primary payment/funding sources. No source is completely dominant.

The Massachusetts robotics cluster is well balanced with regard to primary payment/funding sources. No source is completely dominant, and as a whole, the cluster should be resistant to all but the most severe levels of business contraction, as well as large oscillations in state and national public funding levels.

7.1.2. Key Industries and Application Areas

The Massachusetts robotics cluster as a whole is not reliant on a single, large industry, and therefore is at a reduced risk from the effects of a sector downturn.

The Massachusetts robotics cluster draws revenue from a wide range of disparate industries and other sources, a reflection of the variety of the companies located in the State. This diversity reduces the risks associated with overdependence on a single, large industry segment, and the negative consequences of downturns impacting them. San Diego (defense and communications) and Detroit (automotive) serve as cautionary notes in this regard.

Manufacturing was the largest single target industry for Massachusetts robotics cluster members' products and services, with discrete manufacturing accounting for 19% of the companies, and process manufacturing equaling 4% (Figure 19). For a large percentage of cluster companies, the healthcare industry is a chief source of revenue, as is defense. A number of other industries/markets classified as "Other" also ranked fairly well. This group included utilities (4%) and warehouse/distribution (4%), along with research and exploration (6% and 4%, respectively).

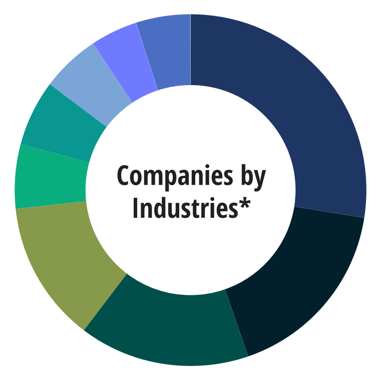
***Additional Insight:** Sizable industries that are not as yet primary markets for Massachusetts robotics cluster products and services include construction/demolition, agriculture, mining, and oil and gas. If companies developing new classes of outdoor mobile service robots, unmanned underwater vehicles, and particularly, commercial drone technologies and services can flourish, Massachusetts robotics cluster companies will expand into these markets as well. In many cases, entirely new companies will be formed.*

Figure 19: Massachusetts Cluster Member Companies by Primary Sectors and Industries

(Source: ABI Research)

Commercial	39%
Industrial	27%
Research	12%
Defense	9%
Public	6%
Consumer	5%
Education	3%

Manufacturing	27%
Defense/Public Safety	17%
Healthcare & Qol	16%
Research/University	13%
Utilities/Oil & Gas	6%
Warehouse/Distribution	6%
Home Care / Entertainment	5%
Agriculture/Mining	4%
Other	5%



** Other includes transportation, K-12 education, retail, and resource management.*

7.2. KEY TECHNOLOGIES, PRODUCTS, AND SERVICES

Massachusetts robotics cluster companies provide a wide variety of robotics products, technologies, and services, with no one class dominating over the others (Figure 20). This is a reflection both of the breadth

The number and range of companies in the Massachusetts robotics cluster eliminates the risk of regional over-specialization, along with the effects of a single-sector collapse.

and diversity of companies making up the sector, and the requirements for developing or operating robotics systems. It is also a measure of the extensive range of form factors that robots can assume. sUAVs, surgical robots, robotic pool cleaners, unmanned surface vehicles, and smart toys just begin to illustrate the form factors. Companies producing solutions for the industrial, consumer, public services, and commercial services markets are all represented.

7.2.1. Technologies and Services for Developing Robotics Systems

For 11% of the companies in the greater Massachusetts robotics cluster, software is a primary offering, usually for the design and development of robotics systems (as opposed to application software). Software was joined by controllers, vision/imaging technology, and other parts and supplies in this regard. Cluster companies also provide engineering and integration services for developing and deploying robotics systems.

As a class, articulated robots, which include most collaborative designs, along with unmanned underwater systems (UUS), play an outsized role within the Massachusetts robotics cluster.

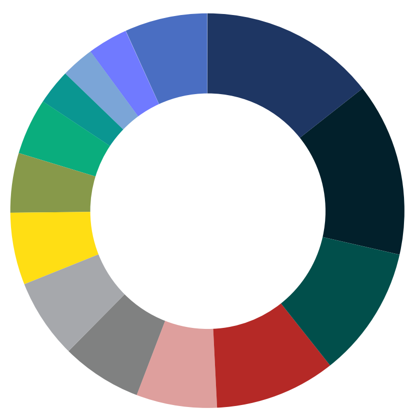
It is notable that the number of companies producing "whole cloth" robotics systems—articulated robots and UUVs —approximates that of businesses selling enabling technologies or offering services that have wide applicability. This indicates that these system types play an outsized role within the cluster..

***More Insight:** During the cluster evaluation process, each Massachusetts robotics company was categorized based on the assignment to each firm of up to three classes of products, technologies, or services out of a total of 74 options. This is a large number of choices for a comparatively small number of companies, and is another contributing factor to the single-digit results given in Figure 20.*

Figure 20: Massachusetts Cluster Member Companies by Primary Classes of Technology, Products, and Services

(Source: ABI Research)

Engineering Services/ Systems Integration	14%
Sensors/Vision/Misc. Hardware	14%
Software/Libraries/SDKs	10%
Industrial Robots	7%
Consumer Robotics	6%
Controllers/Haptics	6%
Marine Systems	6%
End Effectors/Arms/ Manipulators	5%
Prosthetics/Orthotics/ Rehabilitation/Exoskeleton	5%
Laboratory/Cleanroom	3%
Operator, Data & Design Services	3%
Surgical/Interventional Systems	3%
Mobile Platforms / AGVs	1%
Other	7%



7.3. REVENUE, EMPLOYMENT, AND NEW BUSINESS FORMATION

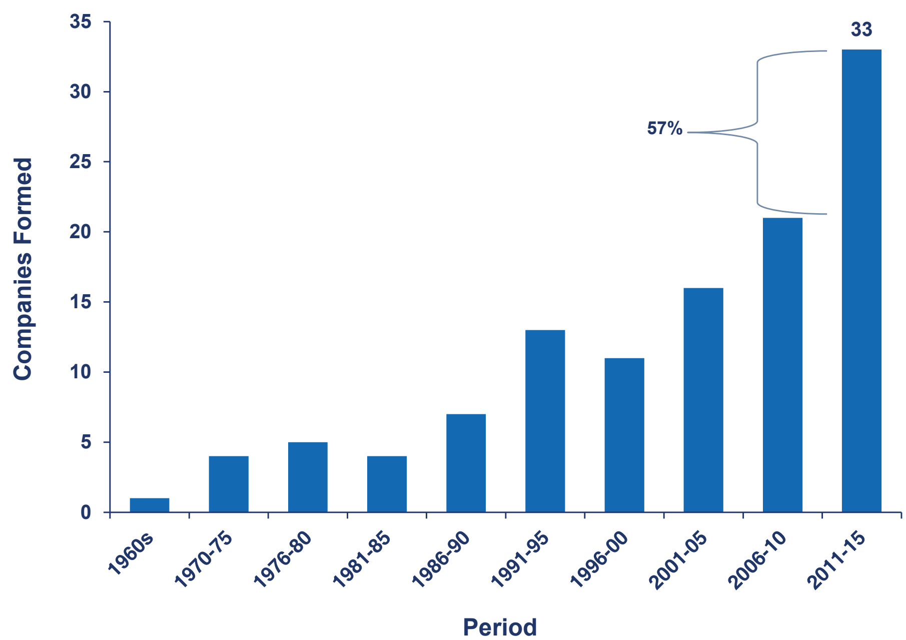
The 122 commercial companies in the Massachusetts robotics cluster generated US$1.6 billion in revenue for their products, technologies, and services in 2015. They also employed approximately 4,716 individuals with the majority consisting of engineers.

In Massachusetts, the rate of robotics business formation over the last decade has been exceptional, with 33 new companies formed since 2011 alone.

One measure of the dynamism and overall health of a technology cluster is the rate of new business formation. In this regard, the Commonwealth's robotics cluster is in good stead. New robotics businesses are being created at a steady rate, especially over the last decade (Figure 21). Between 2011 and 2015, 33 new robotics businesses were created, up 57% from 5 years earlier. Approximately 60% of robotics cluster member companies were formed since 2000.

Figure 21: Massachusetts Robotics Cluster Business Formation

(Sources: ABI Research, Massachusetts Technology Leadership Council)



The rapid growth in the numbers of Massachusetts robotics companies in the last 5 years will be offset somewhat in the future with the failure on the part of some firms. This is a common occurrence among young startups, and robotics companies are particularly susceptible. Compared to other technology startups, software companies particularly, robotics firms require more time to develop working prototypes, stressing fledging businesses lacking deep pockets. Designing for manufacturability, particularly for consumer systems, also delays time-to-market.

Robotics startups take a longer amount of time to bring products to market compared to software and other types of technology startups.

Even with this understanding, it is clear that over the last 5 years the rate of robotics business formation in Massachusetts has been exceptional. Example companies include RightHand Robotics (industrial grasping and manipulation), Jibo (consumer social robots), Locus Robotics (mobile service robots), Aquabotix (unmanned underwater systems), and more.

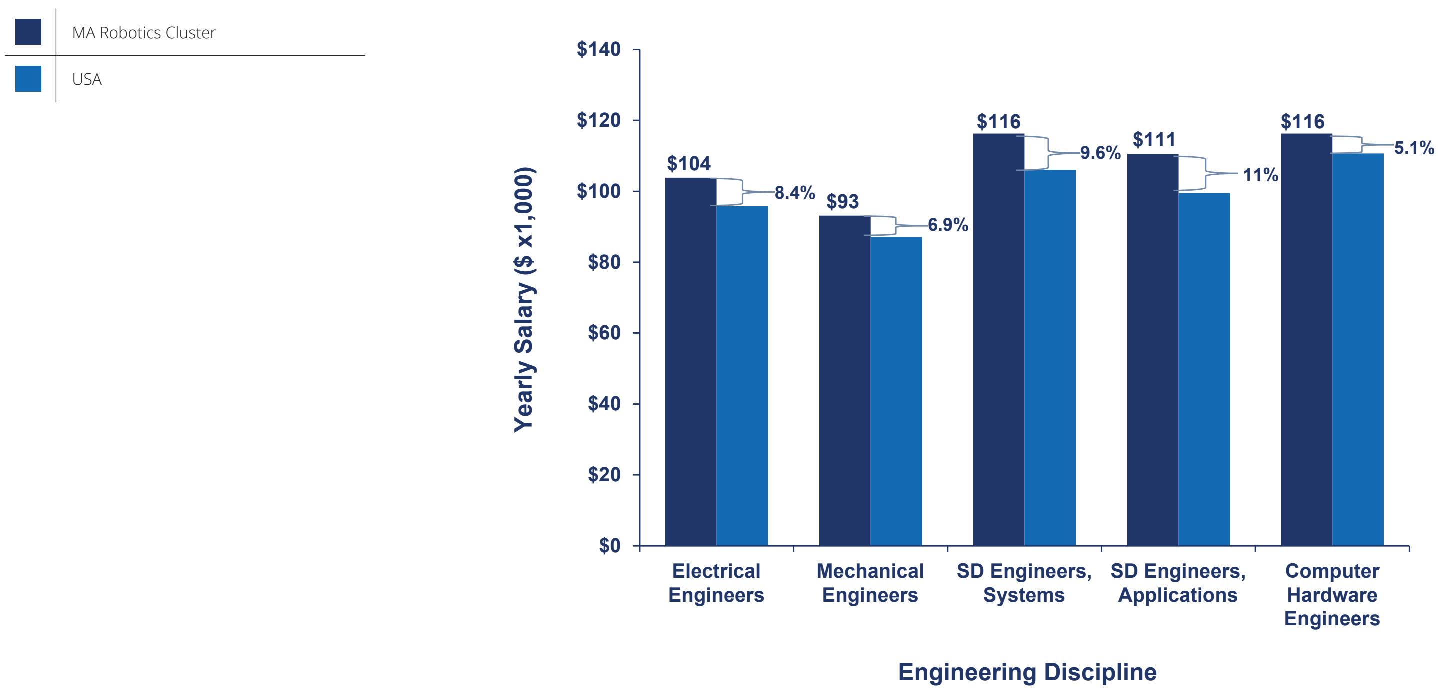
7.4. SALARIES FOR ROBOTICS ENGINEERS

The term "robotics engineer" is rarely used in job descriptions because it is not a formal descriptor in common use. The development of robotics technology requires the combined skills of software, electrical, and mechanical engineers, as well as a good deal of systems engineering support. Determining the average salaries of robotics engineers, therefore, requires that the wages for each of these classes of engineers be considered separate and compared to industry norms.

As described in Figure 22, the average yearly salary for the various classes of engineers commonly employed for robotics development in the Massachusetts robotics cluster region is substantial, and higher than for the United States as a whole. The Massachusetts robotics cluster area salaries are not the highest in the nation. For the most part, that distinction expectedly goes to Silicon Valley and greater San Francisco, and occasionally elsewhere (see Appendix C). Massachusetts engineers, however, consistently earn more than their counterparts in other states (see Appendix C).

Figure 22: Robotics Engineers Average Yearly Salaries, Massachusetts versus United States

(Source: US Department of Labor, Bureau of Labor Statistics)



__More Insight:__ The year 2015 was a banner one for private equity investment for robotics companies. Historically, however, robotics investments have been very limited compared to other sectors, such as social networking, biotech, green tech, and communications. One of the reasons given for the hesitancy on part of the investment community for funding robotics startups is the length of time required to bring products to market. Incubator programs and hardware accelerators can act to reduce the time to develop prototypes, as well as ensure that they are correctly engineered for manufacturability.

7.5. OFFICE LOCATION/RELOCATION OF NON-STATE-BASED ROBOTICS FIRMS

Eastern Massachusetts is a magnet for foreign robotics companies establishing North American regional and subsidiary headquarters.

A significant number of international robotics firms and technology suppliers have made Eastern Massachusetts their regional or subsidiary headquarters. The companies range from personal robotics suppliers Aldebaran and Blue Frog Robotics (France), to precision drive producer Maxon Motor (Switzerland) and exoskeleton maker ReWalk Robotics (Israel). Others, such as Japan's Harmonic Drive, have their U.S. manufacturing headquarters in the area.

A metro Boston address has brand value for companies wishing to be perceived as forward thinking and innovative.

The specific reasons given by robotics firms for a greater Boston regional or subsidiary headquarters vary from company to company, but access to a sizable, qualified labor pool, close proximity to an international airport, and the multiplier effect resulting from agglomerated robotics expertise, are typically cited. Recognition of metropolitan Boston as an international hub for robotics research and innovation is of special note. In addition to the practical benefits, a metro Boston headquarters communicates to customers, stockholders, and the world at large that the company is a robotics leader, and the corporate culture forward thinking and highly innovative, which has a strong brand value.

Robotics companies also locate in Eastern Massachusetts because the region is dominant in their sector of activity, such as the healthcare, defense, research, and education markets. Robotic therapeutic technology provider Hocoma (Switzerland), for which the Boston area's reputation as a world-class healthcare cluster was key, is representative.

***Additional Insight:** Dedicated, ongoing, and often aggressive branding campaigns for specific products or companies are very common, as are branding programs for travel and tourism. Massachusetts has done well branding the Commonwealth as a technology and innovation leader in a variety of industry segments. While common regional branding techniques of the past, such as international junkets and trade shows, do provide value, they can no longer be considered a competitive differentiator, but more "table stakes." More aggressive, non-traditional approaches are now required.*

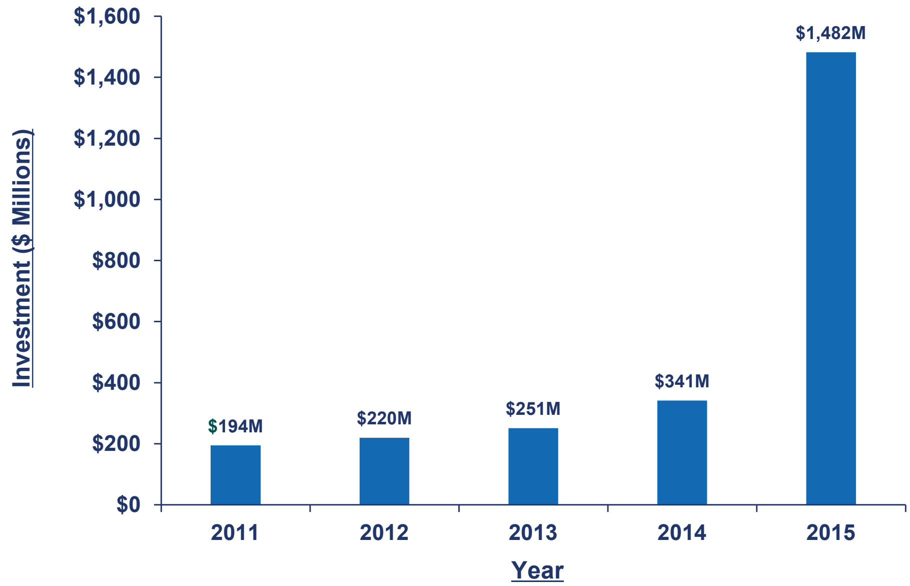
7.6. INVESTMENT IN ROBOTICS

Private sector investment in robotics companies increased dramatically in 2015. Approximately US$1.5 billion was invested, a dramatic increase over the previous year.

