Robotics as an Undergraduate Major: 10 Years' Experience

Prof. Michael A. Gennert, Worcester Polytechnic Institute

Michael A. Gennert is Professor of Robotics Engineering, CS, and ECE at Worcester Polytechnic Institute, where he leads the WPI Humanoid Robotics Laboratory and was Founding Director of the Robotics Engineering Program. He has worked at the University of Massachusetts Medical Center, the University of California Riverside, PAR Technology Corporation, and General Electric. He received the S.B. in CS, S.B. in EE, and S.M. in EECS in 1980 and the Sc.D. in EECS in 1987 from MIT. Dr. Gennert's research interests include robotics, computer vision, and image processing, with ongoing projects in humanoid robotics, robot navigation and guidance, biomedical image processing, and stereo and motion vision. He led WPI teams in the DARPA Robotics Challenge and NASA Space Robotics Challenge and is author or co-author of over 100 papers. His research has been supported by DARPA, NASA, NIH, NSF, and industry. He is a member of Sigma Xi, and a senior member of IEEE and ACM.

Prof. Craig B. Putnam, Worcester Polytechnic Institute

©American Society for Engineering Education, 2018

Robotics Engineering as an Undergraduate Major: 10 Years' Experience

Abstract:
In 2007 Worcester Polytechnic Institute (WPI) launched an undergraduate degree program in robotics. At that time, there were only a handful of universities worldwide offering undergraduate Robotics programs, none in the United States, although many universities included robotics within a discipline such as Computer Science, Electrical Engineering, or Mechanical Engineering. WPI took a decidedly different approach. We introduced Robotics as a multi-disciplinary engineering discipline to meet the needs of 21st century engineering. The curriculum, designed top-down, incorporates a number of best practices, including spiral curriculum, a unified set of core courses, multiple pathways, inclusion of social issues and entrepreneurship, an emphasis on project-based learning, and capstone design projects. This paper provides a brief synopsis, comparison with other approaches, and multi-year retrospective on the program. The curriculum has steadily evolved from the original to its current state, including changes in requirements, courses, hardware, software, labs, and projects. The guiding philosophy remains unchanged, however, providing continuity of purpose to the program. The program has been highly successful in meeting its desired outcomes, including: quantity and quality of enrolled students, ABET EAC accreditation, graduate placement in jobs and graduate school, and overall student learning. The program is assessed using several quantitative measures: enrollment, cohort survival within the program, course and project evaluations, and student placement success. Other, qualitative outcomes are also discussed: results from competitions, interaction with industry, accreditation, and external recognition. The paper concludes with a summary of lessons learned and recommendations for future actions to further robotics education.

1. INTRODUCTION

Robotics—the combination of sensing, computation and actuation in the real world—has experienced phenomenally rapid growth. In academia, recruiting of robotics faculty is at an all-time high and the number of robotics-related conferences and workshops is exploding. In industry, new companies and products appear at an accelerating rate. Public awareness of robotics has also increased dramatically, as concerns over loss of jobs and privacy contrast with excitement over the coolest innovations, competing for technology headlines. We are rapidly approaching the date by which Bill Gates has famously predicted that there will soon be a robot in every home [1]. Growth in robotics is driven by many factors, including the demand for increasingly sophisticated, autonomous systems for security and defense, advanced manufacturing, logistics, health, home maintenance, and interactive entertainment. Meanwhile, the supply side is driven by decreasing cost and increasing availability of sensors, computing, and information storage. To meet the needs of this growing industry, in 2007 Worcester Polytechnic Institute (WPI) launched an undergraduate degree program in Robotics Engineering to educate young men and women in robotics. The paper provides a retrospective look at the program, its evolution, assessment, and lessons learned, expanding on an earlier report [2].

1.1. MOTIVATION

The introduction of the Robotics Engineering program was motivated by several considerations. First, it seemed that the growth of the robotics industry would lead to a demand for engineering talent uniquely qualified to develop robotic systems, much the same way that the growth of the

Aeronautics/Aerospace and Biomedical device industries demanded broadly educated engineers qualified to work in their respective domains. Second, the high level of interest in K-12 robotics activities, such as For Inspiration and Recognition of Science and Technology (FIRST), demonstrated that there would be a natural pipeline of enthusiastic, even passionate, students for college-level robotics. Third, the lack of similar domestic programs meant that the university could assert a leadership position and "capture the market". Fourth, we understood that the economic benefit of any new and promising technology such as robotics will accrue to those who can convert scientific and technological know-how into viable products and systems. Fifth, robotics would be an excellent academic fit for WPI given its position as an innovative, somewhat eclectic, university concentrating on science, engineering, and management. Finally, expense and revenue projections suggested that the program would be financially viable.

1.2. ENGINEERING EDUCATION IN ROBOTICS

Robotics did not exist as an undergraduate engineering degree program in the US until 2007, although universities have offered courses in robotics for over four decades and many introductory-level robotics text books are available. Closely related to Robotics is Mechatronics[1]; the earliest ABET-accredited Mechatronics Engineering program is at California State University, Chico, starting in the mid-1990s. Leaving aside engineering technology degree programs, there are now seven Robotics B.S. degree programs in the U.S. [3]. However, many other universities offer courses on various aspects of robotics and mechatronics, including Robot Programming, Mechatronic Analysis, Mobile Robots, Automatic Control, Industrial Automation, and Cyber-Physical Systems. Several universities offer a cluster of robotics courses, such as concentrations, minors, threads, or focus areas.

