Chapter 17
On the Vertical and Horizontal Integration of Robotics Within Engineering and Computing Education

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Abstract In this paper, we discuss the state of the art of robotics education in the US, the role of partnerships with area schools, cross-disciplinary research and education in robotics at the undergraduate and graduate levels, the importance of a holistic, multi-disciplinary perspective in the recruitment of faculty who facilitate this cross-disciplinary integration, and the future of engineering and computing education in robotics. Interwoven through the paper are case studies showcasing longitudinal and vertical integration of robotics education at Mason.

Keywords Robotics · Engineering education · Workforce development

17.1 Introduction

A recent white paper by Christensen et al., states: "Robotics has the potential to magnify the skilled workforce of the nation by complementing our workforce with automation: teams of people and robots will be able to do more than either could alone. The economic engine of the U.S. runs on the productivity of our people. The rise of automation offers new opportunities to enhance the work of our citizens and drive the innovation and prosperity of our industries. Robotics research creates new options and possibilities for robotics technologies to be explored, evaluated, and transitioned. Most critically, we need research to understand how future robot technologies can best complement our workforce to get the best of both human and

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automated labor in a collaborative team. Investments made in robotics research and workforce development will lead to increased GDP, an increased export–import ratio, a growing middle class of skilled workers, and a U.S.-based supply chain that can withstand global pandemics and other disruptions. In order to make the United States a leader in robotics, we need to invest in basic research, technology development, K-16 education, and lifelong learning" [1].

It is with this backdrop that we discuss the state of the art in robotics education in the United States, for example, universities such as Georgia Tech [2], Worcester Polytechnic Institute [3], Carnegie Mellon [4], and University Michigan [5] creating PhD programs, and in the case of Michigan, an entire department for robotics. At the same time, students arrive at a University as increasingly comfortable users of robotics, whether it is an Alexa in their home ("[i]n 2022, 62% of Americans 18 + use a voice assistant on any device" [6]), a robot cleaning their floor (14% of Americans own a robot vacuum [7]), or a drone they have flown (8% of Americans own a drone, and 15% of Americans report having flown one [8]). It is also common for American college students to have participate in robotics summer camps or school clubs during their K-12 years. Furthermore, whether knowingly or not, many students are exposed to ethical concerns associated with artificial intelligence, for example through tools such as ChatGPT opening new doors to opportunistic cheating [9, 10].

Cummings et al. found that "there is a significant gap between the education and research aims of academia and what is needed in industry and government" [11]. To fill this gap and maintain international superiority in aerospace autonomy, as well as autonomy in other domains, the US needs to promote the convergence in the fields of computer science and domain-specific engineering programs, as well as safety, cybersecurity, and testing. In this paper, we address ways to fill this gap, including the vertical and horizontal integration of robotics education in the engineering and computing curriculum at George Mason University. This integration spans grade levels and disciplinary boundaries. This includes active partnerships at the K-12 level with area institutions directly leading to a pipeline of students joining robotics clubs at Mason, as well as no-cost robotics camps to reach students who may not have access to these types of programs. At the undergraduate curricular level, we interweave collaborative course offerings, capstone projects, and student competitions that develop cross-disciplinary teams of students spanning Computer Science, Electrical and Computer Engineering, Mechanical Engineering, and Systems Engineering and Operations Research. The importance of cross-disciplinary emphasis has been specifically called out by industry [11] and is attractive to students. Our focus on interdisciplinarity results in the retention of many of our best and brightest undergraduates to stay at Mason for graduate research related to robotics, again often crossing traditional disciplinary boundaries from bioengineering to cybersecurity.

Lastly, robotics education provides unique opportunities for translation of university initiatives with respect to diversity, equity, and inclusion (DEI) into pedagogy. For example, it has long been established that facial recognition algorithms can exhibit demographic biases [12, 13]. A study that looked at facial recognition algorithms developed by U.S.-based researchers versus East Asian researchers concluded that "the performance of state-of-the-art face recognition algorithms varies as a joint function of the demographic origin of the algorithm and the demographic structure of the test population" [14]. Algorithms reflect the demographics of where they originate. Self-driving cars are another oft-discussed example of robotics engineering with tremendous potential for positive impact on society. At the same time, the models these vehicles use to identify pedestrians show inequities related to their ability to detect pedestrians with darker skin tones [15–17], or individuals in wheelchairs, mobility scooters, or wearing long skirts [17]. Likewise, algorithms used to automate decision processes across diverse applications, ranging from determining how to dynamically dispatch new public transit options or who should be approved for a home loan, suggest decisions with unintended biases, possibly disproportionately affecting access and economic wellbeing. Mason is one of the most diverse schools in the nation [18], and our strong focus on DEI is included at all levels of robotics education, which leads to building the diverse teams for the robotics solutions of the future.