VC and other private sector investment in robotics companies increased dramatically in 2015, following years of upward, but unexceptional growth (Figure 23). Robotics investments in 2015 represent an increase of more than 330% over the previous year. It should be noted, however, that investing in the years 2011 to 2014 was significant. Funding rounds for robotics investments prior to 2011 were very small, and in some years, non-existent. In some respects, 2014 also represents a turning point, with year-over-year investment increasing more than 35%.

Figure 23: Worldwide VC and Private Sector Robotics Investment

(Sources: Hizook, Robot Report, ABI Research)



* Other includes transportation, K-12 education, retail, and resource management.

U.S.-based companies received 57% of the worldwide VC and private sector robotics investment in 2015, for a total of US$845 million.

Companies headquartered in the United States received the majority of VC and private sector investment dollars in 2015: 57% or approximately US$845 million (Figure 24). According to the National Venture Capital Association (NVCA), this figure represents only 1.4% of the total 2015 U.S. investment figure. Still, this is a sizable amount compared to previous years, and demonstrates an undeniable upward trend.

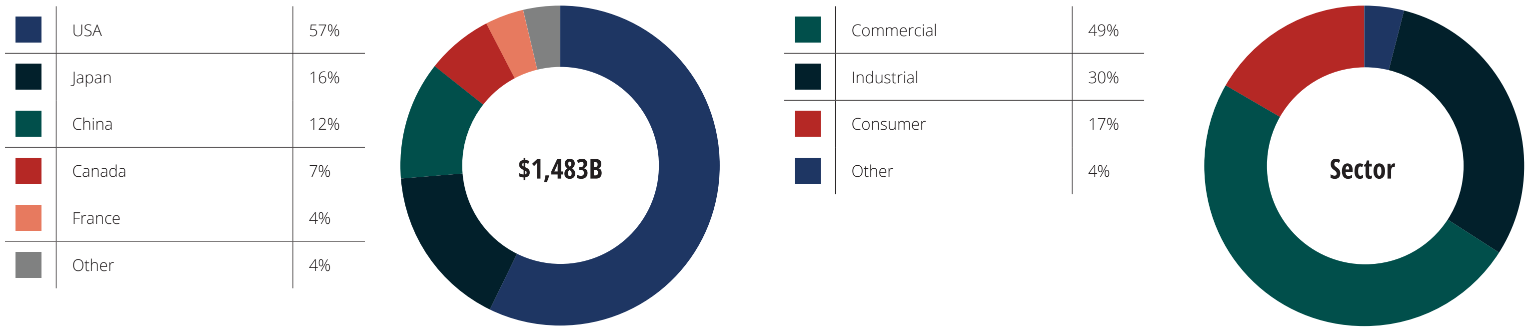
Additional Insight: Even if 2015 comes to be viewed as a robotics investment outlier, robotics investment for 2016 and beyond will continue to be robust. This is contingent on a number of factors, often unrelated, including:

- *Absence of market failures*
- *Continued availability of hardware-centric business accelerators*
- *Increased numbers of robotics exits, initial public offerings (IPOs), and acquisitions*
- *Stability of international financial markets*

As described in Figure 24, when 2015 robotics investments are examined on a per sector basis, it can be seen that the commercial segment dominates, with strong representation by companies developing solutions for the industrial and consumer markets. Venture investment for companies targeting the defense, research, and education sectors are in the low single digits. This is a reflection of investor emphasis on short-term returns, but also of the uncertainties and limited ceiling of public sector investments and public sector growth overall.

Figure 24: 2015 VC and Private Sector Robotics Investment by Country and Sector

(Source: ABI Research, Robot Report)



When 2015 VC and private sector robotics investments are broken down into specific target industries, as well as the technologies/products and services that the funded companies offer, it appears that no discernible trends emerge (Figure 25). This is not entirely correct. While the target industries of recipient companies do vary greatly, there are themes and commonalities in the types of products, technologies, and services developed for them (Table 13). For example, all companies producing mobile ground robots are targeting a combination of the manufacturing, warehouse/distribution, and healthcare industries. These markets share a working environment that is semi-structured, indoors, and heavily peopled.

Similarly, the agriculture, mining, and utilities sectors are the key markets for drone manufacturers and drone operator/data services providers. The majority of the recipient companies producing software/libraries/software development kits (SDKs) were also doing so in support of the UAV sector, and thereby pursuing the agriculture, mining, and utilities sectors indirectly. Sensor/vision system producers offer solutions for multiple classes of robotics providers and, therefore, support a wide range of industries.

Table 13: Target Industries for Robotics Technologies/Products/Services Investments

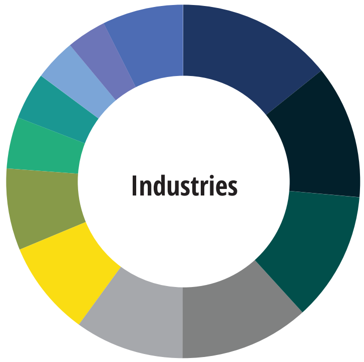
Technologies/Products/Services	Industries
Mobile Platforms/AGVs	Manufacturing, Warehouse/Distribution, Healthcare
UAVs	Utilities, Agriculture, Mining, etc.
Operator Services/Data Services	Utilities, Agriculture, Mining, etc.
Software/Libraries/SDKs	Utilities, Agriculture, Mining, etc.
Sensors/Vision Systems/Hardware	All Systems

(Source: ABI Research)

Figure 25: 2015 Global Robotics Investments by Target Industries and Technologies/Products/Services

(Source: ABI Research, Robot Report)

■	Manufacturing	14%
■	Healthcare & Qol	12%
■	Toy/Hobby/Social	12%
■	Warehouse/Distribution	12%
■	Agriculture	10%
■	Utilizes	9%
■	Mining and Quarrying	7%
■	Transportation	7%
■	Defense/Security/ Public Safety	4%
■	Home Care	4%
■	Retail/Wholesale	4%
■	Other	7%



■	Mobile Platforms/AGVs	15%
■	Software/Libraries/SDKs	15%
■	Unmanned Aerial Vehicles	15%
■	Sensors/Vision Systems/ Enabling Hardware	11%
■	Operator Services/Data Services	10%
■	Consumer Robotics	7%
■	End Effectors/Arms/ Manipulators	5%
■	Controllers	4%
■	Engineering Services/ Systems Integration	4%
■	Industrial Robots	4%
■	Surgical/Interventional Systems	4%
■	Other	9%

** Other includes prosthetics / orthotics / rehabilitation / exoskeletons, lifestyle enhancement, marine systems, laboratory / cleanroom, and networking / connectivity.*

7.7. PRIVATE INVESTMENT IN MASSACHUSETTS-BASED ROBOTICS FIRMS

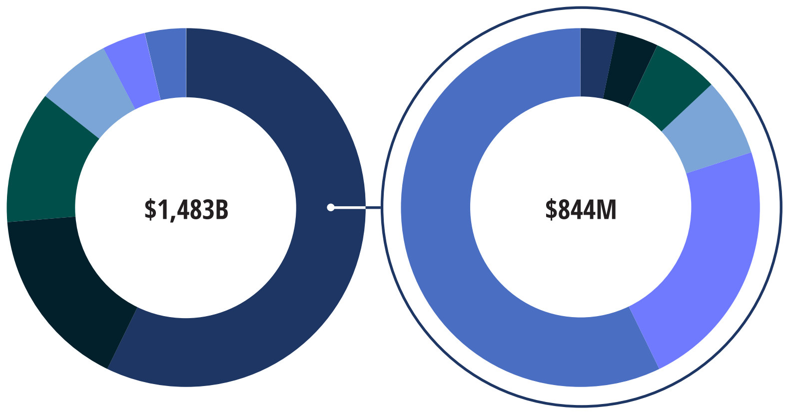
Massachusetts-based companies, all of which are located in the greater Boston metro area, received US$190 million in private investment in 2015.

As noted above, worldwide investments in companies producing robots and robotics technologies, as well as services and enabling technologies that directly support them, increased dramatically in 2015, reaching in excess of US$1.4 billion (see Figure 26). U.S. firms were on the receiving end of the bulk of this funding (57%), taking in approximately US$845 million. Massachusetts-based firms attracted approximately 23% of the investments to companies in the United States, which reached a total of more than US$190 million. Of these, all were located in the greater Boston area.

Figure 26: 2015 VC and Private Sector Robotics Investment, Global and United States

(Source: ABI Research, Robot Report)

USA	57%
Japan	16%
China	12%
Canada	7%
France	4%
Other	4%



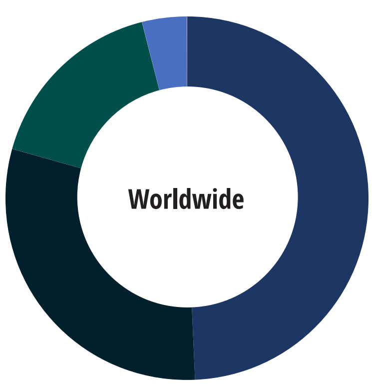
CA	57%
MA	23%
CO	7%
NC	6%
TX	3%
Other	4%

When 2015 Massachusetts robotics investments are compared with the world at large, it can be seen that sector investment proportions are roughly comparable (Figure 27). The commercial segment dominates, with strong representation by those companies developing solutions for the industrial and consumer markets. Venture investment for companies targeting the defense, research, and education sectors is in the low single digits. This is a reflection of investor emphasis on returns in the short term, but also their unease with the uncertainties and limited ceiling of companies reliant on public funding sources.

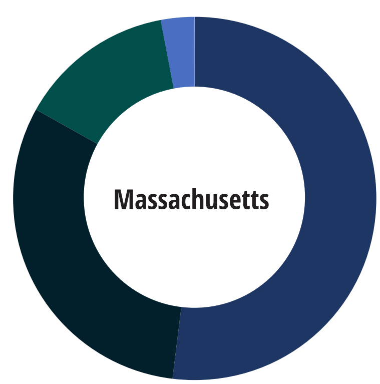
Figure 27: 2015 VC and Private Equity Investment by Sector, Global and Massachusetts

(Source: ABI Research, Robot Report)

Commercial	49%
Industrial	30%
Consumer	17%
Other	4%



Commercial	52%
Industrial	31%
Consumer	14%
Other	3%



Global private investment trends for robotics were reflected, to a large degree, in the funding of Massachusetts-based firms. In both cases, sizable amounts of investment went to companies developing solutions for the manufacturing, utilities, and warehouse/distribution sectors (Figure 28). Investments for companies developing solutions for the utilities industry were almost exclusively commercial drones, and the technologies and services that support their use. The applications, for the most part, are for infrastructure inspection.

Massachusetts-based healthcare robotics firms that recently received investment funding include Medrobotics, Myomo, and BionX Medical Technologies.

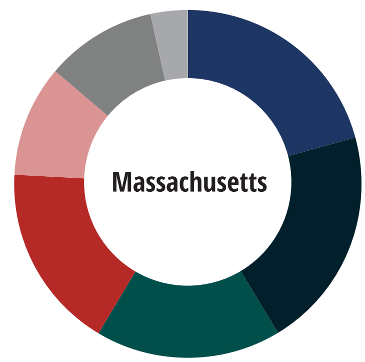
Massachusetts received a greater proportion of investment for those businesses producing robotics products for the healthcare/quality of life (QoL) sector, a consequence of the State's leadership role in this market. Investments in healthcare robotics companies were split among those developing interventional systems, and others offering robotics technologies for rehabilitation or for use in prosthetic devices. Massachusetts firms in this category include Medrobotics, Myomo, and BionX Medical Technologies.

Figure 28: 2015 VC and Private Equity Investment by Target Industry, Global and Massachusetts

(Source: ABI Research, Robot Report)

Manufacturing	14%
Healthcare & Qol	12%
Toy/Hobby/Social	12%
Warehouse/Distribution	12%
Agriculture	10%
Utilizes	9%
Mining and Quarrying	7%
Transportation	7%
Defense/Security/ Public Safety	4%
Home Care	4%
Retail/Wholesale	4%
Other	7%

Healthcare & Qol	21%
Warehouse/Distribution	21%
Manufacturing	17%
Utilizes	17%
Defense/Security/ Public Safety	10%
Toy/Hobby/Social	10
Agriculture	3%



7.8. MASSACHUSETTS INCUBATORS, ACCELERATORS, AND WORKSPACES

Massachusetts is home to incubators and accelerators of all types, offering an assortment of different programs. Some are general purpose, while others focus on industry segments including healthcare, cleantech, and education. No dedicated robotics incubator/accelerator exists, although robotics firms have been accepted into technology-oriented incubator/accelerator programs.

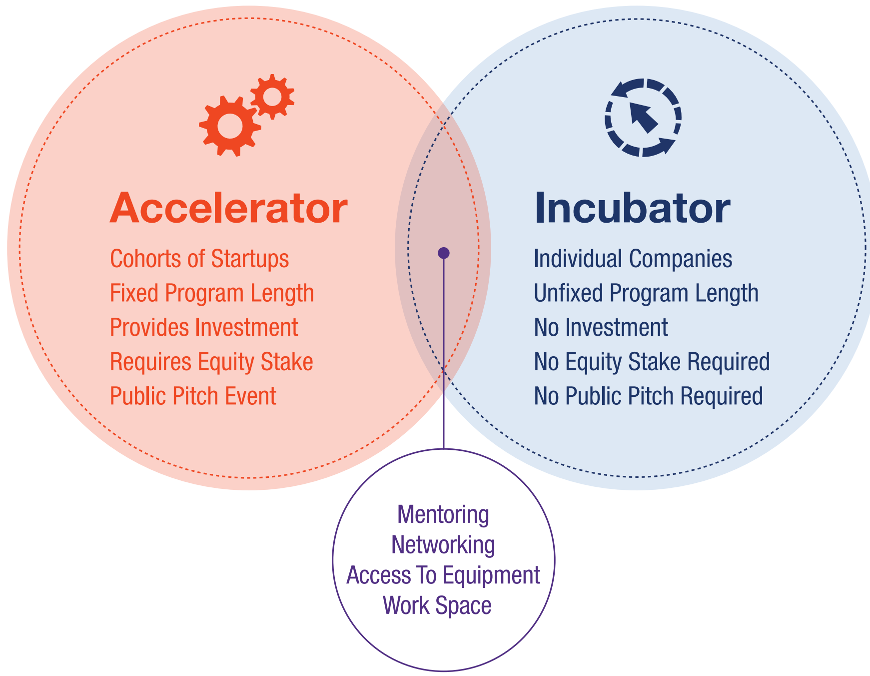
Both startup incubators and accelerators assist young companies to make them both entrepreneurial and successful (Figure 29). They differ in approach and the demands placed on the startups involved. For the most part, accelerators are more suited to more mature companies that are amenable to a structured, rigorous, short-term approach. Incubators are more flexible in their methods, and usually deal with very young firms. For some companies, incubators are used in preparation for entering accelerator programs.

In essence, accelerators are investment companies, and their numbers are increasing. They join VC firms and the investment arm of private companies as an additional source of funding for young companies.

Some incubators and accelerators have proven successful at fostering the development of successful companies. This success, in turn, has bred success. It is estimated that more than 300 accelerators and incubators are now found in the United States. Critics of incubators and accelerators, however, are quick to point out that measures of success, such as number of company launches and the acquisition of follow-on funding, are very uneven, and that the data sources are limited or lacking.

Figure 29: General Characteristics of Accelerators and Incubators

(Sources: Dempwolf, Auer, and D'Ippolito, 2014; ABI Research)



7.8.1. Accelerators

Accelerators, typically for-profit organizations, assist early-stage startups by providing a combination of stipends, workspaces, business mentorships, and connections to potential investors. The participating companies provide an amount of non-controlling equity (usually 5% to 10%). In this sense, accelerators are for-profit investment companies. The selection process for accelerator programs is competitive, which increases the appeal of accepted companies to potential investors.

Hardware accelerators typically provide 3D printers, CNC machines, injection molders, and other equipment used for hardware design, prototyping, and manufacturing.

As their name implies, hardware accelerators are designed to speed the development of hardware technologies, as well as reduce the risk of innovative designs failing to reach the market due to the business and volume manufacturing inexperience of hardware entrepreneurs. Hardware accelerators are distinguished from their more generic counterparts by the on-site availability of 3D printers, computer numeric control (CNC) machines, injection molders, and other equipment used for hardware design, prototyping, and manufacturing. Also, the length of accelerator programs often extends beyond the typical run of 6 to 12 months.