While robotics at the undergraduate level has generally been embedded in traditional engineering or computer science programs, and thus treated as an application area, rather than a separate discipline, an increasing number of US universities have introduced graduate degrees in robotics. Following the success of the undergraduate program, WPI added graduate degrees in Robotics Engineering [4].

2. THE ROBOTICS ENGINEERING MAJOR

The growing robotics industry demands a new kind of engineer. At present, engineers working in the robotics industry are mostly trained in one of Computer Engineering, Computer Science, Electrical Engineering, Mechanical Engineering, or Software Engineering. However, as an inherently interdisciplinary activity, no single discipline provides the breadth demanded by robotics in the future. Truly smart robots rely on information processing, decision systems and artificial intelligence (computer science), sensors, computing platforms, and communications (electrical engineering) and actuators, linkages, and mechatronics (mechanical engineering). Thus, a broad technical education is needed. In effect, robotics engineers must use systems thinking, even early in their careers. Given the above motivations for a robotics degree, a team of WPI faculty members from the departments of Computer Science, Electrical & Computer

[1] No precise and widely-agreed upon definitions exist for either Mechatronics or Robotics. We shall not attempt to provide those here, noting only that Mechatronics tends to emphasize Electromechanical Control systems, oftentimes including Computer Engineering. By contrast Robotics places at least equal emphasis on Computer Science, oftentimes including Artificial Intelligence.

Engineering, Humanities & Arts, and Mechanical Engineering began meeting in spring 2006, with the support of the university administration, to design the degree program. The team took a top-down approach: Vision and goal statements drove objectives, outcomes, and curriculum in turn. After several iterations and revisions, and approval by faculty governance and the Board of Trustees, the program launched in spring 2007 in time to attract students for fall 2007 [5].

2.1. Vision and Goals

The Robotics faculty adopted as a vision the creation of an *Exemplary, nationally recognized, Multidisciplinary center for Education, research, and innovation in Robotics*. The primary goal of the program is to educate engineers for the 21st century, the "enterprising engineers" envisioned by Tryggvason and Apelian [6], who "knows everything, can do anything, collaborates, and innovates." These words succinctly capture the notion that future engineers must be able to find and use information quickly, understand and use the tools to accomplish any task with proficiency, possess the skills to work effectively with anybody anywhere, and have the imagination and entrepreneurial spirit to creatively solve worthy problems. As applied to robotics, that leads to a two-pronged approach: 1) Supply talent to a growing industry, and 2) Start enterprises (ranging from projects to products to companies) to grow the industry, that is, both entrepreneurs and intrapreneurs.

2.2. Program Educational Objectives

Program Educational Objectives (PEOs) define the context and the content of the program. Our PEOs have evolved to better reflect current educational terminology, but the core ideas remain unchanged. The PEOs are that graduates of the Robotics Engineering program are expected to:

1. Successfully
    a. attain professional careers in robotics and related industries, academia, and government;
    b. expand human knowledge through research and development; and/or
    c. develop entrepreneurial engineering activities.
2. Engage in life-long and continuous learning, including advanced degrees.
3. Exert technical leadership over multi-disciplinary projects and teams.
4. Contribute as responsible professionals through community service, mentoring, instructing, and guiding their professions in ethical directions.
5. Communicate effectively to professional and business colleagues, and the public.

The PEOs shape the curriculum in specific ways, especially regarding entrepreneurship, multi-disciplinarity, and ethics, as described later.

2.3. Student Outcomes

Although Robotics is not recognized as a distinct engineering field by ABET, the program was designed to be accreditable under the "General Engineering" criteria, thus, the group adopted the standard ABET program outcomes (a-k) [7]. As applied to Robotics Engineering, graduating students will have:

(a) an ability to apply broad knowledge of mathematics, science, and engineering,
(b) an ability to design and conduct experiments, as well as to analyze and interpret data,

(c) an ability to design a robotic system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability,
(d) an ability to function on multi-disciplinary teams,
(e) an ability to identify, formulate, and solve engineering problems,
(f) an understanding of professional and ethical responsibility,
(g) an ability to communicate effectively,
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context,
(i) a recognition of the need for, and an ability to engage in life-long learning,
(j) a knowledge of contemporary issues, and
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