17.2 K-12 Outreach

17.2.1 The Recruitment Pipeline

A unique benefit to Mason's geographic location with three campuses in Northern Virginia is a dense population of students and educators in our immediate region. Mason's Prince William campus is home to a so-called "Governor's School," a partial-day program for gifted and talented STEM students in the Manassas region. Students in this program have dual enrollment opportunities at Mason for introductory math, science, and engineering courses [19]. Mason also has a unique partnership with Northern Virginia Community College to provide a seamless, dual-enrollment pathway from community college to bachelor's degree [20].

17.2.2 Collaborations with Area Schools

To effectively leverage these relationships into vertically integrated pathways, we prioritize regular dialogue with area STEM educators to ensure we are providing offerings that are both desirable to the current generation of K-12 students and build upon those students' middle and high school experiences. For example, a recent STEM outreach effort at Mason, supported by the Office of Naval Research, sought to develop a kit and standards-aligned curriculum for high-school aged learners in lighter-than-air, biologically inspired, robotics. A key component to that effort was the recruitment of focus group participants, many of whom were area educators, whose feedback was solicited to inform curricular revisions [21]. These purposeful connections to area educators contextualize the multi-disciplinary efforts we are making in robotics education at Mason, as described by the following first-person student experience.

17.2.3 Student Experience: William Denham

As a student in local area schools myself, I was able to discover a career field that I am truly passionate about through my participation in competitive robotics programs. The programs allowed me to find my passion for STEM and led me to pursue a degree in electrical and computer engineering at George Mason University. At George Mason, I was provided with the STEM professionals and company connections to form a competitive robotics team known as Scitech Robotics. This team was created for students such as myself to interact with our coursework in a way that is both interactive and fun. The Vex Robotics University Competition [22] releases a new challenge every year, where student engineers from colleges and universities across the world are challenged to compete against one another, with the best team earning the prestige and honor of being the Vex Robotics World Champion. This group has been very successful in the past few years both on the competition field and each of our members successful in the classroom as well. The program has become known as a platform for engineering excellence in everything that we do, being recognized globally for our efforts and successes. Something that would not have been possible without the STEM Mentors and Educators that we were able to learn and grow with. Now that I have neared the end of my degree completion, I have accepted a position with the local school division, Prince William County Schools as a Robotics Coach and Educator, directly inspiring and helping students find their niche in STEM. As someone who always had strong mentors and teachers to allow me to find, light up, and guide me along my path, it only felt natural to be that mentor and educator giving back to today's students.

Through K-12 STEM outreach in local area schools, I have been able to form meaningful relationships with K-12 students and provide them with exposure to STEM, through competitive robotics. I have witnessed firsthand as my students have become more confident and comfortable in mechanical design, technical documentation, and software development, as a direct result of their participation in robotics programs such as the Vex Robotics Competition. These programs are designed to be an interactive, engaging way to learn seemingly difficult technical skills in a nurturing, and safe environment. These students have been able to find a passion in the robotics field and many of them have decided to pursue a robotics-related undergraduate degree, whether in mechanical engineering, electrical engineering, or computer science. If we're able to harness the students' innate curiosity for solving problems, and critical thinking skills; we can create a talent pipeline of individuals entering the STEM workforce. In the end, attracting more students to STEM comes down to forming relationships, inspiration, and skill.

17.2.4 Camps

To further reinforce the connections between area students, educators and Mason's robotics programming, we have begun to offer robotics camps leveraging RoboNation's SeaPerch and SeaGlide kits [23] for age-appropriate curricula targeting middle school and high school aged learners respectively. These camps provide hands-on maritime robotics experiences coupled with exposure to undergraduate and graduate level research on Mason's Prince William campus, and are offered at no cost to campers, in an effort to provide this opportunity to students who may not otherwise be able to afford such experiences. For further detail, the interested reader is referred to [24].

17.3 Undergraduate Education

From the first AUVSI aerial robotics competition held at Georgia Tech in 1991 to a team of Rutgers students successfully sending an underwater glider across the Atlantic in 2009, the last three decades have seen rapid advancement in the implementation of autonomy into undergraduate education. Figures 17.1 and 17.2, reproduced from [25] and discussed further in [26] provide brief timelines highlighting key moments for academics in aerial and maritime robotics. Notably, as a young academic institution, Mason's College of Engineering and Computing was born just prior to this revolution in autonomous systems. The College of Engineering and Computing was founded in 1985 as the School of Information Technology and Engineering [27]. Some departments within the College date back to those origins, such as the Department of Electrical and Computer Engineering, whereas others are quite young, such as Mechanical Engineering which was formally established in 2015. All departments within the College have grown out of this era of autonomous systems, and in that regard, have developed curricula in which robotics and mechatronics are as foundational as fluid dynamics and circuits.