Notable hardware accelerators that have had success producing robotics technologies include Y Combinator (California), TechFounders (Germany), Lemnos Labs (California), Seedcamp (United Kingdom), and HAX (California). Hardware-centered accelerators in the greater Massachusetts cluster region include Bolt (Boston), MIT Global Founders' Skills Accelerator (Cambridge), and Harvard Innovation Lab (Cambridge). Massachusetts-based accelerators that have robotics alumni include:

- **MassChallenge (Boston):** MassChallenge, which claims to be the world's largest startup accelerator, is open to startup companies in any field. Under the program, which is competitive, companies are awarded grants equaling US$50,000 or US$100,000 after a 4-month program period. Robotics alumni include Hydroswarm and Juice Robotics (underwater vehicles), XactSense (drones and sensors), Bounce Imaging (mobile sensor), and Iron Goat (outdoor mobile robots).

Massachusetts-based accelerators Techstars Boston and MassChallenge have seven robotics alumni between them.

- **Techstars Boston:** Techstars is a highly competitive accelerator program with a very solid reputation. The Techstars terms include a 6% equity stake for US$18,000 seed capital and the option for a convertible note of US$51,000 to US$100,000. Rise Robotics (actuators and exoskeletons) and Neurala (software) are Techstars Boston alumni.

7.8.2. Corporate Accelerators

Large corporations also act as accelerators.

A number of large corporations have also established accelerators, with the objective of improving their capacity for innovation and gaining access to promising new technologies. These corporate accelerators often work in partnership with smaller firms with startup experience, and many also have their own venture investment divisions. Cisco, BMW, Flextronics, Deutsche Telekom, Google, Intel, and Microsoft serve as examples.

7.8.3. Incubators

Unlike accelerators, incubators do not provide capital for startups and do not take an equity stake. Many, but not all, are supported by outside grants from universities or national and state governments. Businesses are also contributors, as are private investors. Incubators are selective, but they do not provide upfront payments. Most incubators are focused on a specific industry or narrow vertical markets.

Four Massachusetts robotics companies are alumni of the Greentown Labs incubator.

Incubators provide mentorship and networking, as well as office and workspace, with some providing tools and other equipment. Typically, program lengths are not fixed. Example incubators include the Advanced Technology Development Center (Georgia), MGE Innovation Center (Wisconsin), and Massachusetts-based Greentown Labs. Greentown, an incubator for cleantech startups, provides co-working space, prototyping facilities, and business services. Robotics firms Autonomous Marine Systems (robotic surface vehicles), Rise Robotics, RailPod (robotic rail inspection systems), and RightHand Robotics (manipulators) are alumni of Greentown.

7.8.4. Co-working Spaces and Makerspaces

The greater Boston area is also home to both co-working spaces and makerspaces, which can provide temporary workspace and, in the case of makerspaces, access to equipment. Examples include WeWork (Boston), Artisan's Asylum (Somerville), and Cambridge Hackspace. Social robot maker Jibo was once housed in the WeWork Boston office.

Additional Insight: *Over the last 5 years, a number of startup incubators and accelerators have been launched, and programs continue to proliferate. It is important to note, however, that startup accelerators have also been discontinued, "pivoted" to another business model, or relocated. Many of these accelerators are startups themselves, and therefore, this behavior is in keeping with other young companies. In other instances, business simply dropped support. For example, Qualcomm, as part of a cost-cutting initiative, ended its partnership with Techstars for the Qualcomm Robotics Accelerator. The announcement came only weeks after the accelerator graduated its first class of 10 robotics startups. Incubators, which are often supported with funding from universities and government sources, are less likely to fall away in this manner.*

7.9. EDUCATION AND RESEARCH

Massachusetts has a well-earned international reputation as an education leader. K-12 education in the Commonwealth consistently ranks among the highest in the United States, as well as globally. Massachusetts is also recognized throughout the world for the quality of its colleges and universities, as well as the groundbreaking research that occurs within the State.

7.9.1. Degree Programs

More than 16 educational institutions in the Boston area have undergraduate engineering programs for disciplines critical to robotics development.

Massachusetts is densely populated with institutes of higher learning. Metropolitan Boston alone is home to more than 50 private and public colleges and universities, and within the entire State and other geographic areas that define the Massachusetts robotics cluster, many more can be found. More than 16 institutions in the Boston area have undergraduate engineering programs for some combination of the three disciplines critical to robotics development: electrical engineering, mechanical engineering, and computer science. Undergraduate robotics engineering programs are rare, although robotics minors are available.

Advanced degree programs for electrical engineering, mechanical engineering, and computer science are also offered at a number of universities in the greater Boston metropolitan area. Worcester Polytechnic Institute (WPI) is notable in that it has a dedicated graduate robotics engineering program. WPI also offers BS and MS degrees in robotics engineering, and was the first institution in the nation to offer all three degrees in robotics.

7.9.2. University Research Laboratories

The Massachusetts robotics cluster is also home to world-class robotics research laboratories and innovation centers. Across 10 Massachusetts academic institutions, in more than 40 separate laboratories and study groups, researchers are performing groundbreaking primary and applied robotics research, as well as carrying out investigations into other associated areas of study. The academic institutions where this critical work is ongoing are given in Table 14. Appendix B provides greater detail.

Table 14: Representative Massachusetts Universities

Boston University	Tufts University
Brandeis University	University of Massachusetts, Amherst
Harvard University	University of Massachusetts, Dartmouth
MIT	University of Massachusetts, Lowell
Northeastern University	WPI

(Source: ABI Research)

The neighboring states of Massachusetts also have universities that are performing important research and contributing indirectly to the greater Massachusetts robotics cluster. Examples include University of Rhode Island, Brown University, Dartmouth College, University of New Hampshire, University of Maine, University of Vermont, University of Connecticut, Yale University, and more.

Massachusetts Spotlight: NASA Awards Two R5 Humanoids to Northeastern and MIT

In November 2015, NASA selected MIT and Northeastern University to receive an advanced Robonaut 5 (R5 or "Valkyrie") humanoid robot, so that research focused on adapting the systems for use in space and possibly on Mars can be conducted. The awarding of the Valkyrie robots followed an extended, competitive selection process, with potential recipients drawn from the international collection of teams that competed in the 2015 DARPA Robotics Challenge. The DARPA Robotics Challenge was designed to foster the development of autonomous robotics capable of performing various emergency response tasks.

The MIT group will work out of the Computer Science and Artificial Intelligence Laboratory (CSAIL) under principal investigator Russ Tendrake. The Northeastern University team will be led by Taskin Padir. Both groups will receive US$250,000 in funding per year for a 2-year period to develop new algorithms that will extend the capabilities, increase the autonomy, and improve the dexterity of the bipedal, 6-foot-tall, 290-pound humanoids. NASA will also provide each research group with on-site and virtual technical support.

7.9.3. Private, Non-profit Research Facilities

Massachusetts is recognized worldwide as a leading center for advanced R&D. This includes private, nonprofit R&D facilities. Two of the more notable examples include Falmouth, Massachusetts-based Woods Hole Oceanographic Institution (WHOI) and the Charles Stark Draper Laboratory (Draper) located in Cambridge, Massachusetts.

The WHOI is the largest independent oceanographic research institution in the United States and a leading developer of marine robotics technologies including the only deep-diving research submersible in the United States, the iconic Alvin Human Occupied Vehicle (HOV). Like Alvin, the Jason series of ROVs, which were

WHOI, the largest independent oceanographic research institution in the United States, is responsible for the development of some of the most iconic marine systems in the world.

famously used to survey the wreck of RMS Titanic, was also developed by WHOI's National Deep Submergence Facility. The marine robotics company Hydroid was spun off from Woods Hole to commercialize another Woods Hole submersible, the REMUS AUV.

In addition to performing research and engineering advanced marine technologies, Woods Hole also boasts of undergraduate, graduate, and postdoctoral programs for educating the next generation of marine scientists, engineers, and entrepreneurs, often in partnership with other institutes of higher learning. For example, in 2016, WHOI reached a milestone: it conferred the 1,000th graduate degree as part of a joint education program between MIT and Woods Hole.

In 2014, Massachusetts awarded WHOI a US$5 million grant for developing marine robotics technologies.

Funding for Woods Hole research has many sources, both public and private. Commercial companies partner with WHOI for the development of new technologies, as do governmental agencies, such as the NSF, the NOAA, the Environmental Protection Agency, and more. Academic institutions such as Cornell University, MIT, the U.S. Naval Postgraduate School, University of Tokyo, and more have partnered with WHOI, as have a number of private foundations. The State of Massachusetts, too, supports the work of Woods Hole. In 2014, the Commonwealth of Massachusetts awarded WHOI a US$5 million grant for developing and testing marine robotics technologies.

Draper has a long history of innovation in multiple fields, many of which intersect with robotics: autonomous navigation, medical devices, AI, and more. This work is often accomplished in partnership with research universities. For example, Draper was recently awarded a US$3.4 million contract by DARPA to develop UAVs that autonomously sense and navigate through unknown environments without external communications or global positioning system support.

7.9.4. Robotics Research at Medical Centers

Massachusetts research hospitals, medical institutions, and rehabilitation centers also perform robotics research and commercialization efforts.

The institutions described above are joined by others performing investigatory robotics work in the many research hospitals, medical institutions, and rehabilitation centers for which Massachusetts is celebrated. Renowned institutions, such as the Lahey Hospital & Medical Center, Tufts Medical Center, Massachusetts Eye and Ear Infirmary, Brigham and Women's Hospital, and others, have their own dedicated robotics research efforts underway, often working in partnership with others from academia and industry. For example, researchers working in the Pediatric Cardiac Bioengineering Lab at Boston Children's Hospital are developing new medical techniques using robotics technologies to improve healthcare results. So, too, are the Pediatric Cardiac Bioengineering Laboratory and Developmental Endoscopy Research Lab at Massachusetts General Hospital.

7.10. NATIONAL LABORATORIES

Massachusetts is home to two federally funded R&D centers that address critical national security issues using advanced technology, including robotics. The first, Lexington-based Lincoln Laboratory, is sponsored by the U.S. DoD and is administered by MIT. Research programs at Lincoln Laboratory deal specifically with robotics, particularly work related to autonomous ground and air systems, and human-robot collaboration.

The National Security Engineering Center (NSEC) in Bedford is also sponsored by the DoD. Administered by the MITRE Corporation, NSEC is actively developing solutions in the areas of unmanned aerial and ground systems, micro robotics, mobile telepresence robots, advanced manipulation, and more.

Lincoln Laboratory and NSEC are Massachusetts-based, federally funded R&D centers that contribute to the overall Massachusetts robotics ecosystem both directly and indirectly.

Lincoln Laboratory and NSEC contribute to the overall Massachusetts robotics ecosystem both directly and indirectly. Ongoing R&D work is often a collaborative effort with outside support from academia and industry, typically from Massachusetts. Broader outreach efforts, ranging from on-site technical workshops to community-based STEM education initiatives, are also common.

7.11. MASSACHUSETTS MILITARY INSTALLATIONS

Massachusetts is home to six military installations, two National Guard bases, and a number of smaller Army Reserve and National Guard units. According to the UMass Donahue Institute, these installations contributed approximately US$1.3 billion to the Massachusetts economy in 2013, the latest year for which figures are available (UMass Donahue Institute, 2015). Among the activities undertaken at these facilities is research, often in partnership with local Massachusetts companies.

7.11.1. U.S. Army Natick Soldier Systems Center

Natick Labs performs research for the DoD, including work involving robotics technologies.

Natick Labs is a DoD research and engineering facility responsible for developing innovative soldier support items, including clothing, food, portable shelters, and warfighter survivability equipment. By extension, the technology developed at the lab can also be used for disaster relief or for other humanitarian purposes. Research, development, and testing activities at Natick Labs have involved robotics technologies such as exoskeletons, advanced sensors and controllers, miniature robots, and more.

Natick Labs offers research, engineering, and testing services to third parties on a fee-for-service basis.

Natick Labs is populated with its own research scientists and engineers, but also partners with academia and private industry on some projects. Engineering and testing services are also available on a fee-for-service basis.

7.11.2. Joint Base Cape Cod

The Federal Aviation Administration (FAA), in accordance with the FAA Modernization and Reform Act of 2012, selected six public entities, located in six different locations throughout the United States, to develop UAS test sites around the United States. The six sites are conducting research into the requirements necessary to safely integrate civil and commercial UAS into the U.S. national airspace (NAS).

The NUAIR Alliance, one of six groups selected by the FAA to develop UAS test sites and carry out research, includes many Massachusetts-based universities and research labs.

One of the six public entities selected to develop the test sites and perform research was the Northeast UAS Airspace Integration Research (NUAIR) Alliance. The non-profit NUAIR Alliance consists of a research network of more than 20 universities and research laboratories, such as MIT, UMass Lowell, WPI, Draper, Cape Cod Community College, and Boston University. Each institution focuses on specific standards, technologies, capabilities, protocols, risks, and procedures.

NUAIR is also made up of New York and Massachusetts private businesses, as well as facilities supporting testing of UAS. Raytheon, ARCON Corporation, and Charles River Analytics are Massachusetts-based NUAIS partner companies. The NUAIR test sites include Griffiss International Airport in New York State and Joint Base Cape Cod (JBCC) in Massachusetts, plus other locations on a case-by-case basis. Testing flights at JBCC sites are coordinated through the Massachusetts Unmanned Aircraft Systems Test Center (MA UASTC). MassDevelopment, the Commonwealth's economic development and finance agency, has contracted with the private firm Avwatch to manage UASTC operations.

Massachusetts private businesses, as well as JBCC, are also part of the NUAIR Alliance.

7.11.3. Fort Devens

For almost 80 years, Fort Devens was an active-duty military base. The 4,888 acre site closed in 1996, and at that time, MassDevelopment, the Commonwealth's finance and economic development agency, purchased the base. Since then, nearly 100 companies have located to Fort Devens (the Massachusetts Army National Guard also maintains a presence). Among them are:

- **Quiet Logistics:** Quiet Logistics is a third-party fulfillment services provider for e-commerce companies. The company has recently spun off Locus Robotics, a maker of indoor mobile service robots for goods-to-man picking.
- **DCS Corp:** DCS Corp is an engineering services firm serving the defense sector. The company has developed solutions for the DoD, often working with outside R&D laboratories, in the areas of UAS and autonomous ground vehicle systems.
- **MagneMotion:** MagneMotion provides electro-magnetic conveyance systems for transportation and material handling, which are often used in conjunction with robotics in a manufacturing automation role. Rockwell Automation, the world's largest supplier of industrial automation solutions, including systems employing robotics technologies, recently announced that it was acquiring MagneMotion. MagneMotion will be incorporated into Rockwell's motion solutions group, which also includes robotics.

7.11.3.1. Devens Interoperability Playground

In 2014, MassDevelopment, the New England chapter of the Association for Unmanned Vehicle Systems International (AUVSI), an international unmanned systems trade group, along with the Mass Technology Leadership Council (MassTLC), a technology business development association, signed a memorandum of understanding (MOU) to work cooperatively toward developing a center of interoperability for unmanned systems at Fort Devens. In 2015 and 2016, Devens IOP hosted a robotics industry trade event at Fort Devens, Devens Robotica. The event will also take place in 2017.

8. GUIDANCE AND RECOMMENDATIONS

> *If you were to ask me, "From all the data you have studied so far, where will the next economic breakthrough come from?" my answer would be: From the combination of the forces within big cities, great universities, and powerful local leaders."*
>
> *—Jim Clifton, CEO of Gallup*

The Commonwealth of Massachusetts has had great success developing and implementing policies that have facilitated and stimulated the growth of many different technology sectors over the years. In particular, the medical device, pharmaceutical, and biotech sectors have enjoyed substantial advancement and growth, leading Massachusetts to become one of the few prominent technology hubs in the world. The robotics industry shares some of the same characteristics and fundamentals as the life sciences technology sector, such as R&D processes that require substantial initial investments, specialized facilities and infrastructure, and a highly skilled and educated workforce.

The growth and success of life sciences industries in Massachusetts offers a blueprint for policy makers to identify and adopt similar programs and initiatives for the robotics industry that have been fundamental in the advancement of life sciences-related sectors. Yet, it is also vital to recognize that the robotics industry poses very unique economic and societal opportunities and challenges unlike any other technology, therefore requiring new unique initiatives, innovative practices, and sector-specific programs.