2.4. CURRICULUM

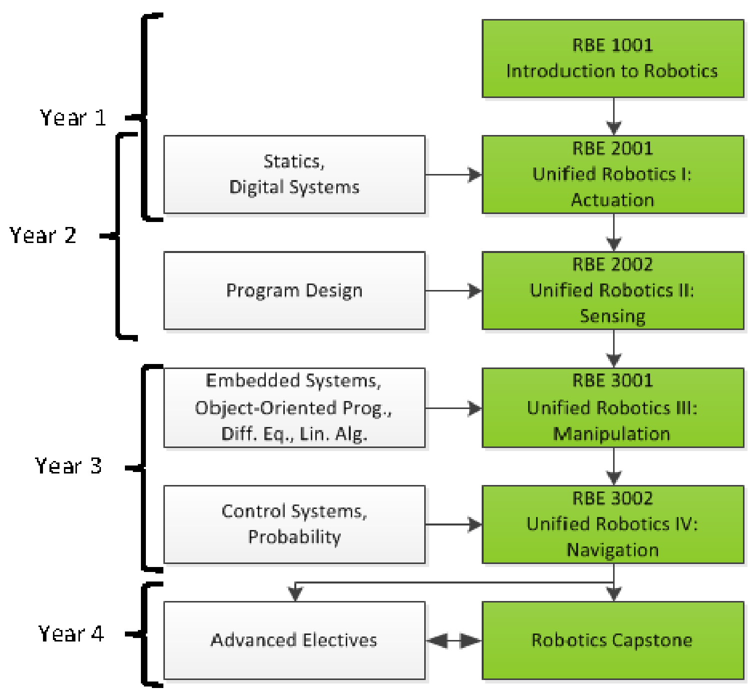

Figure 1. The WPI robotics program is structured around a core consisting of Introduction to Robotics, Unified Robotics I-IV, and the capstone project [8].

The program structure integrates foundational concepts from Computer Science, Electrical & Computer Engineering, and Mechanical Engineering to introduce students to the multidisciplinary theory and practice of Robotics Engineering. For this purpose, a course sequence was created comprising the major educational innovation [9]. The core curriculum consists of Introduction to Robotics at the 1000 level (1st year) and a four-course Unified Robotics sequence at the 2000 and 3000 levels (sophomore and junior years, respectively). Figure 1 provides a graphic overview of the curriculum. All courses are offered over 7-week terms with 4 hours of lecture and 2 hours of laboratory per week. Further, in keeping with the long history of the WPI Plan, the courses emphasize the combination of theory and practice as embodied in project-based learning, hands-on assignments, and student commitment to learning outside the classroom. Robotics Engineering majors are expected to complete all five core courses before beginning a capstone design project in the senior year.

Introductory courses

Our approach is to expose students to an overview of robotics in the first year through **RBE 1001 Introduction to Robotics**. This course serves as a model for subsequent robotics courses, integrating CS, ECE, and ME concepts in a project-based format where weekly hands-on lab and homework assignments build up to a final project. However, after introducing the basics, we entrust further foundational topic coverage to the respective departments. Thus, students take software design courses offered by CS, digital logic and systems courses offered by ECE, and a statics course offered by ME. These courses are typically taken in the first or second year, serving as background for the Unified Robotics course sequence.

Core Course Sequence

The Unified Robotics I-IV course sequence forms the core of the Robotics Engineering program at WPI. While all of the courses have coverage of CS, ECE, and ME concepts, the focus of each course, and therefore the amount of coverage in each area, is different. The first of these courses, **RBE 2001 Unified Robotics I: Actuation** reinforces the concepts introduced in RBE 1001, but mainly focuses on the effective conversion of electrical power to mechanical power, power transmission for purposes of locomotion, and of payload manipulation and delivery. Students form into teams of three and have weekly labs that allow them to further develop their understanding of lecture material. The labs are structured to scaffold students in support of the final project. The final project is introduced early in the term, and the student teams work on it for the duration of the course. The final project is designed to be challenging and to have real-world applicability (at least in theory); it is also intended to be engaging and fun. The current final project for RBE 2001 is a simulation of using a mobile robot to refuel a nuclear reactor. The second sophomore-level course, **RBE 2002 Unified Robotics II: Sensing**, focuses on sensors, circuits, signal processing, and embedded system programming. The final project for this course tasks a small mobile robot to navigate a maze-like structure on a tabletop, find a fire (a candle), extinguish the fire, and report on where the fire was located in the maze. The robot is not allowed to touch the walls of the maze. The level of sophistication in the solutions some teams are using lately is quite impressive; it is not uncommon to have teams attempt (and succeed at) visual SLAM and low-end LIDAR-based solutions. The first of the junior level courses, **RBE 3001 Unified Robotics III: Manipulation,** has the students using a 3-DOF robot arm that was custom-designed and manufactured at WPI. The focus of this course is actuator design, embedded computing and complex response processes. The last of the core courses is **RBE 3002 Unified Robotics IV: Navigation.** In this course students are using TurtleBot™ to develop their understanding of topics such as navigation, position estimation and communications. Concepts of dead reckoning, landmark updates, inertial sensors, and radio location are also explored.

Advanced Courses

Once students complete the Unified Robotics sequence and all the supporting courses in mathematics and engineering, they reach a level (both in depth and breadth) to take more advanced courses. These can come from robotics electives, CS, ECE, and ME courses, or Engineering Science & Design courses from any department or program. Graduate coursework is allowed as well.

Entrepreneurship & Social Issues

As noted earlier in **Vision and Goals**, Robotics Engineering students are expected to “have the imagination and entrepreneurial spirit to creatively solve worthy problems.” ABET accreditation – particularly outcomes (f), (h), and (j) – places additional requirements on the curriculum.

To address these expectations, students in the Robotics Engineering program are required to take at least one Entrepreneurship course. A number of courses can be used to meet this requirement, offering students the flexibility to choose a course that best meets their interests and career goals. The course need not be taken at any particular point in the curriculum, but students most often take their chosen course during the sophomore or junior year.