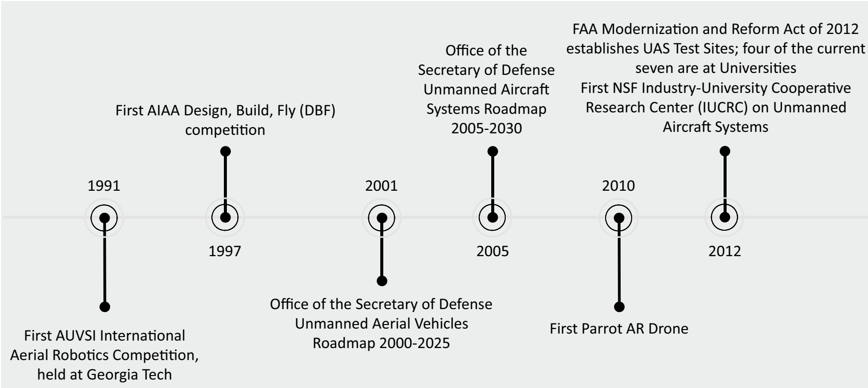

Fig. 17.1 Selected key moments in academic unmanned aerial vehicle history

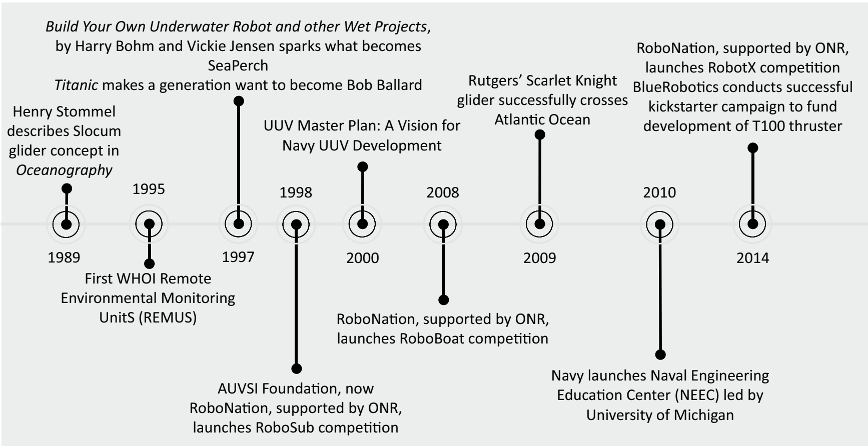

Fig. 17.2 Selected key moments in academic unmanned marine vehicle history

17.3.1 Example Curricular Revisions to Support Undergraduate Education in Robotics

The Mechanical Engineering department identified and implemented three changes that have better prepared students to practice robotics. In 2018, Mechanical Engineering worked together with Electrical and Computer Engineering to revise a two-course sequence in DC and AC circuits into a combined course, ECE 330—Circuit Theory. This gave students the background for more advanced courses in Systems Dynamics and Controls and freed up 3 credit hours to implement the second change, a required course ME 331—Mechatronics. This hands-on course focuses on sensors, microcontrollers, and actuators and is intended to be taken right before senior design commences. The final change was in the 2017 development and subsequently tweaking of ME 151—Practicum in Engineering. This replaced a more general Intro to Engineering course with one focused on algorithmic thinking and solid modelling. This required every student in the Mechanical Engineering program to use code to solve engineering problems and CAD software to create models before beginning their upper-level coursework.

17.3.2 Mechanical Design

Senior design project, also known as capstone, is a curricular requirement for the senior students in engineering programs at Mason in support of ABET's requirement for "a culminating major engineering design experience that (1) incorporates appropriate engineering standards and multiple constraints, and (2) is based on the knowledge and skills acquired in earlier course work" [28].

While Mason's Department of Mechanical Engineering was established in 2015, as early as the 2016–2017 academic year, robotics related projects were provided as capstone design opportunities for students. Robotics and mechatronics projects have included sponsor driven activities, such as developing control systems for motorcycle assistance or building robots to inspect confined spaces for corrosion, storm sewer blockage, or pipeline coating status. And similarly, multidisciplinary projects have facilitated participation in competition, be it maritime robotics focused or toward the development of novel unmanned aerial vehicles. Details on specific capstone experiences can be found in annual brochures posted online which highlight the multidisciplinary student collaborations and faculty mentorship provided for these teams [29].

As robotics at Mason continues to grow, we have found these types of corporate or competition driven culminating design experiences provide students the unique and valuable opportunity to work on multidisciplinary teams drawing from students and faculty across the College of Engineering and Computing. For those students interested in pursuing careers in robotics, this provides a unique opportunity to broaden their exposure beyond the coursework core to their primary discipline. For all participating students this emulates the work environment in which multidisciplinary perspectives are key to successful engineering design and innovation.