8.1. MASSACHUSETTS ROBOTICS CLUSTER

The Massachusetts robotics cluster is healthy and growing. As is typical of most successful clusters, the development of the Massachusetts robotics cluster was mostly gradual as a result of synergies naturally established over time between universities, research institutions, state and local organizations, industry associations, entrepreneurs, the investment community, and industry partners. Organizations like MassRobotics, an independent, non-profit robotics advocacy group, and MassTLC have formed over the years and provide industry-specific events and promotions to support the robotics cluster.

Massachusetts has one of the most innovative and sizeable robotics clusters in the country. In many robotics segments, Massachusetts is ranked as one of the top three states based on revenue and employment. The robotics cluster growth reached a critical mass and became self-sustaining, and the cluster attracted a technology and investment pipeline to withstand any cyclical economic decline. However, the rapid advances in technology, especially software-related applications, such as the emerging field of AI and machine learning, require directed attention and responsiveness in maintaining and strengthening the Commonwealth's competitiveness in the robotics sector.

8.2. CLUSTER STRATEGIES

The Massachusetts robotics cluster support and growth strategy can be divided in four distinct parts. The sustainability and growth of the cluster depends on supporting the entire cluster dynamics, including 1) talent development, 2) technology implementation, 3) brand building, and 4) cluster expansion. Collectively, each strategy is designed to help launch, attract, retain, and grow robotics companies in Massachusetts.

8.2.1. Talent Development

The most important factor in any industry cluster is the presence of a robust, skilled, and innovative labor force. Therefore, workforce education and training at each stage of company growth is critical to the cluster ecosystem. Labor training and education for robotics consist of a broad spectrum, including community college, higher-education, entrepreneurship, skills-based training, and worker re-training.

8.2.2. Encourage Entrepreneurship as a Part of STEM Education

Entrepreneurs have a key role in cluster development and growth. They Start new companies to produce novel products or services, often by commercializing research breakthroughs, but just as likely using existing technologies in new and different ways to solve problems, produce new products, or fill an unexploited niche.

STEM workforce development programs are common throughout the world, the result of many years of efforts to make national and regional economies more competitive. A technically trained workforce and STEM talent pipeline, once decisive competitive differentiators, are now only a necessary, but not sufficient, condition for driving today's innovation economies. The Commonwealth's robotics workforce must be technically educated, but also highly entrepreneurial. Policy makers should develop strategies whenever possible that work to increase the entrepreneurial education and training of their future workforce. One example is to recommend mandating entrepreneurship courses for computer science and mechanical and electrical engineering students attending Massachusetts State universities.

A technically trained workforce and STEM talent pipeline are now only a necessary, but not sufficient, condition for driving today's innovation economies.

8.2.3. Expand Internship and Co-op Opportunities

Many universities and colleges within Massachusetts are a continuous source of an educated workforce, the Commonwealth's greatest economic asset. Failure to retain graduates diminishes the available labor pool for regional businesses, and reduces the odds that non-local firms will locate to Massachusetts based on the availability of an educated workforce. Local employment of graduating students is key to retaining the region's educated workforce, and is easier and less costly than recruiting graduates to Massachusetts.

Employers overwhelmingly cite internship experience as a critical factor when considering hiring new college graduates for full-time positions. Also, industry statistics demonstrate that more than 85% of the companies supporting internships also recruit interns for their full-time workforces. For their part, students consistently name employment as the single most important factor determining whether they will remain in Massachusetts following graduation.

Massachusetts robotics companies seek out and retain student interns in different ways. Some have long-standing relationships with a local university and work directly with placement offices or with department-level heads. Others have their own internal efforts targeting multiple, but often a selective number of schools. Public resources, such as the state-supported internship programs through the MassTech Collaborative, the Massachusetts Life Sciences Center, and the Massachusetts Clean Energy Center, have also been valuable in facilitating the connections between eligible robotics companies and students for internships.

To capture more of the student population educated in Massachusetts colleges and universities, it is recommended that the Commonwealth continue to support internship programs and consider ways to increase participation by robotics firms. These programs should be sure to evaluate their impact on improving the likelihood of college student retention in the State.

Additionally, the Commonwealth should explore the possibility of supporting co-ops, which typically run longer than the 3-month internship programs. Co-ops have been proven to increase the level of regional retention rates for college graduates from private institutions, approximating that of public universities, where these rates are generally higher to begin with.

8.2.4. Develop Workforce Training and Retraining Initiatives

The speed of technology development is increasing at a rapid rate. As a result, the skills demanded by companies are also changing rapidly. In order to maintain a robust source of skilled labor, workforce training and re-training efforts must be included in any technology cluster development strategy. Therefore, there is a need to explore new initiatives, especially for those workers that need assistance acquiring new skills to be more relevant in the technology-based economy. The robotics industry has many applications in manufacturing. Offering manufacturing companies industry-specific workforce development assistance and incentives can be attractive in their expansion and relocation choices.

8.2.5. Technology Implementation: Facilitate Development, Testing, and Validation

The cost and time required to bring new robotics products/technologies to market increases the risk for young startups.

Developing robots and robotics technology is inherently challenging. Hardware is more expensive than software to develop and test. It also typically takes a considerably longer time to design hardware products. Unlike software, hardware designs must be the final product when shipped. Upgrades are difficult and very costly to implement. Releasing a minimally viable product, a common practice for software firms trying come to market quickly, is not applicable for hardware technologies. The cost and time required to bring new robotics products and technologies to market increases the risk for young startups considerably.

Emerging technology trends like autonomous and mobile applications also increases the level of difficulty and costs in robotics systems development and testing. This is especially true for the testing of wide-ranging mobile systems designed to be used in outdoor, unstructured, and often peopled environments. Commercial unmanned aerial and self-driving vehicle markets expected to exhibit exponential growth are notable in this regard.

The high cost and lengthy process of developing robotics technologies make this sector risky for most investors. Hence, VC firms that specialize in software investment outnumber VC firms that invest in early-stage robotics startups. Strategies that can increase the speed and lower the costs of development and testing and validation can lower the risks involved in the development of new robotics technologies and improve the odds for raising private capital.

8.2.6. Ensure Sustained Accelerator and Incubator Activity

In addition to workspace and mentoring, hardware-centric accelerators and incubators typically make available to program companies 3D printers, injection molders, and other equipment used for hardware development. Using these shared resources, companies can quickly and inexpensively develop componentry, molds, and even working prototypes. In some cases, it is possible to generate limited production runs of their products.

Massachusetts is home to many types of incubators and accelerators that provide equipment and workspace. Robotics companies have been launched through their programs.

At this time, the Massachusetts robotics cluster region is home to a number of private, public, and university-sponsored business accelerators and incubators, including Bolt, MIT Global Founders' Skills Accelerator, UMass Lowell Innovation Hub, and the Harvard Innovation Lab. MassChallenge, Techstars, Greentown Labs, UMass Boston Venture Development Center, and Healthbox are notable in that they were instrumental in the launch of a number of robotics companies. At no previous time have young robotics companies had so many options to access equipment, workspace, and mentorship. For the future, Massachusetts should examine if accelerator and incubator resources are adequate and suitable to meet continued demand or whether demand outstrips existing assets and resources.

8.2.7. Ensure Continued Support for Testing Centers

Unlike accelerators and incubators, for-profit centers for robotics testing do not exist. Many commercial companies and research laboratories do have private testing facilities, but they are often unavailable to others. However, Massachusetts is home to multiple open testing centers that are publicly funded to some degree and available to industry collaboration, such as the University of Massachusetts NERVE Center, the Massachusetts Unmanned Aircraft Systems Test Center and the Center for Marine Robotics at Woods Hole Oceanographic Institution.

These sites are not being used to full capacity at this time, but given the nascence of the emerging robotics markets they serve, as well as unresolved regulatory issues, this is to be expected. It is recommended that these centers, and possibly others, remain open with Commonwealth support as appropriate in the event of funding shortfalls, and continually be monitored regarding technical advancement, regulatory requirements, and market trends. Also, discounts for testing services should be made available for Massachusetts firms, and possibly subsidized for in-state startups. In addition, the totality of the robotics testing capabilities should be used to brand the Commonwealth as the leader for commercial robotic systems testing.

8.2.8. Offer Low-cost Loans for Development, Prototyping, and Testing Tools

The engineering and testing of robotics technology differs from the development of software, as well as many types of hardware. Robotics engineers require mature, robust, integrated software development environments. It is through such tools that custom development and integration, which is slow, costly, and error prone, can be replaced by a more rigorous, productive, abstracted approach. Robotics companies must also prototype and test their hardware and, in some cases, engineer them for manufacture. Development environments, prototyping and machining tools, and testing products can be costly, perhaps prohibitively so for young companies. It is recommended that a mechanism be established so that startups can be provided with access to low-interest loans for the purchase of such technologies, perhaps working in cooperation with Massachusetts-based companies providing these technologies; for example, the Mass Developement Emerging Technology Fund.

8.2.9. Leverage State Procurement for Validation

Investigate policies that would allow the State to acquire robotics technologies and apply them if deemed suitable to the task and contributory to their purpose. Policies that would facilitate acquisition by the State of pre-commercial robotics products produced by Massachusetts' companies should be investigated, and applied if suitable to a given task and would validate newly emergent robotics technologies to the larger marketplace.

8.2.10. Maintain a Simple, Stable Regulatory Environment

Massachusetts should develop regulatory policies that are most conducive to development and testing. The Commonwealth should avoid implementing state-specific regulatory policies before or beyond those required by the federal government. If prematurely adopted, State-sponsored regulatory initiatives and legislation can produce unintentional consequences such as creating confusion and ambiguity, which ultimately may slow innovation.

8.3. BRAND BUILDING: BRAND AND MARKET THE CLUSTER

Elements of a branding and marketing strategy should include:

The Massachusetts robotics cluster should be rebranded as the Massachusetts Robotics and Intelligent Systems Cluster or Massachusetts Robotics Innovation Cluster.

1. **Rebrand the Cluster:** Brand the Massachusetts robotics cluster as the Massachusetts Robotics and Intelligent Systems Cluster (the Massachusetts Robotics Innovation Cluster is also appropriate). This better reflects today's popular understanding of the intersection of AI and robotics, the increasing levels of autonomy exhibited by robotics devices, and technological trends going forward. The term is also inclusive for critical technologies and significant market sectors that intersect with robotics, such as autonomous vehicles, the IoT, and more.

2. **Launch Aggressive Marketing Campaign:** Formulate, begin, and sustain a comprehensive marketing campaign highlighting the many strengths and capabilities of the Massachusetts

robotics, autonomous, and intelligent system (RAIS) cluster. The work should be undertaken by a professional public relations or marketing firm, and developed in conjunction with public and private contributors to the robotics clusters.

3. **Highlight Research Dominance:** Emphasize research, the basis for most innovation and the area where Massachusetts is dominant, over investment and other measures of cluster strength. Stress the lack of equivalence between the number and quality of Massachusetts universities and research centers with that of other robotics centers. Also, stress innovation in outbound marketing material and communication with business and technical media ("the Massachusetts Robotics Innovation Cluster").

4. **Brand the STEM-E Workforce:** All regional robotics clusters state that they are home to a sizable, technically educated workforce. Massachusetts is exceptionally strong in this regard, but going forward, for marketing and branding activities, as well as media interactions, the qualifier of "entrepreneurial" should be added. Not only is the Commonwealth a dominant research and innovation center, it is home to a very large, educated, and entrepreneurial workforce.

5. **Promote Relocations:** As part of robotics marketing and branding material developed by Massachusetts, highlight companies that have relocated to Boston, or set up regional offices.

6. **Formalized, Proactive Tech, and Business Media Outreach:** Media outreach efforts must be proactive, regular, and outbound, and not solely reactionary based on media requests following cluster member announcements or for general information for media-generated storylines.

7. **Aggressively Solicit Events:** Aggressively seek out and solicit the leading international business, investment, and academic conferences in an effort to have them locate events in Boston. Examples include XPONENTIAL (a massive event), the IEEE ICRA (emphasis on research and technologies on the cusp of commercialization), and RoboBusiness (emphasis on investment and business development). Incentives and special attention should be considered.

8. **Deepen Event Participation:** The Massachusetts robotics cluster should continue to increase its presence at national and international trade shows and conferences. Hospitality suites, in addition to a booth on the conference show floor, should be considered for strategic events.

8.4. STRENGTHEN AND ENHANCE CLUSTER DYNAMICS

It is not advised that Commonwealth policy makers do direct investments to pick winners in the robotics technology space. However, Massachusetts can play a critical role by supporting programs and initiatives that facilitate knowledge transfer, networking, commercialization, cooperation, and partnership development that will result in opportunities for Massachusetts robotics companies.

8.4.1. Strengthen Cluster Ties

The Commonwealth can support the robotics cluster in ways that strengthen the value chain through intraregional cooperative initiatives with technology clusters where technological, investment, market, and other synergies are strong. Examples include MedTech and GreenTech.

Additionally, cluster leaders should seek to increase formal and informal cluster networking opportunities and collaboration initiatives with sector-specific regional clusters in Europe and Asia. Again, the focus should be on cluster partners where synergies are strong, such as those with competencies in UMS, advanced manipulation, and indoor mobile robots.

8.4.2. Increase Local Demand

Increasing the use of robots and robotics technologies in Massachusetts companies serves to: 1) improve competitiveness of the regional cluster and 2) geographically concentrate innovation and economic growth under the cluster model. In the case of the Massachusetts robotics cluster, this is the greater Boston metropolitan area.

The Commonwealth can help to educate and incentivize Massachusetts businesses to adopt robotics technologies. Emphasis should be placed on small-to-medium manufacturers, a large percentage of which have not adopted robotics automation and missed out on the benefits of robotic industrial automation, such as increased productivity, quality, and overall competitiveness.

8.4.3. Strategically Support Nascent and Emerging Submarkets

Within the robotics cluster, state support aligned to particular high-priority subsectors where the Massachusetts industry exhibits underlying strengths may be appropriate in order for the Commonwealth to best capture new economic opportunities. For example, manufacturing, healthcare, and sectors employing commercial UAS are examples of sizable markets where global business (push and pull), social, and political drivers intersect to provide long-term, uninterrupted demand, and also build on the Commonwealth's historical strengths to support the greater Massachusetts economy.

Additionally, maritime robotics is a greenfield opportunity with widespread cluster support and deep historical roots in the area. This field of the robotics sector is small and riskier, but the upside potential is massive. Other areas that build on existing cluster strengths, exhibit a strong predisposition for growth, and have high strategic value (and therefore strong potential for high levels of private investment and long-term market viability) include autonomous transportation, advanced manipulation, and logistics automation.

8.4.4. Support New Business Formation

For the robotics industry, new business formation is primarily new technology driven. Innovative startups provide a large portion of the cluster growth and expansion; therefore, the Commonwealth should monitor the robotics startup formation ecosystem and assess the need for new programs and initiatives to stimulate new business formation.

A number of research universities generate patented intellectual property that, in turn, is commercialized either through licensing to established companies or startup formation. The Massachusetts robotics cluster has already achieved critical mass that provides a steady supply of entrepreneurs, executives, and employees who have industry-specific expertise. A number of incubators and accelerators provide startup facilities and mentorship support. Additionally, associations and networking organizations play an integral role in building a vibrant robotics community. Yet, the Commonwealth can play a facilitator role to engage cluster leadership to assess the cluster health, expedite the transfer of good practices, and perform consensus building to leverage collective resources.

Another integral part of new business formation is the capital formation. A number of seed-funding sources are available for technology startups, such as federal technology development grants like the SBIR and STTR grants. Massachusetts has one of the highest numbers of awards with these grants in the nation. Additional sources of seed capital are available through universities and other State organizations. Continued support by the Commonwealth of the new business formation ecosystem is an integral part of maintaining a thriving robotics cluster in Massachusetts.

9. EVALUATION AND IMPLEMENTATION METHODOLOGY

Goals are only wishes unless you have a plan.

—Melinda Gates, Co-founder, Bill & Melinda Gates Foundation

As noted above, this report has the overarching goal of providing a roadmap that can be used by policy makers to expand the State's robotics innovation economy. Of course, fostering growth implies prior knowledge as to the status of the cluster. This information allows cluster performance to be gauged and compared to previous levels, so that policy measures can be adjusted accordingly. Thus, any cluster development strategy must include a discussion of the following:

- **Evaluation Methodology:** What is the state of the Massachusetts robotics cluster currently and ongoing?
- **Implementation Methodology:** What course of action should the State undertake to expand the Massachusetts robotics cluster?

Additional Insight: *Some issues related to public sector initiatives designed to drive Massachusetts robotics innovation are beyond the scope of this report. Examples include business, immigration, and tax policy that are the purview of the U.S. national government or international standards for robotics technologies and supporting infrastructure. K-12 STEM educational initiatives, while clearly important and under state control at some level, are not limited to robotics innovation, and are addressed in other studies, as are issues such as infrastructure investment.*

9.1. EVALUATION METHODOLOGY

Any implementation methodology intended to expand the State's robotics innovation economy must begin with an overall strategic assessment of the cluster. This report provides a snapshot of the Massachusetts robotics cluster in its current state, as well as a review of the cluster's history and the expected performance of the various robotics sectors in which cluster companies are competing. But going forward, the assessment process must be continuous, and not dependent on the infrequent issuance of reports of variable coverage, quality, and depth. To do so requires that the following initial steps be taken:

Going forward, the cluster assessment process must be continuous.