Students are also required to take a Social Implications course. The goal is to sensitize the students to the expected, and unexpected, ways that robotics has and will continue to influence society. Again, there are several courses that students may choose from and flexibility as to when they can take it. Some of these courses are offered by the Social Sciences and Policy Studies faculty, but there are courses offered by other departments as well, such as Social Implications of Information Processing (offered by Computer Science) and a newly-offered Social Implications of Robotics course.

Capstone Design

The culmination of the Robotics Engineering curriculum is the senior capstone design project. As with the core Robotics Engineering courses, this is intended to be a team-based effort. Teams usually consist of two-four students, but in rare cases have numbered as many as 12 and occasionally as few as one.

The capstone project satisfies the outcomes in Table 1. The project must encompass the breadth of the design experience, including conceptualization, requirements, design, implementation, evaluation, and documentation. The final project report must address all of these areas, as well as societal issues as appropriate, including professional responsibility, ethical and environmental considerations, sustainability, aesthetics, and safety.

Table 1. University-wide outcomes addressed by the capstone project.

Students who complete a Senior Capstone Project will:
1. apply fundamental and disciplinary concepts and methods in ways appropriate to their principle areas of study
2. demonstrate skill and knowledge of current information and technological tools and techniques specific to the professional field of study
3. use effectively oral, written and visual communications
4. identify, analyze and solve problems creatively through sustained critical investigation
5. integrate information from multiple sources
6. demonstrate an awareness and application of appropriate personal, societal, and professional ethical standards
7. practice skills, diligence, and commitment to excellence needed to engage in lifelong learning

2.5. Best Practices

A number of Best Practices were adopted during program development. These include:

- Top-down development from Vision and Goals to Program Educational Objective to Student Outcomes to Curriculum to Courses to Resources.
- Bottom-up faculty buy-in. The primary impetus for the program came from faculty who were interested in developing it.
- Spiral curriculum. RBE 1001 Introduction to Robotics touches on a number of topics, including statics, circuit analysis, behavior-based programming, and PID control, that later courses explore in greater depth.
- Multi-disciplinary approach. Each course integrates elements of CS, ECE, and ME. For example, RBE 2001 Unified Robotics I: Actuation uses mechanical actuator models, while also exploring their electrical characteristics, and how one writes software to control them. All courses were initially taught by teams of faculty as the expertise needed to teach each course was developed.
- Active learning is used in many of the core robotics courses [10].
- Progressive increase in level of autonomy in each course. The robots developed in each course progress from tele-operation to line-following to total autonomy.
- Tight integration of lecture material with laboratory assignments [11].
- Community-building. Many activities serve to build a sense of community amongst Robotics Engineering majors. These include Meet-and-Greet events early in the school year, the establishment of an honor society and Women in Robotics Engineering student groups, and the shared Robotics Teaching Lab open 24/7. The Robotics Teaching Lab, shared across all five core courses, also promotes a sense of community (Figure 2).

Figure 2. Robotics laboratory late at night before a term project is due.

2.6. Comparison to other approaches

The most significant difference between this and other approaches is the tight integration of CS, ECE, and ME concepts across the curriculum to produce a unified experience. Students do not see themselves as traditional engineering majors who specialize in robotics, they truly see themselves as Robotics Engineers. By contrast, some other robotics and mechatronics programs are offered by a single department or pair of departments. Other differences are the early and continued exposure to robotics, whereby engineering principles are taught in a robotics context, and the program's flexibility, with many ways to satisfy degree requirements.

3. Program Evolution

With no pre-existing curriculum to serve as a template, the faculty used its aggregate educational wisdom to design the curriculum and courses, expecting to update the curriculum as experience accumulated. The basic structure of the curriculum remains unchanged; however some content, courses, and projects have changed.

Unified Robotics I-IV have been tweaked, with a few minor topic additions, deletions or shifting of material; none serious enough to merit a change in course description. In addition, this course sequence or equivalent is now required to ensure that all Robotics Engineering majors have a common core set of knowledge.

Robotics hardware and languages have been changed to reflect changes in robotics platforms used for homework, labs, and projects. Four of the five core courses originally used the VEX platform with RBE 3001 Unified Robotics III using a custom-designed processor board based on the Atmel AVR644P microcontroller. Neuron Robotics DyIO controllers and associated Unix-based Bowler Deployment Modules (BDM) [12] were tried in 2011 for RBE 1001-2002. Although this HW/SW combination provided unique capabilities, it lacked the large installed user base of the Arduino platform. Thus, these courses have now migrated to the Arduino controller running the Sketch (actually C/C++) language. RBE 3001 has undergone several revisions to the hardware, now using custom-designed 3D printed manipulators and custom boards. RBE 3002 uses UNIX to handle the heavy computational load associated with mapping and navigation as part of the TurtleBot [13]. Table 2 summarizes the hardware and languages.

Table 2. Summary of hardware and languages used.

Course	Initial		Also used		Current	
	Hardware	Language	Hardware	Language	Hardware	Language
RBE 1001	Vex	EasyC, C	DyIO	Java	Arduino	C
RBE 2001	Vex	C	DyIO	Java	Arduino	C
RBE 2002	Vex	C	DyIO, BDM	Java	Arduino	C
RBE 3001	Custom	C	-	-	Custom	C, Python, MATLAB
RBE 3002	Vex	C	Laptop	C	TurtleBot™	C

The Computer Science requirement originally comprised Algorithms and Software Engineering. However, the Algorithms course, which is oriented more towards analysis than implementation, did not prepare students adequately for Software Engineering, which uses object-oriented design and programming extensively. Replacing the Algorithms requirement with Object-Oriented Programming better prepares students for Software Engineering.