17.3.3 Student Experience: Emina Sinanovic

I was first introduced to robotics when I joined For Inspiration and Recognition of Science and Technology (FIRST) Robotics Team during high school in 2017. At FIRST, I joined the software team and extended my involvement to the mechanical and electrical subteams. I realized I enjoyed my experience being part of the software team. Because of this experience and my enjoyment of robotics, I decided to pursue my Bachelor's Degree in Computer Science at George Mason University (GMU). Due to my demanding coursework, I was unable to grow my interest in robotics further because of time constraints.

When I came to GMU in 2020, I found a robotics club called BOT Robotics that I was interested to be a part of. Unfortunately at the time, they did not have a software component because it was geared towards the engineering students. I was curious of other opportunities that would include a software aspect to it, and a student suggested that I reach out to Dr. Cameron Nowzari to be part of a Capstone project. My experience with the Capstone project was amazing. I enjoyed my time with my teammates quite a lot. We collaborated and brainstormed ideas to establish a functional drone and an accompanying camera. This was a lot of work, but extremely rewarding in the end. The software aspect of the team was exciting: it was my first time working with a camera, and there was a limited amount of memory afforded for both the camera and software to fly the drone. Figuring out how to work with them both and ensuring that they would not interfere with each other was challenging. I am forever grateful that I was given this opportunity to be part of this project and to be part of the team.

17.3.4 Extracurricular Activities and Undergraduate Research

The following subsections provide brief examples of characteristic extracurricular and undergraduate research opportunities for Mason students across multiple disciplines interested in Robotics.

17.3.4.1 SciTech Robotics

As referred to previously in the student experience commentary by William Denham in Sect. 16.2.3, SciTech Robotics is a student-organized robotics club formed to participate in VEX-U robotics competition. While the specific rules are updated every year, the competition usually requires students to build and program robots that can search objects in the game arena and interact with them (e.g., pick them up and throw into a goal). Such game set ups naturally lead the students to face various challenges in robotics and autonomy including mechanical design, controls, computer vision, programming etc. The competition also includes a technical report that prepares the students on scientific writing. The current team consists of about ten students across Mechanical Engineering, Electrical and Computer Engineering, and Computer Science departments complementing each other to tackle various challenges listed above. Since VEX-U provides its own set of modular components (e.g., microcontroller, sensors, and actuators) the students are able to focus their attention on the overall system design without extensive domain knowledge. This trait makes the robotics club to have low entry point and allows interested freshman and sophomore to dive into robotics research.

17.3.4.2 Patriot Pilots

Another program designed to integrate all types and levels of skills are the Patriot Pilots: a team of undergraduate and graduate students led by 3 faculty members in Electrical and Computer Engineering and Mechanical Engineering participating in a twice-a-year national Lighter-Than-Air (LTA) aerial robotics competition. The 6th event is planned to be hosted for the first time at Mason April 24–28, 2023. There will be at least 6 teams including the University of Florida, Virginia Tech, Baylor University, West Virginia University, Lehigh University, and George Mason University. Each team will have a "How-It-Works" table showing our undergraduate students how all the robots work at our student celebration day Mason Day.

17.3.5 Student Experience: Violetta Rostobaya

Multidisciplinary approach to robotics is vital for the future of engineering and computer science education. As an undergraduate mechanical engineering student, I expressed interest in control theory and system dynamics, which lead me to join a research group. Being an undergraduate member of the lab seeded the idea of choosing academia as a career pathway. Participating in reading groups along with graduate students from different fields let me learn more about their experiences with robotics and graduate education. Consistent participation and socialization only solidified my further decision to apply for a PhD program.

During my time in the lab as an undergraduate student I have also expanded my knowledge of controls, robotics and, surprisingly, game theory. Early outreach by faculty members allowed me to have an early head start in research and planning for graduate program. Being part of robotics research community also showed me robotics is not just an engineering science in its most traditional way, but as a constellation of sciences coming together to explore technology through different approaches and methods.

17.4 Graduate Education

At the graduate level, we have deliberately aimed to develop multi-disciplinary pathways for students seeking to advance their knowledge in robotics and autonomous systems, be it through bachelor-accelerated masters offerings, cross-disciplinary PhDs, or introducing students to cutting edge topics like translational AI and current research.