9.1.1. Develop a Commercial Class Database

Monitoring and analysis of the cluster's performance requires the development and maintenance of a commercial class database under the stewardship of a state-appointed entity.

9.1.2. Formally Define Cluster Members

To eliminate ambiguity, reduce subjectivity, and increase the accuracy of future assessments, cluster membership must be defined as formally as possible. As noted earlier in this study, cluster membership should be limited to those entities that meet the following requirements:

- **Headquarters:** Commercial cluster members should be headquartered in Massachusetts, or have an office in the State that is a major subsidiary or regional division office.

- **Primary Robotics Cluster:** The focus of this report is the primary robotics cluster which consists of over 97% of all robotics companies in the State (see Appendix H). Formally defined, the primary robotics cluster consists of the concentration of localized, mutually supportive businesses found within 50-mile radius of Boston and Cape Cod. The robotics companies outside this area lack the critical mass and concentration to form another regional robotics cluster.

- **Revenue or Support:** Commercial cluster companies must derive approximately 35% or more of their revenue from robotics products, technologies, or services, or a "robotics" division or subsidiary within a larger firm must do the same. Exceptions can be made for startups without revenue, as well as larger firms evaluating robotics opportunities or supporting the cluster in other ways.

- **Universities and Labs:** Massachusetts-based private and public university research laboratories; national laboratories and testing centers; or private, non-profit laboratories with currently active robotics research programs or initiatives are cluster members.

9.1.3. Utilize a Modernized Taxonomic Framework

Cluster companies should be classified based on a sector-oriented framework.

Cluster companies should be classified based on a sector-oriented framework that provides information pertaining to the industries they serve, as well as the ultimate source of revenue or research funding (see Figure 1). This scheme provides for multilevel company descriptors that can be used to better assess the state of the cluster and provide for deeper, more meaningful analysis. It also better accords with the NAICS standardized taxonomy for industries, along with similar standards used throughout the world.

9.1.4. Standardize Company Descriptors

To reduce ambiguity and facilitate analysis, cluster member companies should be classified according to a schema similar to that given in Appendix E, or a variation of the same. At a minimum, each company should be categorized as follows:

- 2 Sectors
- 2 Industries
- 3 Technologies/Products/Services

9.1.5. Simplify, Limit, and Standardize Cluster Indicators

Both cluster assessment (and expansion) strategies are dependent on formal descriptions and measurement of specific performance indicators. Unfortunately, opinions vary greatly as to which factors are most impactful for the creation and ongoing development of innovation clusters, and those that are optimal for gauging growth. Moreover, many competing cluster theories and innovation frameworks have emerged over time, each bringing to the discussion their own characterizations as to what constitutes success, as well as performance factors and other indices used to measure and achieve it (Davis et. al., 2006). Often, cluster indicators are only weakly predictive of economic performance, and their complexity can make them ill-suited as the basis for informed decision making.

Often cluster performance indicators are too numerous, complex, statistically unmeasurable, and only weakly predictive of economic performance.

The proliferation of disparate, often competing, cluster performance indices can make the task of describing, measuring, and optimizing cluster performance challenging. With each index, an additional level of complexity, and often uncertainty, is added to the process. This, in turn, extends or even postpones the cluster assessment process, both of which come at a cost. It also can limit the frequency by which cluster assessments are made, an important consideration in a rapidly expanding, dynamic technology sector such as robotics.

Overly complex assessment metrics reduce the frequency and increase the cost of cluster analysis.

For this study, ABI Research recommends a pragmatic, and ultimately more efficient, "less is more" approach for employing cluster performance indicators. Cluster innovation policy is enhanced when performance indices and assessment processes are:

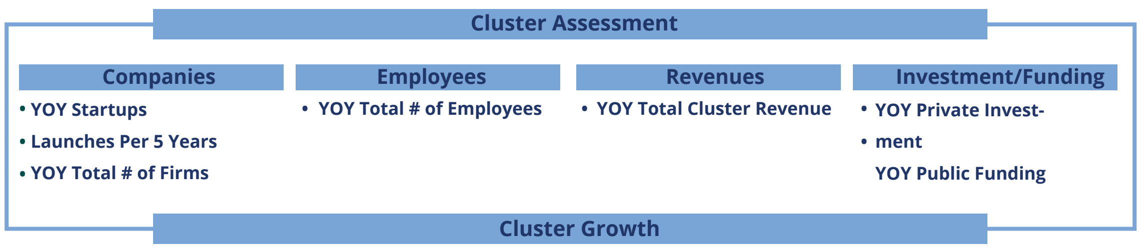
- **Understandable:** It should be possible to define cluster performance indicators clearly, easily, and without ambiguity. They should be readily understandable by policy makers and others. In the same spirit, they should also be as limited in number as reasonably possible.
- **Measurable:** Cluster performance indicators should be statistically measurable, and easily so.
- **Meaningful:** Cluster performance indicators should be open to meaningful interpretation, and speak to business development and market growth.
- **Repeatable:** Cluster performance analysis should be a consistent, easily repeatable, and, perhaps, a largely mechanical process.
- **Comparable:** It should be possible to easily and quickly compare performance metrics across similar technology clusters worldwide.
- **Regular:** The process of gauging cluster performance should be undertaken regularly.

In accordance with the principals listed above, ABI Research believes that performance indicators for cluster assessment and the development of cluster expansion strategies should be limited to the following (Figure 30, below):

- **Companies:** The number of startups, small established firms, and large established firms operating within the cluster (descriptions given below)
- **Employees:** The number of total employees employed in Massachusetts robotics cluster companies or the robotics divisions of cluster companies
- **Revenues:** The yearly total revenue attributable to Massachusetts robotics cluster companies, or the revenue contribution of robotics divisions of cluster companies
- **Investment/Awards:** The amount of private investment and public sector funding attracted by Massachusetts robotics cluster companies, or the robotics divisions of cluster companies

Figure 30: Recommended Cluster Performance Indicators

(Source: ABI Research)



9.2. THE IMPLEMENTATION METHODOLOGY

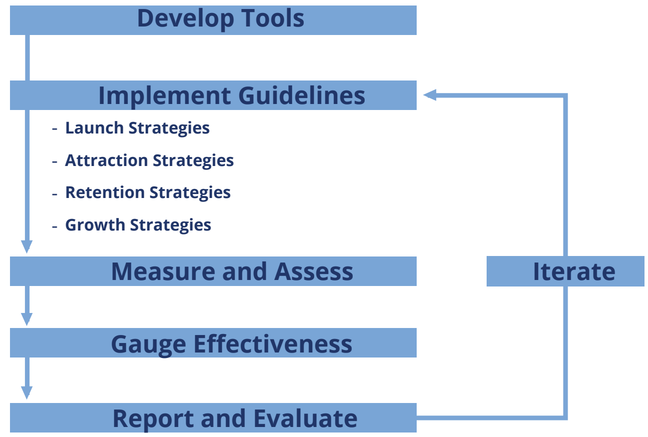
The purpose of this report is to provide a roadmap that can be used by policy makers to enlarge the State's robotics innovation economy. "Roadmap" implies fixed goals, and often the inclusion of a timeline. The launch, attract, retain, and grow measures outlined in the Guidance and Recommendations section above are not tied to, nor do they adhere to, a strict timeline. There is no "5-year plan." There are objectives, but like the robotics sector itself, they are not fixed, and are sure to change according to time and circumstance.

Frequent, detailed, yet simplified cluster assessment is the key.

The implementation methodology that is advocated is, in effect, an iterative, agile, self-correcting process designed both to continually monitor the cluster's performance and guide policy decisions. Frequent, detailed, yet simplified assessment is the key. This approach is more efficient, effective, and less costly than the development of staged roadmaps, and can be used to augment further studies if necessary. The process consists of six phases as given in Figure 31, and described in greater detail below.

Figure 31: The Implementation Methodology

(Source: ABI Research)



9.2.1. Phase 1: Develop the Tools

The implementation methodology begins with the development of the tools to measure cluster performance—to make measurable what is currently unmeasurable, and to do so in a manner that is straightforward and consistent. The first, immediate, and critical step, therefore, is to execute the tasks given in the evaluation methodology described earlier.

9.2.2. Phase 2: Implement Recommendations

The second phase of the implementation methodology calls for carrying out the measures given in the Guidance and Recommendations section. It is assumed that some of the recommendations will be acted upon, and others not. Even if certain measures are agreed to, such as developing a STEM-E workforce, expanding internship programs, or professionalizing the branding/marketing of the cluster, they will take a significant amount of time to implement, and their results an even longer period to manifest. For these reasons and more, the guidelines and recommendations cannot be directly linked to explicit, fixed timelines.

Guidelines and recommendations cannot be directly linked to explicit, fixed timelines, but they can be prioritized.

The cluster development recommendations have been ranked (Table 15 and Appendix F). High-priority rankings connote both greater urgency and a greater anticipated impact. It should be noted that high-priority measures are largely designed to increase overall entrepreneurial activity, as well as aid young startups by removing barriers to innovation and commercialization. They also call for direct support, when necessary, to those companies in strategic markets with a strong potential for growth but that are too small to attract investor interest, or for sectors that map to the Commonwealth's economic or historical strengths. Examples of the latter include the manufacturing, healthcare, and maritime sectors.

High-priority recommendations are designed to increase overall entrepreneurial activity, as well as aid young startups.

Table 15: Prioritized Recommendations to Accelerate Cluster Development and Increase Impact	
Recommendation	**Priority**
Launch Strategies	
Develop a STEM-E Workforce	3
Monitor Accelerator and Incubator Activity	3
Offer Low-cost Loans	2
Procure Pre-commercial Technologies	1
Attraction Strategies	
Professionally Brand/Market the Cluster	3
Employ Incentives	2
Retention Strategies	
Expand Internship Programs	3
Launch Co-op Program	3
Growth Strategies	
Support Testing Centers	3
Increase Local Demand	3
Increase Cluster Cooperation	2
Support Strategic or Nascent Markets	3
Leverage Existing Experience and Expertise	2

(Source: ABI Research)

9.2.3. Phase 3: Measure and Assess Performance

Regular, consistent assessment is key. It is recommended that cluster assessment based on the key performance indicators take place quarterly. If significant trends are uncovered (see Gauge Effectiveness, below), more rigorous analyses using additional performance metrics can then take place.

9.2.4. Phase 4: Gauge Effectiveness

Following the assessment phase, the effectiveness of policy-driven measures, as well as the impact of general business, technology, and investment tends, can be determined:

Company creation is the primary metric of success for launch strategies.

- **Gauging Effectiveness of Launch Strategies:** The key metric of success for launch strategies is the number of new Massachusetts robotics cluster companies established over a fixed period of time. Investment, especially from private sector sources, is a secondary measure, as well as the quantity of firms launched over the course of 5 or even 10 years.

- **Gauging Effectiveness of Attraction Strategies:** Indicators for success would be the number of companies or subsidiary offices established in the State over a fixed period of time. Other indicators include the number of employees working at the sites and the amount of revenue generated by them.

- **Gauging Effectiveness of Retention Strategies:** Retention rates for graduates of both the public and private universities and colleges of Massachusetts can be determined, but they cannot be linked directly to robotics cluster growth. Internships are only loosely tied to increased retention rates, especially for graduates of private universities, and breaking out robotics programs from other internships is a complex and time-consuming undertaking, thereby decreasing the chance that cluster assessments will be performed regularly and in a consistent manner.If the State were to fund robotics co-op programs, which are more strongly tied to graduate retention rates even for private school graduates and can be linked to specific robotics firms, then an additional retention performance metric can be devised.

- **Gauging Effectiveness of Growth Strategies:** The success of cluster growth strategies can be roughly determined by the growth in the number of employees at both small and large established robotics companies, as well as the revenue they generate.

9.2.5. Phase 5: Report and Evaluation

Cluster assessment reports are made available to policy makers on a regular basis.

Concise cluster performance assessment reports are made available to policy makers, and possibly others, on a regular basis, highlighting pertinent indices and trends. In light of this information, existing cluster acceleration measures are evaluated and adjusted as necessary. New recommendations can also be put forth.

9.2.6. Phase 6: Iterate the Process

The final stage of the overall implementation methodology is to iterate through all the stages beginning with Phase 2.

10. REFERENCES

Brun, L. 2012. "ROV/UAV Trends." Duke University Center on Globalization, Governance, and Competitiveness (CGGC). Available: www.cggc.duke.edu/pdfs/2012-09-01_Brun_ROV_AUVtrends_MarineTechnologyReporter.pdf.

Butter, M., A. Rensma, J. van Boxsel, S. Kalisingh, M. Schoone, M. Leis, G. J. Gelderblom, G. Cremers, M. de Wilt, W. Kortekaas, A. Thielmann, K. Cuhls, A. Sachinopoulou, and I. Korhonen. 2008. "Robotics for Healthcare." Available: ec.europa.eu/newsroom/dae/document.cfm?doc_id=2935.

Crafts, N. F. R. 2004. "Steam as a General Purpose Technology: A Growth Accounting Perspective." *Economic Journal* 114: 338–51.

Davis, C. H., D. Arthurs, E. Cassidy, and D. Wolfe. 2006. "What Indicators for Cluster Policies in the 21st Century?" Organization for Economic Co-operation and Development (OECD). Available: www.oecd.org/sti/inno/37443546.pdf.

Dempwolf, C. S., J. Auer, and M. D'Ippolito. 2014. "Innovation Accelerators: Defining Characteristics among Startup Assistance Organizations." Small Business Administration, Office of Advocacy. Available: www.sba.gov/sites/default/files/rs425-Innovation-Accelerators-Report-FINAL.pdf.

Florida, R., and K. M. King. 2015. "Rise of the Global Startup City." Available: http://martinprosperity.org/media/Rise-of-the-Global-Startup-City.pdf.

Gettinger, D. 2016. "Drone Spending in the Fiscal Year 2017 Defense Budget." Bard College Center for the Study of the Drones. Available: http://dronecenter.bard.edu/files/2016/02/DroneSpendingFy17_CSD_1-1.pdf.

Graetz, G., and G. Michaels. 2015. "Robots at Work." Centre for Economic Performance, Discussion Paper No. 1335. Available: http://cep.lse.ac.uk/pubs/download/dp1335.pdf.

Haltiwanger, J., R. S. Jarmin, and J. Miranda. 2013. "Who Creates Jobs? Small versus Large versus Young." *Review of Economics and Statistics* XCV. Available: www.mitpressjournals.org/doi/pdf/10.1162/REST_a_00288.

Heinemann, F. 2015. "Corporate Accelerators: A Study on Prevalence, Sponsorship, and Strategy." Available: www.florianheinemann.com/assets/ThesisFlorianHeinemannCorporateAccelerators.pdf.

International Federation of Robotics. 2015-1. "World Robotics 2015: Industrial Robots."

International Federation of Robotics. 2015-2. "World Robotics 2015: Service Robots."

Kane, T. 2010. "The Importance of Startups in Job Creation and Job Destruction." Available: www.kauffman.org/~/media/kauffman_org/research reports and covers/2010/07/firm_formation_importance_of_startups.pdf.

Kara, D. 2015. "Small Unmanned Aerial Systems (sUAS) Solutions Ecosystem." ABI Research. PT-1340. Available: www.abiresearch.com/market-research/product/1021128-small-unmanned-aerial-systems-suas-solutio/.

Massachusetts Technology Leadership Council. 2012. "The Massachusetts Robotics Revolution." Available: http://c.ymcdn.com/sites/www.masstlc.org/resource/resmgr/annual_reports/masstlc_robotics_final_web.pdf.

Mell, P., and T. Grance. 2011. "The NIST Definition of Cloud Computing." NIST Special Publication 800-145. Available: http://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-145.pdf.

Quigley, M., B. Gerkey, K. Conley, J. Faust, T. Foote, J. Leibs, E. Berger, R. Wheeler, and A. Y. Ng. 2009. "ROS: An Open-Source Robot Operating System." ***Proceedings of Open-source Software Workshop of the International Conference on Robotics and Automation (ICRA)***.

UMass Donahue Institute. 2015. "An Economic Contribution Analysis and Overview of Massachusetts Military Installations." Available: www.massdevelopment.com/assets/pdfs/annual-reports/Military_Installation_Report_Final.pdf.

UNCTAD. 2015. "Information Economy Report 2015: Unlocking the Potential of E-commerce for Developing Countries." Available: http://unctad.org/en/PublicationsLibrary/ier2015_en.pdf.