The Mathematics requirement originally listed Calculus, Differential Equations, Discrete Mathematics, and Probability or Statistics. However, in order to prepare students for RBE 3002 Unified Robotics IV: Navigation, which is based on probabilistic reasoning in multivariable systems, the Statistics option was eliminated in favor of Probability and a Linear Algebra requirement was added. Discrete Mathematics, formerly needed as background for Algorithms, was also dropped as a requirement to make room for the addition of Linear Algebra.

Robotics Electives have been a moving target as courses have been added, dropped, and revised in other departments. Initially, the program maintained a list of approved elective courses. That has since been replaced by allowing students to take any Engineering Science & Design courses, with at least 2 at the senior or graduate level. This allows students to apply robotics to another discipline, such as aerospace or biomedical engineering, or concentrate on CS, ECE, or ME for robotics, or to take advanced graduate-level work.

Social Implications
A new course was developed by one of the Robotics Engineering faculty members specifically to appeal to students in the major. This was because most of the existing courses that could be used to meet this requirement were mainly Government and Interdisciplinary in focus. There is also the Social Implications of Information Processing course offered by Computer Science. There was a course offered by Social Sciences and Policy Studies called The Society-Technology Debate. That course was popular with Robotics Engineering majors, but the course was dropped when the lone faculty member who taught it retired several years ago. The situation then was that none of the currently offered courses were particularly enticing to the Robotics Engineering majors, so a new course (Social Implications of Robotics) was developed that would specifically address the interests and needs of these students. The course has only been offered twice at this point but is proving to be very popular with a wealth of topics to examine such as job loss due to robotics and automation, robots in the military, robotics and the law, human-robot relationships, robotics and elder/child/healthcare, ethics related to self-driving vehicles, and many others.

Robotics Engineering Capstone Design Projects
There has been some experimentation with alternative ways to fulfill the capstone design requirement. One notable experiment was associated with the 2012-2015 DARPA Robotics Challenge. While most of the work for this project was done by graduate students, post-docs, engineers, and faculty, interested undergraduates were given tasks appropriate to their background and skills. Students could participate as early as their freshman year, earning small amounts of capstone credit spread out across their entire undergraduate experience if desired.

Capstone project sponsorship has increased steadily. Sponsorship mechanisms vary from direct financial support to support in-kind to a mix of the two. In recent years WPI has had projects sponsored by companies or organizations such as: General Electric, Amazon Robotics, Arthur G. Russell Company, DARPA, FIRST, and New Balance.

4. Quantitative Assessment

Assessment is a continuous process motivated by a desire to improve the program. Here we examine several quantitative measures of performance: Enrollment trends, cohort survival, student course and project evaluations, and student placement.

4.1. Enrollment

When the program was first proposed, the business plan was based on a projected 20-30 majors in the first year, rising to 30-50 students per cohort, for a steady-state total enrollment of 120-200 students. Much to our surprise, 80 students declared Robotics as their major in the first year, reflecting pent-up demand, as a number of sophomores and even a few juniors changed majors into the new program. Each cohort thereafter as been 50-100 students, so that there are now 397 majors in the program, as shown in Figure 3, making it the 4^{th} most popular major at WPI. Notably, Robotics Engineering draws students from a wider geographic range than is usual at WPI. WPI's entering class averages 25% from outside New England; for Robotics Engineering majors, it is 50%.