17.4.1 Bachelors-Accelerated Masters Programs

The College of Engineering and Computing offers 63 Accelerated Master's options. The main benefit for students is the ability to double count up to 12 credits towards both their BS and MS degrees allowing completion of both degrees in as little as 5 years. While many of these are options are for completing a Master's degree in the same field as a Bachelor's degree, some allow students to earn a Master's degree in a different discipline. Mechanical Engineering established 8 such programs as an option for students. It leverages the broad background of an ME and gives them a path to MS degrees in other robotics related fields such as Bioengineering, Electrical Engineering, and Systems Engineering.

17.4.2 Cross-Disciplinary PhDs

In addition to 'traditional' pathways to PhDs that can be autonomy or robotics intensive via the Departments of Computer Science, Electrical and Computer Engineering, or Bioengineering, Mason has also created multiple interdisciplinary pathways that graduate students may pursue. Two of note include options for Mechanical Engineering concentrations to either an Information Technology PhD or a Systems Engineering and Operations Research PhD. As described in Mason's catalog, "The Information Technology (INFT) PhD is a signature degree of the College of Engineering and Computing. The program focuses on the science, engineering, and technology of information processing, an area of study ripe for innovation in a world driven more and more by data. The PhD in INFT accommodates rigorous and cross-disciplinary PhD study that does not fit with PhD program requirements of a single VSE department" [30]. Similarly, the Mechanical Engineering concentration to the Systems Engineering and Operations Research PhD allows graduate students to pursue a degree emphasizing mechanical engineering systems, such as robotic systems.

That said, we have also begun formulating a truly multidisciplinary PhD serving the needs of learners from industry, government, or academic careers in mechatronics, robotics, or automation engineering. Foundational to the degree would be a core that ensures fundamental disciplinary knowledge in computer science, cybersecurity engineering, electrical and computer engineering, and mechanical engineering. While students would then specialize in their specific subdomain, such a program would ensure that a mechanical engineering working in prosthetics, for example, has a fundamental understanding of how to cyberharden a system to prevent malicious attacks, a computer scientist developing cybersecure software understands the physical implementation requirements of mechanical systems, or that an engineer working in construction understands the role of robotics in automation. It is this multidisciplinary perspective that we see as vital long-term to creating the graduates who will develop new autonomous systems for defense applications, design human–computer teaming solutions for the supply chains of the present and future, manage the health of large civil infrastructure, deploy autonomous systems post-disaster to support community recovery, and create robotic interventions for the medical industry.

17.4.3 Student Experience: Vanessa Barth

My experience at George Mason University started as an undergraduate student in the department of Mechanical Engineering where I was exposed to the foundations of robotics, namely computer programming, circuit theory, control theory, dynamics, and mechatronics. One of my favorite undergraduate courses was aeronautics, although not a robotics course, it was what led to my interest in unmanned and autonomous systems and desire for a future career in academia. A timely opportunity came about to stay at Mason for graduate school and conduct research in maritime robotics, with a focus on unmanned and autonomous systems, under Dr. Leigh McCue. I jumped at the chance to stay at a school I knew I would thrive at and be a part of exciting research. Recently, my work involving gaze control of an underwater remotely operated vehicle was successful during in-water demonstrations, and I am now extending my gaze control method to surface boats.

Beyond school and research, I had the opportunity to take part in the 2022 RobotX competition in Sydney, Australia with a team comprised of Mason students, alumni, and faculty advisor. This was a great experience that allowed me to use what I’ve learned in my education and research to achieve tasks using a drone. In my research, I have used serial communication to send messages from my computer to a vehicle and vice versa. I used this prior knowledge during the competition to achieve the task of using sockets to send messages to a server. In the end, although our drone crashed due to high winds, we walked away proud that we had made it into the finals for the search and rescue task. Being a part of this team proved to me once more that robotics is a blend of different disciplines and would not exist if one were missing.

17.4.4 Translational AI

While the rise of artificial intelligence (AI) across many domains has been wide and swift with many positive benefits, increasingly companies and government agencies are learning that there is often significant drawback to this technology. A major limitation to the deployment of systems with embedded AI is a lack of understanding of foundational principles in the design and development of such systems, especially in a safety–critical context. Often, agencies and companies focus on integrating AI into hardware or traditional rule-based software systems and struggle to adequately consider the strengths and weaknesses of AI and user interactions, as well as testing and policy implications. They also have difficulty in adapting their work practices to adequately consider the profound changes that embedding non-deterministic AI software have on both products and work processes, as well as workforce development.

A recent survey of companies and government agencies investing in autonomous systems ranked their top research and development areas as (1) safety, (2) cybersecurity, (3) system integration, (4) certification, and (5) human-autonomous system interaction. Unfortunately, this same survey showed that most of these topics were not important in the eyes of senior academics [11]. Thus, there is a gap in the skill sets industry needs and those courses available to students that provide them with the necessary multidisciplinary background to translate AI into actual systems that have the capacity to significantly impact human welfare.