U.S. Department of Defense. 2013. "Unmanned Systems Integrated Roadmap FY2013-2038." Available: http://archive.defense.gov/pubs/DOD-USRM-2013.pdf.

Office of the Under Secretary of Defense. 2015. "United States Department of Defense Fiscal Year 2016 Budget Request." Available: comptroller.defense.gov/Portals/45/Documents/defbudget/fy2016/FY2016_Budget_Request_Overview_Book.pdf.

Office of the Under Secretary of Defense. 2016-1. "Program Acquisition Cost by Weapon System: United States Department of Defense Fiscal Year 2017 Budget Request." Available: comptroller.defense.gov/Portals/45/Documents/defbudget/fy2017/FY2017_Weapons.pdf.

U.S. Department of Defense. 2016-1. "Research, Development, Test & Evaluation, Army: U.S. Department of Defense Fiscal Year (FY) 2017 President's Budget Submission." Available: asafm.army.mil/Documents/OfficeDocuments/Budget/budgetmaterials/fy17/rforms//vol1.pdf.

11. APPENDIX A: LIST OF FIGURES

Figure 1: Robotics Sector Taxonomy by Funding Source and Supported Markets and Industries 14

Figure 2: Annual Worldwide Installations of Industrial Robots 16

Figure 3: Drivers for Industrial Robotics Growth 17

Figure 4: Collaborative Robots, Total Worldwide Revenue by Year 18

Figure 5: Annual Worldwide Installations of Professional Service Robots 20

Figure 6: The Healthcare Robotics Sector 21

Figure 7: Aging Populations in the United States 22

Figure 8: Projected U.S. DoD Unmanned Systems Funding 27

Figure 9: Total Worldwide Commercial sUAS Ecosystem Annual Revenue 33

Figure 10: Automating Manufacturing, Warehousing, and Distribution Center Logistics Operations 35

Figure 11: U.S. Retail E-commerce Sales as a Percent of Total Quarterly Retail Sales 36

Figure 12: Worldwide Consumer Robotics Product Shipments and Revenue 39

Figure 13: Robotic Vacuums/Floor Cleaners, Worldwide Revenue 40

Figure 14: UUV Worldwide Revenue, 2015 to 2020 45

Figure 15: Global ADAS Market, 2016 to 2026 49

Figure 16: NHTSA Vehicle Automation Levels 50

Figure 17: IoT Connected Objects 52

Figure 18: Commercial Robots Supporting ROS 55

Figure 19: Massachusetts Cluster Member Companies by Primary Sectors and Industries 58

Figure 20: Massachusetts Cluster Member Companies by Primary Classes of Technology, Products, and Services 59

Figure 21: Massachusetts Robotics Cluster Business Formation 60

Figure 22: Robotics Engineers Average Yearly Salaries, Massachusetts versus United States 61

Figure 23: Worldwide VC and Private Sector Robotics Investment 63

Figure 24: 2015 VC and Private Sector Robotics Investment by Country and Sector 64

Figure 25: 2015 Global Robotics Investments by Target Industries and Technologies/Products/Services 65

Figure 26: 2015 VC and Private Sector Robotics Investment, Global and United States 66

Figure 27: 2015 VC and Private Equity Investment by Sector, Global and Massachusetts 66

Figure 28: 2015 VC and Private Equity Investment by Target Industry, Global and Massachusetts 67

Figure 29: General Characteristics of Accelerators and Incubators 68

Figure 30: Recommended Cluster Performance Indicators 86

Figure 31: The Implementation Methodology 87

12. APPENDIX B: LIST OF TABLES

Table 1: The Massachusetts Robotics Cluster at a Glance 5
Table 2: Features of Robots and Robotics Technology 9
Table 3: Representative Massachusetts Industrial Robotics Companies 18
Table 4: Representative Massachusetts Healthcare Robotics Companies 25
Table 5: Representative Massachusetts Defense Robotics Companies 30
Table 6: Representative Massachusetts Field Robotics Companies 33
Table 7: Representative Massachusetts Logistics Robotics Companies 36
Table 8: Representative Massachusetts Consumer Robotics Companies 38
Table 9: Representative Massachusetts Education and Research Robotics Companies 42
Table 10: Representative Massachusetts Unmanned Underwater Vehicles Companies 44
Table 11: Representative Massachusetts Advanced Manipulation Companies 48
Table 12: Representative Massachusetts Automated and Autonomous Vehicle Companies 51
Table 13: Target Industries for Robotics Technologies/Products/Services Investments 64
Table 14: Representative Massachusetts Universities 71
Table 15: Prioritized Recommendations to Accelerate Cluster Development and Increase Impact 88

13. APPENDIX C: RESEARCH LABORATORIES

13.1. MASSACHUSETTS UNIVERSITY RESEARCH LABORATORIES

Boston University (Boston, MA)

- Andersson Lab
  www.bu.edu/anderssonlab
- Human Adaptation Laboratory
  http://sites.bu.edu/movement
- Hybrid & Networked Systems Group
  http://sites.bu.edu/hyness
- Multi-robot Systems Lab
  http://sites.bu.edu/msl

Brandeis University (Waltham, MA)

- Ashton Graybiel Spatial Orientation Laboratory
  www.brandeis.edu/graybiel/index.html

Harvard University (Cambridge, MA)

- Harvard Biorobotics Lab
  http://biorobotics.harvard.edu
- Harvard Microrobotics Laboratory
  http://micro.seas.harvard.edu
- Harvard Robotics Laboratory
  http://hrl.harvard.edu
- Pediatric Cardiac Bioengineering Lab
  http://robotics.tch.harvard.edu/main/index.php
- Wyss Institute
  http://wyss.harvard.edu

Massachusetts Institute of Technology (Cambridge, MA)

- AUV Laboratory at MIT Sea Grant
  http://auvlab.mit.edu
- Biomimetic Robotics Lab
  http://biomimetics.mit.edu
- Distributed Robotics Laboratory (CSAIL)
  http://groups.csail.mit.edu/drl/wiki/index.php?title=Main_Page
- Field and Space Robotics Laboratory
  http://robots.mit.edu/index.htm
- Hatsopoulos Microfluids Laboratory
  http://web.mit.edu/hml/HML.html
- Interactive Robotics Group (CSAIL)
  http://interactive.mit.edu
- Learning & Intelligent Systems Group (CSAIL)

http://lis.csail.mit.edu/new/research.php
- Model-based Embedded and Robotic Systems Group (CSAIL)
  http://groups.csail.mit.edu/mers
- Multimodal Understanding Group (CSAIL)
  https://groups.csail.mit.edu/mug
- Nonlinear Systems Laboratory
  http://web.mit.edu/nsl/www
- Personal Robots Group (Media Lab)
  www.media.mit.edu/research/groups/personal-robots
- Robot Locomotion Group (CSAIL)
  http://groups.csail.mit.edu/locomotion
- Robotic Mobility Group
  http://web.mit.edu/mobility

Northeastern University (Boston, MA)
- Robotics and Intelligent Vehicles Research Laboratory (RIVeR Lab)
  http://robot.neu.edu/research

Tufts University (Medford, MA)
- Automated Systems and Robotics (ASAR) Lab
  https://sites.google.com/a/tufts.edu/asar
- Developmental Technologies Research Group
  http://ase.tufts.edu/devtech
- Human Robot Interaction Laboratory
  http://hrilab.tufts.edu
- Neuromechanics and Biomimetic Devices Lab (BDL)
  http://ase.tufts.edu/biology/labs/trimmer

University of Massachusetts, Amherst
- Laboratory for Perceptual Robotics
  www-robotics.cs.umass.edu
- Mechatronics and Robotics Research Laboratory
  www.ecs.umass.edu/mie/mrrl
- Process Automation Lab
  http://mie.umass.edu/process-automation-lab

University of Massachusetts, Dartmouth (North Dartmouth, MA)
- Ocean Observation Laboratory (OCEANOL)
  www.smast.umassd.edu/OCEANOL

University of Massachusetts, Lowell (Lowell, MA)
- Robotics Lab
  http://robotics.cs.uml.edu

Worcester Polytechnic Institute (Worcester, MA)
- Automation and Interventional Medicine (AIM) Laboratory
  http://aimlab.wpi.edu
- Autonomous Robotic Collaboration (ARC) Lab
  http://arc.wpi.edu
- Popovic Labs
  http://users.wpi.edu/~mpopovic/index.html
- Soft Robotics Lab
  http://softrobotics.wpi.edu
- Stinger Labs: Eclectic Robotics & Automation
  http://stinger.wpi.edu

13.2. NEW ENGLAND UNIVERSITY LABORATORIES/WORKING GROUPS

Brown University (Providence, RI)

- Center for Vision Research
  http://cvr.brown.edu/aboutcvr.html
- Humans to Robots Laboratory
  http://h2r.cs.brown.edu

University of Connecticut (Storrs, CT)

- Advanced Laboratory for Automation, Robotics, and Manufacturing (ALARM)
  www.engr.uconn.edu/alarm

University of Rhode Island (Kingston, RI)

- Robotics Laboratory for Complex Underwater Environments (R CUE)
  http://wiki.egr.uri.edu/mediawiki/index.php/R_CUE

Yale University (New Haven, CT)

- Grab Lab
  www.eng.yale.edu/grablab

14. APPENDIX D: WAGES FOR ROBOTICS ENGINEERS

14.1. ELECTRICAL ENGINEERS*

Massachusetts and United States	Annual Mean Wage	Versus Mass Robotics Cluster	Versus U.S.
Massachusetts	US$103,660	-0.2%	8.2%
United States	US$95,780	-7.8%	N/A
Mass Robotics Cluster Areas	**Annual Mean Wage**		**Versus U.S.**
Boston-Cambridge-Quincy	US$104,480		9.1%
Barnstable Town	US$85,960		-10.3%
Brockton-Bridgewater-Easton	US$97,790		2.1%
Framingham	US$109,560		14.4%
Haverhill-North Andover-Amesbury	US$88,470		-7.6%
Lawrence-Methuen-Salem	US$93,380		-2.5%
Lowell-Billerica-Chelmsford	US$102,560		7.1%
New Bedford	US$106,200		10.9%
Peabody	US$96,570		0.8%
Taunton-Norton-Raynham	US$105,720		10.4%
Worcester	US$94,420		-1.4%
	Weighted Mean = US$103,827		
Top Paying U.S. States	**Annual Mean Wage**	**Versus Massachusetts**	**Versus U.S.**
California	US$114,730	10.7%	19.8%
Alaska	US$111,540	7.6%	16.5%
Massachusetts	US$103,660	0.0%	8.2%
District of Columbia	US$103,260	-0.4%	7.8%
Washington	US$102,750	-0.9%	7.3%
Top U.S. Metropolitan Area	**Annual Mean Wage**	**Versus Mass Robotics Cluster**	**Versus U.S.**
San Jose-Sunnyvale-Santa Clara	US$128,220	23.5%	33.9%
Fresno	US$117,880	13.5%	23.1%
San Francisco-San Mateo-Redwood City	US$117,620	13.3%	22.8%
Stockton	US$117,140	12.8%	22.3%
Wilmington, NC	US$116,300	12.0%	21.4%

(Source: U.S. Department of Labor, Bureau of Labor Statistics)*

14.2. MECHANICAL ENGINEERS*

Massachusetts and United States	Annual Mean Wage	Versus Mass Robotics Cluster	Versus U.S.
Massachusetts	US$103,660	11.3%	19.0%
United States	US$87,140	-6.4%	N/A
Mass Robotics Cluster Areas	**Annual Mean Wage**		**Versus U.S.**
Boston-Cambridge-Quincy	US$93,510		7.3%
Barnstable Town	US$85,010		-2.4%
Brockton-Bridgewater-Easton	US$87,340		0.2%
Framingham	US$96,780		11.1%
Haverhill-North Andover-Amesbury	US$88,790		1.9%
Lawrence-Methuen-Salem	US$87,070		-0.1%
Leominster-Fitchburg-Gardner	US$81,590		-6.4%
Lowell-Billerica-Chelmsford	US$93,710		7.5%
New Bedford	US$83,180		-4.5%
Peabody	US$102,360		17.5%
Taunton-Norton-Raynham	US$116,780		34.0%
Worcester	US$78,760		-9.6%
	Weighted Mean = US$93,137		
Top Paying U.S. States	**Annual Mean Wage**	**Versus Massachusetts**	**Versus U.S.**
Alaska	US$123,660	19.3%	41.9%
New Mexico	US$100,970	-2.6%	15.9%
California	US$99,360	-4.1%	14.0%
Texas	US$99,080	-4.4%	13.7%
Louisiana	US$98,390	-5.1%	12.9%
Top U.S. Metropolitan Area	**Annual Mean Wage**	**Versus Mass Robotics Cluster**	**Versus U.S.**
Anchorage	US$125,260	34.5%	43.7%
Taunton-Norton-Raynham	US$116,780	25.4%	34.0%
San Jose-Sunnyvale-Santa Clara	US$111,720	20.0%	28.2%
Washington-Arlington-Alexandria	US$110,060	18.2%	26.3%
Boulder	US$109,920	18.0%	26.1%

(Source: U.S. Department of Labor, Bureau of Labor Statistics)*

14.3. SOFTWARE DEVELOPERS, SYSTEMS SOFTWARE*

Massachusetts and United States	Annual Mean Wage	Versus Mass Robotics Cluster	Versus U.S.
Massachusetts	US$114,350	-1.7%	7.8%
United States	US$106,050	-8.8%	N/A
Mass Robotics Cluster Areas	**Annual Mean Wage**		**Versus U.S.**
Boston-Cambridge-Quincy	US$116,270		9.6%
Brockton-Bridgewater-Easton	US$109,450		3.2%
Framingham	US$111,240		4.9%
Haverhill-North Andover-Amesbury	US$107,780		1.6%
Lawrence-Methuen-Salem	US$94,070		-11.3%
Lowell-Billerica-Chelmsford	US$117,930		11.2%
Peabody	US$95,460		-10.0%
Taunton-Norton-Raynham	US$114,060		7.6%
Worcester	US$111,670		5.3%
	Weighted Mean = US$116,270		
Top Paying U.S. States	**Annual Mean Wage**	**Versus Massachusetts**	**Versus U.S.**
California	US$124,070	8.5%	17.0%
Massachusetts	US$114,350	0.0%	7.8%
New Jersey	US$113,620	-0.6%	7.1%
Washington	US$113,610	-0.6%	7.1%
Vermont	US$113,610	-0.6%	7.1%
Top Paying U.S. Metropolitan Areas	**Annual Mean Wage**	**Versus Mass Robotics Cluster**	**Versus U.S.**
San Jose-Sunnyvale-Santa Clara	US$138,410	19.0%	30.5%
Oakland-Fremont-Hayward	US$124,220	6.8%	17.1%
Baltimore-Towson	US$123,860	6.5%	16.8%
Los Angeles-Long Beach-Glendale	US$120,690	3.8%	13.8%
San Francisco-San Mateo-Redwood City	US$120,400	3.6%	13.5%

(Source: U.S. Department of Labor, Bureau of Labor Statistics)*

14.4. SOFTWARE DEVELOPERS, APPLICATIONS*

Massachusetts and United States	Annual Mean Wage	Versus Mass Robotics Cluster	Versus U.S.
Massachusetts	US$109,670	-0.8%	10.2%
United States	US$99,530	-10.0%	N/A
Mass Robotics Cluster Areas	**Annual Mean Wage**		**Versus U.S.**
Boston-Cambridge-Quincy	US$112,630		13.2%
Brockton-Bridgewater-Easton	US$88,880		-10.7%
Framingham	US$100,610		1.1%
Haverhill-North Andover-Amesbury	US$100,900		1.4%
Lawrence-Methuen-Salem	US$108,090		8.6%
Lowell-Billerica-Chelmsford	US$109,230		9.7%
Peabody	US$83,790		-15.8%
Taunton-Norton-Raynham	US$99,230		-0.3%
Worcester	US$104,600		5.1%
	Weighted Mean = US$110,562		
Top Paying U.S. States	**Annual Mean Wage**	**Versus Massachusetts**	**Versus U.S.**
California	US$119,970	9.4%	20.5%
Washington	US$115,370	5.2%	15.9%
Massachusetts	US$109,670	0.0%	10.2%
Maryland	US$108,300	-1.2%	8.8%
New York	US$107,020	-2.4%	7.5%
Top Paying U.S. Metropolitan Areas	**Annual Mean Wage**	**Versus Mass Robotics Cluster**	**Versus U.S.**
San Jose-Sunnyvale-Santa Clara	US$142,370	28.8%	43.0%
Oakland-Fremont-Hayward	US$121,200	9.6%	21.8%
San Francisco-San Mateo-Redwood City	US$117,610	6.4%	18.2%
Seattle-Bellevue-Everett	US$117,460	6.2%	18.0%
Baltimore-Towson	US$114,350	3.4%	14.9%