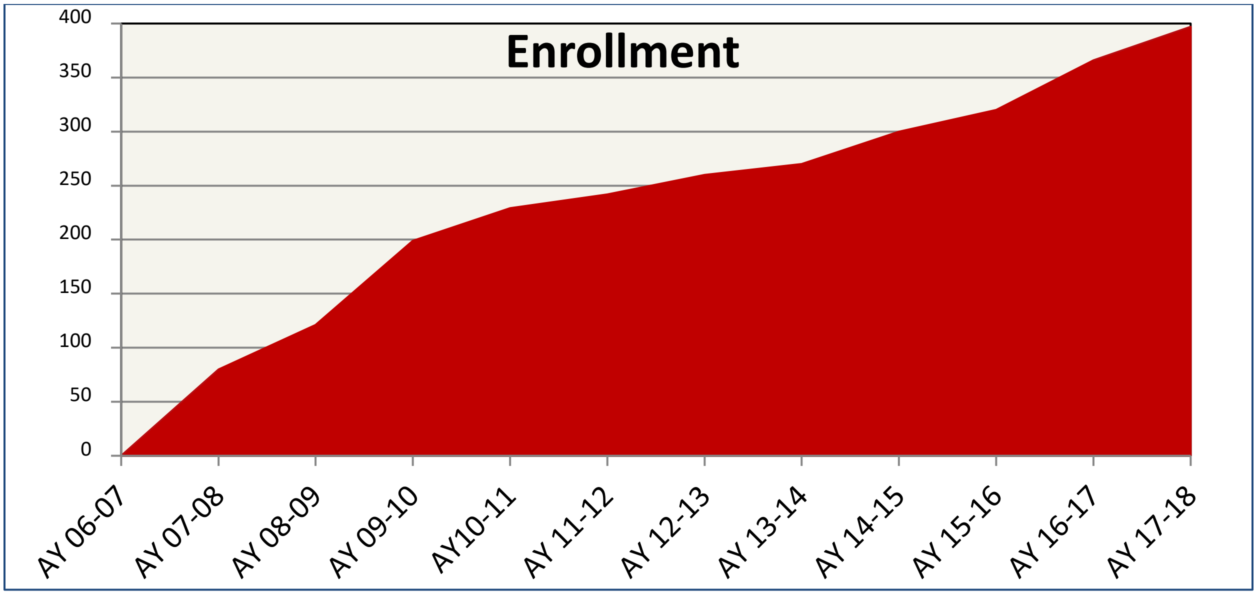

Figure 3. Robotics Engineering undergraduate enrollment.

4.2. Cohort Analysis

It is instructive to break down the total enrollment by year and class, as shown in Figure 4, where each cohort is viewed together. Note that unlike Figure 3, which includes double majors, the data in Figure 4 do not include double-majors. The overall growth in enrollment is apparent. We also see that most cohorts grow from freshman to sophomore years as some undeclared freshmen choose to major in Robotics Engineering. The increase in the number of seniors over the number of juniors is more likely due to "super-seniors" who do not graduate with their initial cohort, but instead delay graduation by a year or two, rather than changes of major in the senior year. In any case, the number of graduates closely tracks the junior class.

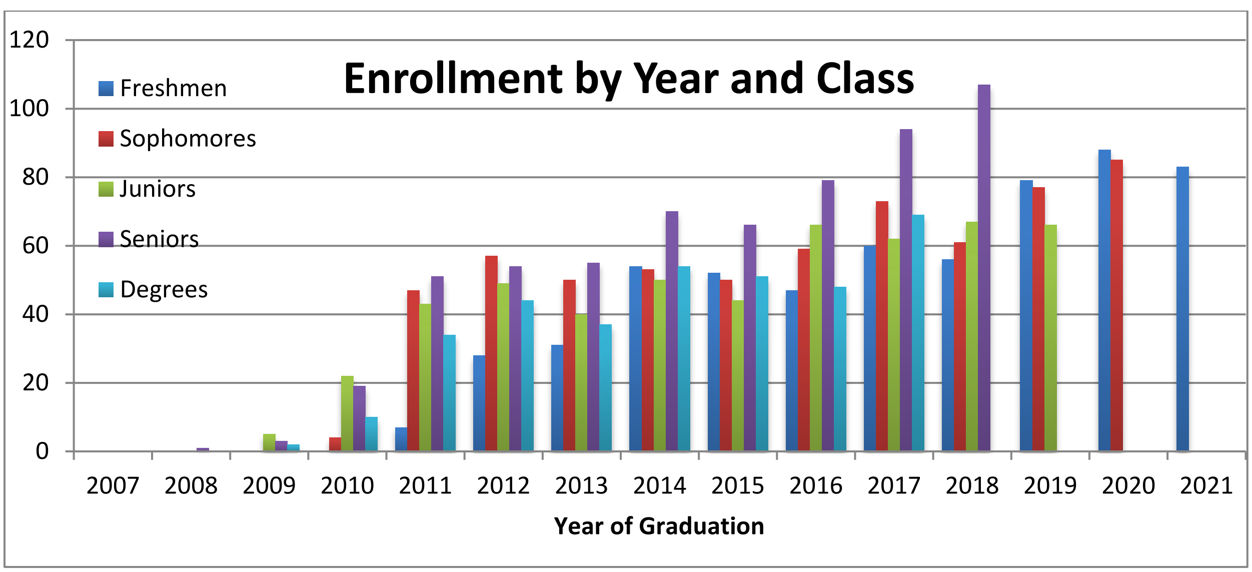

Figure 4. Enrollment by Year of Graduation and Class.

Table 3 shows the average cohort survival for the classes of 2012-2017, ignoring the first years of program start-up transients. Overall, 15% more students graduate than declare as freshmen, indicating that overall retention in the program, net of inflow and outflow, is high.

Table 3. Cohort Survival. Averages from classes of 2012-2017.

	Cohort Survival '12-'17
Freshman → Sophomore	1.34
Sophomore → Junior	0.91
Junior → Senior	1.35
Senior → Degree	0.73
Freshman → Degree	1.15

4.3. Student Course and Project Evaluations

Student course evaluations are generated at the end of each course. These are a common evaluation used across all WPI courses and are returned to faculty shortly after the course ends. There is a limited ability to include course-specific questions if the instructor so chooses. This is all done with paper Scantron™ forms. Student participation is generally good, but there is concern that participation rates will drop with a planned shift to an online form [14]. Student course evaluations include over 25 questions. Here we focus on three of the more important questions. Q1: My overall rating of the quality of this course is …, Q2: My overall rating of the instructor's teaching is …, and Q9: The amount I learned from the course was … . Responses are on a 5-point Likert scale ranging from 1 (lowest) to 5 (highest). Figure 5 (expanded and updated from [15]) shows student course evaluations for all courses in the Robotics Engineering core. Inter-instructor variability is the most significant contributor to the variation in responses. Note the close correlation among Overall quality, Instructor rating, and Learning. Figure 5 demonstrates that it is possible to achieve excellent course evaluations in the core courses and that all measures have improved.