To help fill this gap, Mason is considering development of graduate programs in translational AI, which will integrate foundational elements of AI (such as machine learning, optimization, and computer vision) in a risk-based systems framework. The goal is to develop practitioners that can leverage a first-principles approach to developing and implementing AI in real-world applications, and also understand holistically the strengths and weaknesses of such systems. Students will focus on constructing and deploying AI-based systems that are safe, trustworthy and equitable. The vision includes two tracks in engineering and public policy (including law and ethics), but these students will form cohorts so the two groups can learn from one another. The goal is to provide returning professionals with an updated skill set so that they can understand how AI-enabled systems meet requirements, the unique design and deployment constraints of such systems, and also are ready to tackle the future of work issues that AI-enabled systems raise.

17.4.5 Seminar Series

Departmental seminar series provide opportunities for cross-disciplinary idea pollination with discipline-specific application. For example, the Department of Civil, Environmental and Instructure Engineering has hosted speakers with expertise in connected and autonomous vehicles, structural health monitoring via drones, construction automation, and trusted AI systems for transit, which elucidate the role of automation, robotics and AI in supporting our infrastructure and infrastructure systems. In supplement to department-level activities, in the fall semester of 2022, Mason launched a new seminar series that invites internal and external speakers conducting research in the field of robotics and controls. The main motivation behind the initiation of this series was to provide a central place where robotics-related faculty and their students from all departments could regularly meet. The weekly seminars are contributing to the horizontal integration of robotics research in the College of Engineering and Computing. The technical talks, followed by a Q&A session and casual discussion over lunch, are providing opportunities for researchers from Computer Science, Electrical and Computer Engineering, Mechanical Engineering and other departments to start new collaborations beginning from a simple exchange of ideas to development of joint grant proposals.

17.4.6 Student Experience: Dinesh Karri

Robotics has become an integral part in the society in the past few decades. I got interested in robotics as a kid playing with several toys and decided to pursue my degrees in this field. Unfortunately, most universities, especially in India, where I did my undergrad from, overlooked the importance on building interdisciplinary skills on development of robotic systems and how it incorporates different fields of engineering like computer science, mechanical, electrical engineering, electronics, and communication engineering.

Defend the Republic is a research-based competition between multiple research groups to play a game of soccer with multiple balls in adversarial 3D environments autonomously. But to accomplish this the challenge took place in stages. The First stage was to create a system which can be tele-operated to accomplish the given tasks and gain intuition on how the autonomy should look like. Joining Defend the Republic (DTR) project 3 years ago where we had to build a teleoperated system to participate in this competition, I realized how important it is to develop skills in the above stated fields to build one single robotic system. I started the project as a master's student under the guidance of the professors where I built a robot from the ground up. Me being a controls engineer, I did not have much knowledge in the mechanical, computer science and communication aspects of it. But in this project, I got to work with several PhD students from different disciplines to learn and brainstorm ideas for the system which I was successfully able to build, test, and deploy.

Then as a PhD student I lead a group of students when the rules of the competition moved toward autonomy. In the team, we had PhD, masters, undergraduate students and highschoolers with backgrounds in electrical, computer, embedded systems, mechanical, and computer science who became integral parts of the development of the system.

In projects like this, everyone on the team, irrespective of type of engineering background, have a lot learn and a lot of gain from by collaborating and making decisions on the future career choices. Most of the students who worked with us, have either made career choices with respect to the newfound interest in robotics and others have opted to perceive academic paths in robotics to be a part of this interdisciplinary field. This was helpful even more so for high school students to get a taste of robotics hands-on experience which sparked interest in pursuing the field.

17.5 Faculty Recruitment and Development

17.5.1 Faculty Recruitment

Robotics is a thoroughly cross-disciplinary area of technology, requiring expertise in a large variety of both STEM and non-STEM disciplines. For a university to achieve a suitable critical mass of activity in both research and education in robotics, it is necessary for the university and its relevant departments to make significant investments in recruitment of faculty across the different disciplines of robotics. But recruiting outstanding faculty is not enough. In order to fully realize the significant benefits and impacts such a critical mass of faculty can achieve, it is necessary for the leadership within the university at all levels to be fully invested in the spirit of cross-disciplinary collaboration and to make a commitment to sustain it over a long period of time.

While many faculty recruits in robotics will specialize primarily in some area of a “home discipline,” such as mechanical engineering, computer science, or cognitive psychology, many newly-minted PhDs nowadays come equipped with substantial cross-disciplinary expertise of their own. Universities that are experienced with large cluster recruitments or are effective at leveraging joint appointments of faculty in multiple departments can build up a critical mass of faculty in robotics in a short period of time. Other universities may prefer to make gradual additions to faculty as budgets permit, while also recruiting existing faculty into nascent efforts around robotics. In the following subsections two recent robotics hires, one junior and one senior, provide their personal insight.