(Source: U.S. Department of Labor, Bureau of Labor Statistics)*

14.5. COMPUTER HARDWARE ENGINEERS*

Massachusetts and United States	Annual Mean Wage	versus Mass Robotics Cluster	Versus U.S.
Massachusetts	US$115,620	-0.6%	4.5%
United States	US$110,650	-4.8%	0.0%
Mass Robotics Cluster Areas	**Annual Mean Wage**		**Versus U.S.**
Boston-Cambridge-Quincy	US$115,660		4.5%
Framingham	US$114,740		3.7%
Lawrence-Methuen-Salem	US$105,750		-4.4%
Lowell-Billerica-Chelmsford	US$124,290		12.3%
Worcester	US$125,540		13.5%
Weighted Mean = US$116,283			
Top Paying U.S. States	**Annual Mean Wage**	**versus Massachusetts**	**Versus U.S.**
California	US$123,270	6.6%	11.4%
Maryland	US$117,730	1.8%	6.4%
Virginia	US$116,240	0.5%	5.1%
Massachusetts	US$115,620	0.0%	4.5%
District of Columbia	US$113,940	-1.5%	3.0%
Top Paying U.S. Metropolitan Areas	**Annual Mean Wage**	**versus Mass Robotics Cluster**	**Versus U.S.**
San Jose-Sunnyvale-Santa Clara	US$136,220	17.1%	23.1%
San Francisco-San Mateo-Redwood City	US$130,470	12.2%	17.9%
Worcester	US$125,540	8.0%	13.5%
Lowell-Billerica-Chelmsford	US$124,290	6.9%	12.3%
Baltimore-Towson	US$123,020	5.8%	11.2%

** Source: U.S. Department of Labor, Bureau of Labor Statistics*

15. APPENDIX E: COMPANY DESCRIPTORS

Sector	Industries	Technology/Products/Services	
		INDUSTRIAL/PROFESSIONAL/RES-ED	
Defense	Public – Defense		Articulated Robots
Civil	Public – Security		SCARA Robots
Research	Public – Public Safety		Parallel Robots/Delta Robots
Education	Public – Emergency Response		Linear Robots
Industrial	Public – Resource Management		Collaborative Robots
Commercial	Public – Other		
Consumer			Indoor Mobile Platforms
	Res-Ed – K-12 Education		Outdoor Mobile Platforms
	Res-Ed – College/University		Indoor Mobile Manipulation Platforms
	Res-Ed – Vocational Training		Outdoor Mobile Manipulation Platforms
	Res-Ed – Research		Automated Guide Vehicles (AGVs, Tugs, Carts)
	Res-Ed – Exploration		Autonomous Forklifts (Forklift AGVs)
	Res-Ed – Other		Autonomous Transportation Systems (Auto, Truck, Monorail, etc.)
	Industrial – Discrete Manufacturing		Micro Arial Vehicles (Drones)
	Industrial – Process Manufacturing		Small Unmanned Aerial Vehicles (Drones)
	Industrial – Construction/Demolition		Medium Unmanned Aerial Vehicles (Drones)
	Industrial – Oil and Gas		Large Unmanned Aerial Vehicles (Drones)
	Industrial – Mining and Quarrying		Unmanned Underwater Vehicles
	Industrial – Agriculture		Unmanned Surface Vehicles
	Industrial – Other		
			Micro/Nano
	Commercial – Healthcare and QoL		Laboratory/Cleanroom
	Commercial – Utilities		Surgical/Interventional Systems
	Commercial – Transportation		Prosthetic/Orthotic Systems
	Commercial – Warehouse/Distribution		Rehabilitation/Therapeutic Systems
	Commercial – Wholesale		Lifestyle Enhancement
	Commercial – Retail		
	Commercial – Other		Guide/Informational/Greeting
			Marketing/Sales
	Consumer – Home/Lawn/Pool		Humanoids
	Consumer – Toy and Hobby		Soft Robotics
	Consumer – Home Healthcare/QoL		Mobile/Fixed Telepresence
	Consumer – Social/Entertainment		Exoskeletons
	Consumer – Personal Transport		
	Consumer – Other		Other Industrial
			Other Commercial
			Other Education/Research

		CONSUMER	
			Consumer – Home Care/Lawn Care/Pool Care
			Consumer – Robotic Toys
			Consumer – Hobbyist/Toy Drones
			Consumer – Hobby Robots/Hobby Kits
			Consumer – Educational/Kits
			Consumer – Social/Entertainment Robots
			Consumer – Home Healthcare/QoL
			Consumer – Other
		ENABLING TECHNOLOGY	
			Tech – Actuators/Motors/Servos
			Tech – Arms/Manipulators
			Tech – Batteries/Power Supplies
			Tech – Controllers
			Tech – Development Tools/SDKs/Libraries
			Tech – Electronics
			Tech – End Effectors (Grippers)
			Tech – End Effectors (Tools)
			Tech – Human Robot Interaction (HRI)/Haptics
			Tech – Materials
			Tech – Microcontrollers/Microprocessors/SoC
			Tech – Networking/Connectivity
			Tech – Other
			Tech – Parts and Supplies
			Tech – Screens/Monitors
			Tech – Sensors/Sensing Systems
			Tech – Software
			Tech – Tools and Machinery
			Tech – Video/Vision/Imaging
			Tech – Wheels/Casters
		SERVICES	
			Services – System Integration/Programming
			Services – Operator Services: UAVs (Drones)
			Services – Operator Services: UUVs
			Services – Operator Services: USVs
			Services – Distributors/Wholesalers
			Services – Consulting/Engineering
			Services – Legal
			Services – Design Services
			Services – Sales/Marketing/Public Relations
			Services – Data Acquisition/Processing/Management
			Services – Research/Consulting
			Services – Media/Events
			Services – Other

16. APPENDIX F: PRIORITIZED RECOMMENDATIONS

Table 15: Prioritized Recommendations to Accelerate Cluster Development and Increase Impact

Recommendation	Priority
Launch Strategies	
Develop a STEM-E Workforce	3
Monitor Accelerator and Incubator Activity	3
Offer Low-cost Loans	2
Procure Pre-commercial Technologies	1
Attraction Strategies	
Professionally Brand/Market the Cluster	3
Employ Incentives	2
Retention Strategies	
Expand Internship Programs	3
Launch Co-op Program	3
Growth Strategies	
Support Testing Centers	3
Increase Local Demand	3
Increase Cluster Cooperation	2
Support Strategic or Nascent Markets	3
Leverage Existing Experience and Expertise	2
1 = Low Priority, 3 = High Priority	

17. APPENDIX G: ACRONYMS USED IN THIS REPORT

3D	Three Dimensional
3PL	Third-party Logistics
ADAS	Advanced Driver Assistance System
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
ALS	Amyotrophic Lateral Sclerosis
ATE	Automated Test Equipment
AUV	Autonomous Underwater Vehicle
AUVSI	Association for Unmanned Vehicle Systems International
BLS	U.S. Bureau of Labor Statistics
CAGR	Compound Annual Growth Rate
CBO	Congressional Budget Office
CNC	Computer Numeric Control
CSAIL	Computer Science and Artificial Intelligence Laboratory
DARPA	Defense Advanced Research Projects Agency
DHHS	U.S. Department of Health and Human Services
DoD	Department of Defense (U.S.)
DOF	Degrees of Freedom
EMG	Electromyography
EOA	End-of-arm
EOD	Explosive Ordnance Disposal
FAA	Federal Aviation Administration
FY	Fiscal Year
GDP	Gross Domestic Product
HOV	Human Occupied Vehicle
HW	Hardware
IED	Improvised Explosive Device
IFR	International Federation of Robotics
IoT	Internet of Things
IP	Internet Protocol
IPO	Initial Public Offering
ISO	International Organization for Standardization

ISR	Intelligence, Surveillance, and Reconnaissance
JBCC	Joint Base Cape Cod
MA UASTC	Massachusetts Unmanned Aircraft Systems Test Center
MassTLC	Mass Technology Leadership Council
MIT	Massachusetts Institute of Technology
MOU	Memorandum of Understanding
MS	Multiple Sclerosis
MTLC	Massachusetts Technology Leadership Council
NAICS	North American Industry Classification System
NAS	National Airspace
NASA	National Aeronautics and Space Administration
NERVE	New England Robotics Validation and Experimentation Center
NGO	Non-governmental Organization
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSEC	National Security Engineering Center
NSF	National Science Foundation
NUAIR	Northeast UAS Airspace Integration Research
NVCA	National Venture Capital Association
OEM	Original Equipment Manufacturer
PC	Personal Computer
QoL	Quality of Life
R&D	Research and Development
RAIS	Robotic, Autonomous, and Intelligent Systems
RDT&E	Research, Development, Test, and Evaluation
REMUS	Remote Environmental Monitoring Unit System
RIA	Robotics Industries Association
ROI	Return on Investment
ROS	Robot Operating System
ROV	Remotely Operated Vehicle
SBIR	Small Business Innovation Research (grant)
SCARA	Selective Compliance Assembly Robot Arm
SDK	Software Development Kit
SoC	System-on-a-chip
STEM	Science, Technology, Engineering, and Mathematics
STTR	Small Business Technology Transfer Research (grant)
sUAV	Small Unmanned Aerial Vehicle

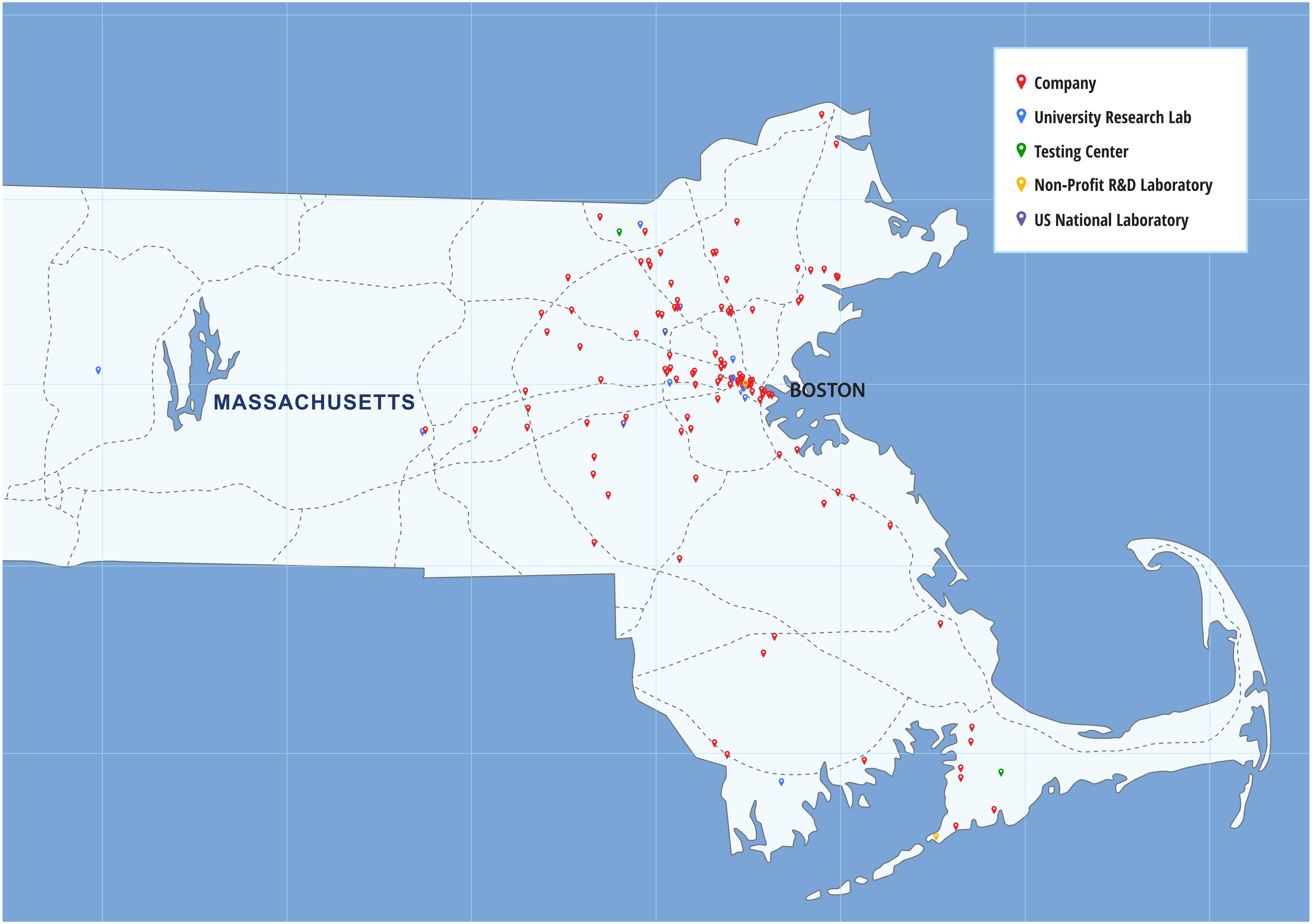
sUGV	Small Unmanned Ground Vehicle
SW	Software
TRI	Toyota Research Institute
UAS	Unmanned Aerial System
UGS	Unmanned Ground System
UGV	Unmanned Ground Vehicle
UMS	Unmanned Maritime System
UNCTAD	United Nations Conference on Trade and Development
UUS	Unmanned Underwater System
UUV	Unmanned Underwater Vehicle
VC	Venture Capital
WHOI	Woods Hole Oceanographic Institution
WPI	Worcester Polytechnic Institute

18. APPENDIX H: MASSACHUSETTS ROBOTICS CLUSTER COMPANIES

Company Name	City	Web Site
Advanced Control System Corporation	Pembroke	www.acsmotion.com
AirVentions	Boston	www.airventions.com
AblaCor Medical Corporation	Needham	www.ablacor.com
Aldebaran Robotics	Boston	www.aldebaran-robotics.com
Amazon Robotics	North Reading	www.amazonrobotics.com
Andrew Alliance	Boston	www.andrewalliance.com
AndrosRobotics	Cambridge	www.androsrobotics.com
Aquabotix Technology	Fall River	www.aquabotix.com
Artaic	Boston	www.artaic.com
Ascend Robotics	Cambridge	www.ascendrobotics.com
AutoGen	Hollisten	www.autogen.com
Autonomous Marine Systems	Somerville	www.automarinesys.com
Axis New England	Danvers	www.axisne.com
Barrett Technology	Newton	www.barrett.com
Bigbelly	Needham	www.bigbelly.com
BionX Medical Technologies (BiOM, iWalk)	Bedford	www.iwalk.com
BitFlow	Woburn	www.bitflow.com
Black-I Robotics	Tyngsboro	www.blackirobotics.com
Bluefin Robotics	Quincy	www.bluefinrobotics.com
Boston Dynamics (Google)	Waltham	www.bostondynamics.com
Boston Engineering Corporation	Waltham	www.boston-engineering.com
Bounce Imaging	Boston	www.bounceimaging.com
Brooks Automation	Chelmsford	www.brooks.com
C2 Innovations	Stow	www.c2enterprise.com
Celera Motion	Bedford	www.celeramotion.com
Charles River Analytics	Cambridge	www.cra.com
Cognex	Natick	www.cognex.com
Corindus Vascular Robotics	Waltham	www.corindus.com
Custom Systems and Controls	Framingham	www.custom-sys.com
CyPhy Works	Danvers	www.cyphyworks.com
Dangel Robotics & Machinery	Bedford	www.dangelrobots.com
Deep Sea Systems International	Falmouth	www.deepseasystems.com
Digilab	Hollisten	www.digilabglobal.com
Dinkum Software	Falmouth	www.dinkumsoftware.com
Dolan-Jenner Industries	Boxborough	www.dolan-jenner.com
Electromechanica	Mattapoisett	www.electromechanica.com
Empire Robotics	Boston	http://empirerobotics.com
enAero Technologies	North Andover	www.enaero.com