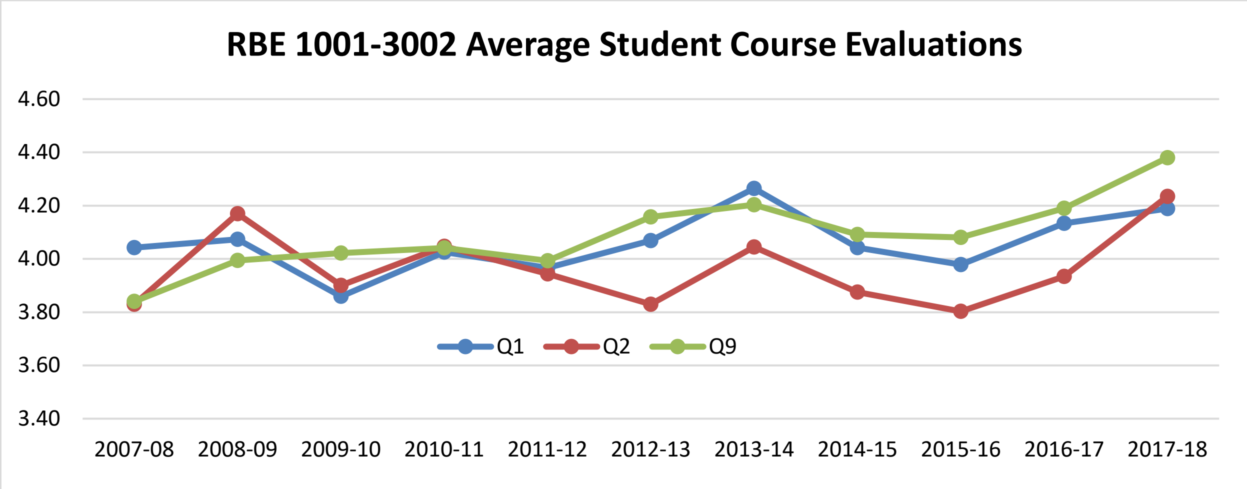

Figure 5. Average student course evaluations for RBE 1001-3002. Q1: Overall quality, Q2: Instructor rating, Q9: Amount learned.

Faculty also generate their own evaluation of how each course went. This is done with a form that was developed by Robotics Engineering. These are collected and become input into the periodic ABET assessment process as well as our own internal course review processes.

In the last term of the academic year, there is a day set aside for capstone project presentations. There are no undergraduate classes on Project Presentation Day. All senior capstone project teams prepare a 15-minute formal presentation; they also prepare a poster for poster sessions that run throughout the day. Students who are not yet involved in capstone projects are encouraged to attend the presentations to familiarize themselves with how they are done and to generate awareness of the types and level of projects undertaken. The formal presentations are reviewed by students in the audience, faculty, sponsors, and invited guests. These reviews are collected for the purposes of awarding prizes for the best projects. They also become part of the periodic capstone project review process, which is described next.

The Robotics Engineering program has developed a review process for the content and quality of senior capstone projects. Each student completes an evaluation form and the faculty advisor(s) also fill out their own project evaluation form. Other programs at WPI have similar processes. The faculty-generated form asks the advisor(s) to evaluate the students' work against all of the ABET educational outcomes. In addition, the outcomes shown in Table 1 are evaluated.

A variety of analyses are done on the capstone-related data. These include:

- Project and advising team make-up
- Grade distribution
- Academic level and topical content
- Overall academic merit
- Documentation quality
- Rate of project sponsorship
- Oral presentation evaluations

The collected data is collated and reviewed every few years and is presented to the Robotics Engineering faculty as part of our continuous improvement process. The goal is to ensure that there is a consistent understanding across the faculty regarding expectations for the quality of the work and how that work should be assessed in terms of grades awarded.

4.4. STUDENT PLACEMENT

Robotics Engineering majors do quite well upon graduation, as evidenced by graduate school placement and employment as shown in Figure 6. Data are within 6 months of graduation. Over this period, 70% of known graduates are employed and 21% are in graduate school, for an overall success rate of 91%. Graduates who are in military service or who are both employed and in graduate school are listed as employed.

GRADUATE SCHOOL

On average, 21% of Robotics Engineering majors continue directly into graduate school. Over the past four years, graduates have enrolled in graduate programs at CMU, Columbia U., Drexel U., ETH Zurich, MIT, Northeastern U., U. California Berkeley, U. California San Diego, U. Hawaii Manoa, and WPI.