17.5.2 Faculty Experience: Quentin Sanders

Prior to joining Mason, I had the opportunity to work at a Silicon Valley based company that prided itself on innovation through interdisciplinary collaboration. Our project in particular was focused on developing a robotic exoskeleton to assist people with mobility challenges. The project by nature is inherently interdisciplinary, but it is quite common to find teams working on similar projects composed solely of engineers. This often leads to solutions that achieve a goal (i.e. technological innovation) but do not meet the need of the user. The composition of our team consisted of biomechanics specialists, roboticists, apparel designers, and user experience researchers. It is the interdisciplinary nature of our team that allowed us to develop a novel robotic device that's performance well exceeded current state of the art devices. I have seen how interdisciplinary collaboration can lead to highly impactful devices, and this is especially true in the area of robotics. I was attracted to Mason because they sought to create a similar culture of interdisciplinary collaboration. I think this is reflected by the University's willingness to hire me into a joint appointment position in the bioengineering and mechanical engineering departments.

17.5.3 Faculty Experience: Missy Cummings

Professor Mary "Missy" Cummings, a recent new hire to George Mason, is an example of Mason's growing focus on interdisciplinarity. She was appointed jointly across three departments, Mechanical, Electrical and Computer, and Computer Science. While two-department joint hires routinely occur at other universities, three is unusual, but critical according to Missy. Robotics is inherently interdisciplinary, with no challenge belonging to any single domain. Students and junior faculty want the ability to work across departments and even colleges, so breaking down barriers between departments, schools and colleges will be critical for successful robotics workforce development. Mason's youth as a university allows it to be more agile and less mired in stale traditions that current-day students find archaic. Indeed, industry shares this same sentiment, so interdisciplinarity is the key to recruiting and producing the kind of talent industry (and academia) need.

17.6 Conclusions

Taken on a point-by-point level, these efforts are not unique. Taken in whole, however, this unified effort leads to comprehensive, multi-disciplinary education in robotics facilitating pathways for students from K-12 to PhD covering northern Virginia, including some of the largest school districts in the Commonwealth of Virginia (181,000 students in Fairfax County Public Schools [31], which is the 11th largest school district in the United States and largest in Virginia [32], 89,468 students in Prince William County Schools [33], which is the 34th largest school district in the United States and second largest in Virginia [32, 33], and 27,586 students in Arlington Public Schools [34]) coupled with being a pathway to bachelor's degrees for students beginning their college education at Northern Virginia Community College (the second largest community college in the United States [35]). For reference, the locations in which Mason's Bioengineering (BENG), Civil, Environmental, and Infrastructure Engineering (CEIE), Computer Science (CS), Cyber Security Engineering (CYSE), Electrical and Computer Engineering (ECE), Mechanical Engineering (ME), Systems Engineering and Operations Research (SEOR) departments offer activities at each of these levels is summarized in Fig. 17.3—emphasizing the strong geographic reach of Mason throughout Northern Virginia and specifically in Fairfax, Prince William County (SciTech Campus), and Arlington. This figure represents a snapshot at the time of this writing. Departmental presences on all three campuses is dynamic and continues to grow with the growth of the University at large.

This geographic reach, coupled with horizontal integration across disciplinary domains and vertical educational integration from K-12 to faculty levels, is an enabler for meeting the industry need for a growing workforce in this field. Looking to a few industry examples in particular, we note that automation and robotics in warehouses and the supply chain are quickly transforming the industry and becoming a major economic driver. "Robotic warehouse automation is currently a small portion

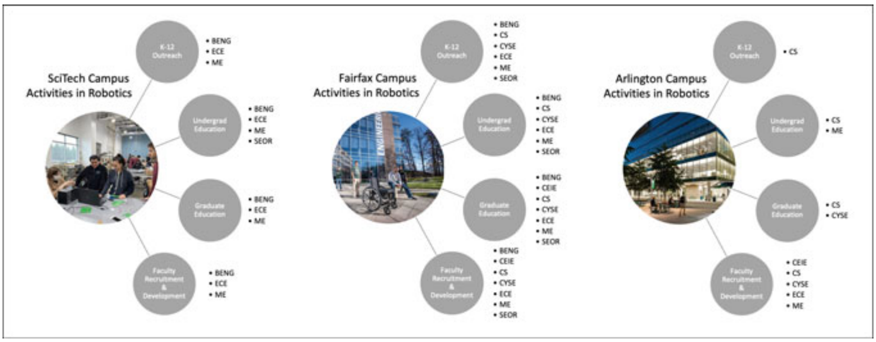

Fig. 17.3 Mapping of departmental involvement in K-12, undergraduate, graduate, and faculty development activities in robotics across Mason's three Virginia campuses