Endeavor Robotics	Bedford	www.endeavorrobotics.com
Energid Technologies	Cambridge	www.energid.com
Falmouth Scientific	Cataumet	www.falmouth.com
Franklin Robotics	Lowell	www.franklinrobotics.com
Gears Educational Systems	Hanover	www.gearseds.com
Geartronics Industries	North Billerica	www.geartronics.com
Gibson Engineering	Norwood	www.gibsonengineering.com
Goddard Technologies	Beverly	www.goddardtech.com
GTC Falcon	Plymouth	www.gtcfalcon.com
Harmonic Drive	Peabody	www.harmonicdrive.net
Harvest Automation	North Billerica	www.harvestai.com
HeuristicLab	Waltham	http://dev.heuristiclab.com
HGH Infrared Systems	Cambridge	www.hgh-infrared.com
HighRes Biosolutions	Woburn	www.highresbio.com
HITEC Sensor Solutions	Littleton	www.hitecorp.com
Hocoma	Norwell	www.hocoma.com
Hstar Technologies	Cambridge	www.hstartech.com
Humatics	Cambridge	http://site.humatics.com
Hydroid (Div KONGSBERG Maritime)	Pocasset	www.hydroid.com
Hydroswarm	Boston	www.hydroswarm.com
iAutomation	Beverly	www.i-automation.com
ICONICS	Foxborough	www.iconics.com
iFixRobot	Billerica	www.ifixrobot.com
Innovent Technologies	Peabody	www.innoventtech.com
Insightfil	Boston	www.artaichealth.com
Interactive Motion Technologies	Watertown	www.interactive-motion.com
intuVision	Woburn	www.intuvisiontech.com
iRobot	Bedford	www.irobot.com
Iron Goat	Boston	www.irongoattech.com
InnovaSea	Boston	
Jibo	Boston	www.jibo.com
KinderLab Robotics	Waltham	http://kinderlabrobotics.com
KLEENLine	Newburyport	www.kleenline.com
Locus Robotics	Andover	www.locusrobotics.com
Manta Product Development	Cambridge	www.mantadesign.com
Mass Automation Corporation	Borne	www.massautomation.com
Medrobotics	Raynham	www.medrobotics.com
Mekinesis	Arlington	
Middlesex Industries	Woburn	www.midsx.com
Mini-Mole	Danvers	www.minimole.com
MRSI Systems	North Billrica	www.mrsisystems.com
Myomo	Cambridge	www.myomo.com
Neurala	Cambridge	www.neurala.com
Neuron Robotics Cooperative	Worcester	www.neuronrobotics.com
nuTonomy	Cambridge	www.nutonomy.com
OceanServer Technology	Fall River	www.ocean-server.com
Omnetics	Topsfield	www.omnetics.com
OMNIlife science	East Taunton	www.omnils.com
Oracle Engineering	Sudbury	www.asktheoracle.com

Orchid Technologies Engineering and Consulting	Maynard	www.orchid-tech.com
Owl Labs	Somerville	www.meetingowl.com
Panoptes	Cambridge	www.panoptesuav.com
Performance Motion Devices	Boxborough	www.pmdcorp.com
Persimmon Technologies	Wakefield	www.persimmontech.com
Philips Research North America	Cambridge	www.research.philips.com
Polymer Corporation	Rockland	www.polymercorporation.com
PowerHydrant	Waltham	www.powerhydrant.com
Protonex	Southborough	www.protonex.com
QinetiQ North America	Waltham	www.qinetiq-na.com
RailPod	Boston	www.rail-pod.com
Ranger Automation Systems	Shrewsbury	www.rangerautomation.com
Ras Labs	Quincy	www.raslabs.com
Raytheon	Waltham	www.raytheon.com
Rethink Robotics	Boston	www.rethinkrobotics.com
ReWalk Robotics	Marlborough	www.rewalk.com
RightHand Robotics	Somerville	www.righthandrobotics.com
Riptide Autonomous Solutions	Somerville	www.riptideas.com
Rise Robotics	Somerville	www.riserobotics.com
Robai	Cambridge	www.robai.com
Robotix USA	Cambridge	www.robotixedu.com
RPU Technology	Needham	www.rpuinc.com
RT Engineering	Franklin	www.rteng.com
Scanifly	Boston	www.scanifly.com
Scientific Systems Company	Woburn	www.ssci.com
Sea Machines Robotics	Cambridge	www.sea-machines.com
6 River Systems	Boston	www.6river.com
Soft Robotics	Concord	www.softroboticsinc.com
Symbotic	Wilmington	www.symbotic.com
Teledyne Marine Systems	North Falmouth	www.webbresearch.com
Titian Software	Westborough	www.titian.co.uk
Toyota Research Institute	Cambridge	www.tri.global
UAS Development	Holliston	www.uasdevelopment.com
Vaccon Company	Medway	www.vaccon.com
Vecna Technologies	Cambridge	www.vecna.com
Vishwa Robotics and Automation	Arlington	http://vishwarobotics.com


Company
University Research Lab
Testing Center
Non-Profit R&D Laboratory
US National Laboratory
MASSACHUSETTS
BOSTON

Geartronics Industries
100 Chelmsford Road
North Billerica, MA 01862
Category: Company

Middlesex General Industries
6 Adele Road
Woburn, MA 01801
Category: Company

Gibson Engineering
90 Broadway
Norwood, MA 02062
Category: Company

QinetiQ North America
350 2nd Ave
Waltham, MA 02451
Category: Company

Dolan-Jenner Industries Incorporated
159 Swanson Road
Boxborough, MA 01719
Category: Company

Teledyne Marine Systems
49 Edgerton Drive
North Falmouth, MA 02536
Category: Company

Digilab Genomic Solutions
84 October Hill Rd Ste 12
Hollisten, MA 01746
Category: Company

Elm Electrical
68 Union Street
Westfield, MA 01085
Category: Company

Hitec Corporation
537 Great Road
Littleton, MA 01460
Category: Company

RT Engineering Corporation
1 Kenwood Cir
Franklin, MA 02038
Category: Company

Vaccon Company
9 Industrial Park Road
Medway, MA 02053
Category: Company

Scientific Systems Company
500 W Cummings Park # 3000
Woburn, MA 01801
Category: Company

Oracle Engineering Incorporated
114 Old Lancaster Road
Sudbury, MA 01776
Category: Company

Brooks Automation
15 Elizabeth Drive
Chelmsford, MA 01824
Category: Company

Polymer Corporation
180 Pleasant Street
Rockland, MA 02370
Category: Company

Advanced Control System Corporation
35 Corporate Park Drive
Pembroke, MA 02359
Category: Company

Cognex
One Vision Drive
Natick, MA 01760
Category: Company

Deep Sea Systems International
1130 Massachusetts 28A
Falmouth, MA 02534
Category: Company

Charles River Analytics
625 Mt Auburn Street
Cambridge, MA 02138
Category: Company

MSRI
101 Billrica Avenue
North Billrica, MA 01862
Category: Company

Iconics
100 Foxboro Blvd
Foxborough, MA 02035
Category: Company

Berkshire Group LTD
184 Falcon Drive
Westfield, MA 01085
Category: Company

Dangel Robotics & Machinery
119 Great Road
Bedford, MA 01730
Category: Company

KleenLine
7 Opportunity Way
Newburyport, MA 01950
Category: Company

Falmouth Scientific
1400 Route 28A
Cataumet, MA 02534
Category: Company

Ranger Automation
820 Boston Turnpike
Shrewsbury, MA 01545
Category: Company

Barrett Technology
73 Chapel Street
Newton, MA 02458
Category: Company

iRobot
8 Crosby Drive
Bedford, MA 01730
Category: Company

Custom Systems and Controls
132 Winter Street
Framingham, MA 01702
Category: Company

Innovent Technologies
6 Centennial Drive
Peabody, MA 01960
Category: Company

Titian Software
1500 W Park Dr # 160
Westborough, MA 01581
Category: Company

Boston Dynamics (Google)
78 4th Ave
Waltham, MA 02451
Category: Company

Performance Motion Devices Incorporated
80 Central Street
Boxborough, MA 01719
Category: Company

Bitflow
400 W Cummings Park #5050
Woburn, MA 01801
Category: Company

Axis New England
6 Cherry Hill Drive
Danvers, MA 01923
Category: Company

Celera Motion
125 Middlesex Tpk.
Bedford, MA 01730
Category: Company

Boston Engineering Corporation
300 Bear Hill Road
Waltham, MA 02451
Category: Company

GTC Falcon Incorporated
118 Long Pond Road Ste E
Plymouth, MA 02360
Category: Company

MANTA Product Development
25 First St
Cambridge, MA 02141
Category: Company

Mass Automation Corporation
6 Colonel Drive
Borne, MA 02532
Category: Company

Orchid Technologies Engineering & Consulting
147 Main Street
Maynard, MA 01754
Category: Company

Autogen
84 October Hill Road
Hollisten, MA 01746
Category: Company

J+H Machine
24 Oakland Street
Amesbury, MA 01913
Category: Company

RPU Technology
173 Dedham Ave
Needham, MA 02492
Category: Company

Bluefin Robotics
553 South St.
Quincy, MA 02169
Category: Company

Dinkum Software
PO BOX 1345
Falmouth, MA 02541
Category: Company

Goddard Technologies
100 Cummings Ctr # 233G
Beverly, MA 01915
Category: Company

iAutomation
500 Cummings Center
Beverly, MA 01915
Category: Company

Interactive Motion Technologies
80 Coolidge Hill
Watertown, MA 02472
Category: Company

OMNILife Science
50 O'Connell Way
East Taunton, MA 02718
Category: Company

Vecna Technologies
36 Cambridge Park Drive
Cambridge, MA 02140
Category: Company

Protonex Technology Corporation
153 Northboro Road
Southborough, MA 01772
Category: Company

Electromechanica
13 Industrial Drive Rear
Mattapoisett, MA 02739
Category: Company

Energid Technologies
1 Miffin Place
Cambridge, MA 02138
Category: Company

Hydroid (Div KONGSBERG Maritime)
6 Benjamin Nye Cir
Pocasset, MA 02559
Category: Company

ReWalk Robotics
33 Locke Drive
Marlborough, MA 01752
Category: Company

Corindus Vascular Robotics
309 Waverly Oaks Road
Waltham, MA 02452
Category: Company

Gears Educational Systems
105 Webster Street
Hanover, MA 02339
Category: Company

Amazon Robotics
300 Riverpark Drive
North Reading, MA 01864
Category: Company

Bigbelly
150 A Street, Suite 103
Needham, MA 02494
Category: Company

Mekinesis
88 Summer Street
Arlington, MA 02474
Category: Company

Oceanserver Technology
151 Martine Street
Fall River, MA 02723
Category: Company

Ras Labs
300 Congress Street
Quincy, MA 02043
Category: Company

HighRes Biosolutions
299 Washington Street
Woburn, MA 01801
Category: Company

Myomo
1 Broadway, 14th Floor
Cambridge, MA 02142
Category: Company

Aldebaran Robotics
374 Congress St.
Boston, MA 02210
Category: Company

Black-I Robotics
141 Middlesex Road
Tyngsboro, MA 01879
Category: Company

Medrobotics
475 Paramount Drive
Raynham, MA 02767
Category: Company

Hocoma
77 Accord Park Drive
Norwell, MA 02061
Category: Company

intuVision
10 Tower Office Park #200
Woburn, MA 01801
Category: Company

Neurala
17 Sellers Street
Cambridge, MA 02139
Category: Company

Artaic
21 Drydock Ave.
Boston, MA 02210
Category: Company

BionX Medical Technologies (BiOM, iWalk)
4 Crosby Drive
Bedford, MA 02142
Category: Company

Harmonic Drive LLC
247 Lynnfield Street
Peabody, MA 01960
Category: Company

HGH Infrared
One Broadway, 14th Floor
Cambridge, MA 02142
Category: Company

Hstar Technologies
625 Mt Auburn Street
Cambridge, MA 02138
Category: Company

Symbotic
200 Research Drive
Wilmington, MA 01887
Category: Company

CyPhy Works
16 Electronics Ave
Danvers, MA 01923
Category: Company

Harvest Automation
85 Rangeway Road
North Billerica, MA 01862
Category: Company

Jaybridge Robotics
62 Whittemore Ave.
Cambridge, MA 02140
Category: Company

Neuron Robotics Cooperative
95 Prescott Street
Worcester, MA 01605
Category: Company

RailPod
371 Dorchester Ave
Boston, MA 02143
Category: Company

Rethink Robotics
27 Wormwood Street
Boston, MA 02210
Category: Company

Robai Corporation
1 Mifflin Place
Cambridge, MA 02138
Category: Company

Autonomous Marine Systems
28 Dane Street
Somerville, MA 02143
Category: Company

Vishwa Robotics and Automation
32 Orvis Road
Arlington, MA 02474
Category: Company

AirVentions
337 Summer Street
Boston, MA 02210
Category: Company

Persimmon Technologies
178 Albion Street
Wakefield, MA 01880
Category: Company

Andrew Alliance
Copley Square
Boston, MA 02116
Category: Company

Aquabotix Technology
10 N Main Street
Fall River, MA 02720
Category: Company

PowerHydrant
1560 Trapello Road
Waltham, MA 02451
Category: Company

AndrosRobotics
97 Hancock Street, Unit 1
Cambridge, MA 02139
Category: Company

Bounce Imaging
114 Western Avenue
Boston, MA 02163
Category: Company

Empire Robotics
12 Channel Street
Boston, MA 02210
Category: Company
enAero Technologies
733 Turnpike St., #141
North Andover, MA 01845
Category: Company

iFixRobot
572 Boston Road
Billerica, MA 01821
Category: Company

Jibo
230 Congress Street
Boston, MA 02111
Category: Company

Albacor Medical Corporation
60 Richard Road
Needham, MA 02492
Category: Company

Humatics
123 Albany Street
Cambridge, MA 02139
Category: Company

Rise Robotics
28 Dane Street
Somerville, MA 02143
Category: Company

Sea Machines
62 Whittemore Ave Number 8
Cambridge, MA 02140
Category: Company

Soft Robotics
140 Hawthorne Ln
Concord, MA 01742
Category: Company

KinderLab Robotics
7 Sun Street
Waltham, MA 02453
Category: Company

Owl Labs
26 Concord Ave. #2
Sommerville, MA 02143
Category: Company

Panoptes
90 Broadway
Cambridge, MA 02142
Category: Company

Right Hand Robotics
28 Dane Street
Somerville, MA 02143
Category: Company

Robotix USA
1267 Cambridge Street #2
Cambridge, MA 02139
Category: Company

Scanifly
358 Chestnut Hill Ave #301b
Boston, MA 02135
Category: Company

UAS Development
24 Water Street
Holliston, MA 01746
Category: Company

Ascend Robotics
245 First St
Cambridge, MA 02142
Category: Company

Franklin Robotics
110 Canal Street
Lowell, MA 01852
Category: Company

Heuristic Labs
1560 Trapelo Road
Waltham, MA 02451
Category: Company

Hydroswarm
21 Drydock
Boston, MA 02451
Category: Company

Insightfil
21 Drydock Ave.
Boston, MA 02210
Category: Company

Iron Goat
21 Drydock, 6th Floor
Boston, MA 02210
Category: Company

Locus Robotics
100 Burtt Road
Andover, MA 01810
Category: Company

MiniMole
11 Summer Street
Danvers, MA 01923
Category: Company

Philips Research North America
2 Canal Park, 3rd Floor
Cambridge, MA 02141
Category: Company

Riptide Autonomous Solutions
28 Dane Street
Somerville, MA 02359
Category: Company

Endeavor Robotics
8 Crosby Drive, MS 6-2
Bedford, MA 01730
Category: Company

Six River Systems
117 Beaver Street
Waltham, MA 02452
Category: Company

C2 Innovations
102 Peabody Drive
Stow, MA 01775
Category: Company

Boston University
One Silber Way
Boston, MA 02215
Category: University Research Lab

Brandeis University
415 South Street
Waltham, MA 02453
Category: University Research Lab

Harvard University
Massachusetts Hall
Cambridge, MA 02138
Category: University Research Lab

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
Category: University Research Lab

Northeastern University
360 Huntington Avenue
Boston, MA 02115
Category: University Research Lab

Tufts University
419 Boston Avenue
Medford, MA 02155
Category: University Research Lab

University of Massachusetts, Amherst
300 Massachusetts Avenue
Amherst, MA 01003
Category: University Research Lab

University of Massachusetts, Dartmouth
285 Old Westport Road
Dartmouth, MA 02747
Category: University Research Lab

University of Massachusetts, Lowell
1 University Avenue
Lowell, MA 01852
Category: University Research Lab

Worcester Polytechnic Institute
100 Institute Road
Worcester, MA 01609
Category: University Research Lab

New England Robotics Validation and
Experimentation Center
1001 Pawtucket Boulevard
Lowell, MA 01854
Category: Testing Center

Joint Base Cape Cod
158 Reilly Street
Buzzards Bay, MA 02542
Category: Testing Center

Woods Hole Oceanographic Institution
86 Water Street
Woods Hole, MA 02543
Category: Non-Profit R&D Laboratory

Draper Laboratory
555 Technology Square
Cambridge, MA 02139
Category: Non-Profit R&D Laboratory

National Security Engineering Center
202 Burlington Road
Bedford, MA 01730
Category: US National Laboratory

Lincoln Laboratories
244 Wood Street
Lexington, MA 02420
Category: US National Laboratory

U.S. Army Natick Soldier Systems Center
Kansas Street
Natick, MA 01760
Category: US National Laboratory

Published September 19, 2016

©2016 ABI Research

Post Office Box 452 • 249 South Street
Oyster Bay, New York 11771 USA
Tel: +1 516-624-2500
www.abiresearch.com