of overall warehouse automation spending, but it is growing rapidly. Advisory firm Interact Analysis predicts the mobile robotics market could grow from approximately $3.6 billion in 2021 to $18 billion in 2025. The number of warehouse facilities with mobile robots is also projected to expand from 9000 in 2020 to 53,000 in 2025. In addition, Interact Analysis forecasts a total of 2.1 million robots in service by the end of 2025 with 860,000 of these shipped during that year alone. Interact Analysis includes mobile robots as a component of the broader warehouse automation market, which it expects to grow from $49.6 billion in 2020 to $69 billion in 2025. Fixed automation systems such as automated storage and retrieval systems (AS/RS), conveyor belts and sorters will eclipse other forms of automation for the foreseeable future" [36]. Looking specifically to Amazon, "[t]oday, Amazon has more than 200,000 mobile robots working inside its warehouse network, alongside hundreds of thousands of human workers…. This robotics race—led by Amazon—will have a seismic impact on the warehouse industry, which employs more than 1.1 million Americans today" [37].

Furthermore, continued development of autonomous and remotely operated vehicles remains a growth sector, as noted in a Businesswire report which states: "The global market for Offshore AUV [autonomous underwater vehicle] and ROV [remotely operated vehicle] estimated at US$3.3 Billion in the year 2020, is projected to reach a revised size of US$7.2 Billion by 2026, growing at a CAGR of 14.3% over the analysis period" [38]. The report goes on to describe the contributions of these types of robotic and autonomous systems toward human safety, science, defense, energy, infrastructure, and food by stating: "The rising use of ROVs in a variety of industries, including search and rescue, marine biology, military, oil and gas, submerged infrastructure, and aquaculture, as well as advancements in ROV technology, is anticipated to drive growth in the segment. The need for big AUVs for military and defense applications, as well as oil and gas exploration, is driving the expansion of the AUV market segment" [38].

As another industry sector experiencing rapid growth, surgical robots have in relatively short time gone from science fiction to practice. "Within 20 years since the regulatory approval of the first surgical robot, more than 3000 units were installed worldwide, and more than half a million robotic surgical procedures were carried out in the past year alone. The exceptionally high speeds of market penetration and expansion to new surgical areas had raised technical, clinical, and ethical concerns. However, from a technological perspective, surgical robots today are far from perfect, with a list of improvements expected for the next-generation systems. On the other hand, robotic technologies are flourishing at ever-faster paces. Without the inherent conservation and safety requirements in medicine, general robotic research could be substantially more agile and explorative. As a result, various technical innovations in robotics developed in recent years could potentially be grafted into surgical applications and ignite the next major advancement in robotic surgery" [39].

Particular opportunity for robots and autonomous systems for economic impact has been highlighted by the COVID-19 pandemic; "The COVID-19 pandemic has revealed many needs that could be solved in part through the use of robotics, with sufficient investment in research, development, and job training. For example, in

2017 hospitality was a $1.6 trillion sector, one that now has additional needs for disinfection, cleaning, maintenance, and socially distanced services. Similar needs are present in healthcare to provide safety to healthcare workers and patients alike. In agriculture, robotics could provide assistance where there is now a lack of seasonal workers to harvest crops. Robotics can address the supply chain issues that were revealed by COVID-19, including the need to manufacture critical PPE and other necessary items in the U.S. Autonomous trucks could increase the efficiency of our supply chain while also increasing road safety" [1]. Research and Markets reports that in 2022 the global logistics robotics market was valued at $15.2 billion with a prediction for this to grow to $58.6 billion in 2028 [40]. They go on to report, "An increase in the number of logistics and warehousing companies that are incorporating robots to improve speed and efficiency and remain competitive in the market are propelling the demand for logistics robots worldwide. Moreover, the adoption of advanced technologies, such as robotic warehousing and logistics technologies, is growing on account of the sudden outbreak of the coronavirus disease (COVID-19) and the consequent lockdowns imposed by governments of various countries to prevent the transmission of the pandemic" [40]. In a market analysis by Astute Analytica, they note that "Covid-19 triggered the deployment of food delivery robots when social distancing and human interface became difficult and avoidable" while forecasting that "The Global Indoor Delivery Robots Market is anticipated to witness a major jump in its revenue from US$ 16.63 Mn in 2021 to US$ 253.76 Mn by 2030" [41].

It is with this common understanding of industry workforce need that we highlight the critical importance of the horizontally and vertically integrated educational structure described here, weaving together K-12, undergraduate, graduate, and faculty activities in robotics and autonomous systems, across multiple departments. This may provide an outline for institutions working to develop a similarly multi-disciplinary institutional structure to support robotics research and education.

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