Industry

On average, 70% of Robotics Engineering majors are employed within 6 months of graduation. They have been employed at over 140 companies in the robotics and other industries. Examples of robotics companies include: Amazon Robotics, Bossa Nova Robotics, Carnegie Robotics, Empire Robotics, iRobot, and Rethink Robotics. Other companies include Apple, General Dynamics, General Electric, Google, SpaceX and Tesla. Average starting salary in 2016 was $73,276,

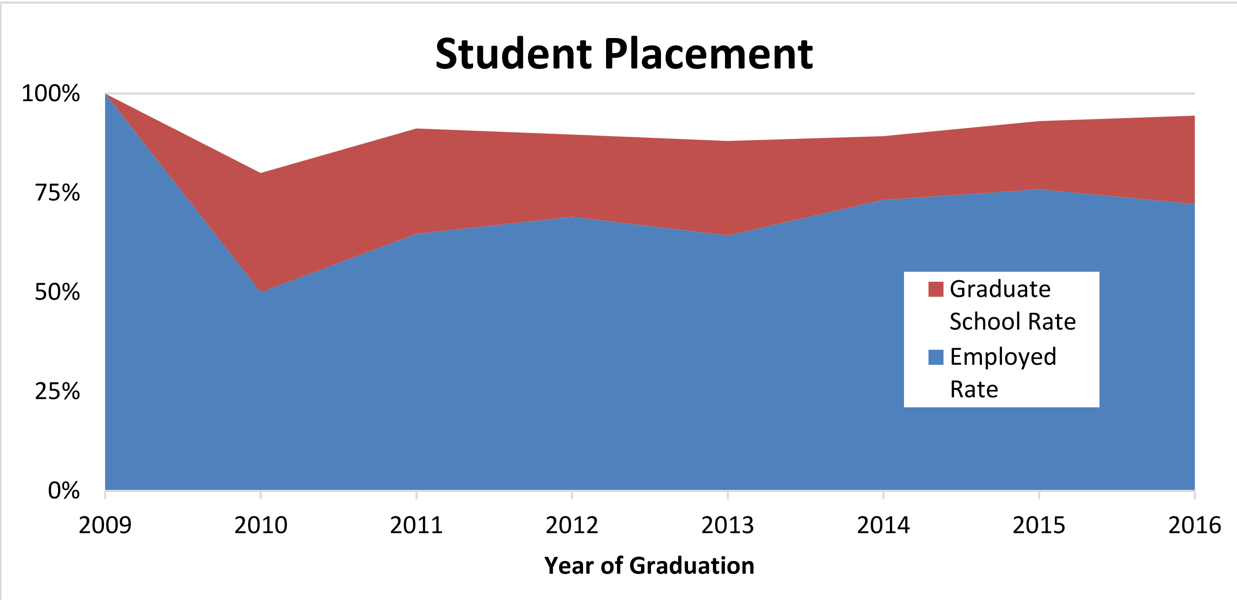

Figure 6. Student Placement. Employed rate includes military service and students who are both in graduate school and employed. Data are from within 6 months of graduation.

5. Qualitative Assessment

Several qualitative measures also provide evidence of program success.

5.1. Accreditation

Following graduation of the first students, the Robotics Engineering program applied for ABET accreditation under General Engineering criteria. Accreditation was awarded in summer 2011. Subsequently, the program was re-accredited in summer 2015.

5.2. Competitions

WPI has been involved in robotics-related competitions for many years, actually predating the creation of the Robotics Engineering program by at least 15 years. In some cases, a team from WPI has competed; in many other cases, WPI hosted the competition. Table 4 shows the competitions, when held, and where applicable, how the WPI team fared.

5.3. External Recognition

In addition to the visibility garnered through robotics competitions, the Robotics Engineering program was awarded the 2016 ABET Innovation award for

Table 4. Summary of WPI involvement in robotics competitions.

Competition Name	Year(s)	Result
NASA Lunar Regolith Excavation Challenge	2009	1st place
Sailbot International Robotic Competition	2016	1st place (1m class)
	2017	World Champions
DARPA Robotics Challenge	2013 - 2015	7th place (out of 25 finalists)
First Robotics Competition (FRC)	1992	Begins hosting Team 190
	2006 - present	Team 190 wins 26 local/ regional/national awards
	2007	Team 190 wins National Championship
	2006 - present	Hosting Regional, District, or District Championship
First Lego League (FLL) State Championships	2006 - present	Host Qualifying and State Championships. Manage state tournament program
NASA (RASC-AL) Exploration Robot-Ops Competition	2011	1st place
Battlecry (FRC off-season competition)	2006 - present	Hosted by WPI
VEX Robotics		
Savage Soccer	2006 - present	Hosted by WPI
BattleBots	2009	WPI-sponsored team takes 1st place
	2015	WPI-sponsored team takes 1st place
BattleBot IQ (college division)	2006	1st place
Cornell Cup	2011 - 2016	Grand Champion, 2x 1st place, Honorable Mention
Micromouse	2015 - 2017	
NASA Centennial Challenge (Sample Robot Return Mission)	2012 - 2016	Hosted by WPI
Robotic Mining Competition	2016	
	2017	Innovation award
RICC	2009, 2011	Hosted by WPI
Sabertooth	2011	2nd Place RICC
Intelligent Ground Vehicle Competition	2010	Rookie of the year
Team Oryx	2010 – 2011	1st place (twice)
RASC-AL Robot-Ops	2011 - 2013	1st place (twice), 3rd place

"developing and implementing the first ABET-accredited undergraduate Robotics Engineering program in the United States. The program incorporates an innovative, project-based curriculum that integrates computer science, engineering and entrepreneurship. It is producing large numbers of successful graduates, while serving as a model for Robotics Engineering programs at other institutions." [16]

5.4. Industry Interaction

One of the program strengths is the close interaction with industry. This interaction takes many forms, such as:

- Colloquia on campus by industrial colleagues and invited talks at industry by faculty,
- Sponsored undergraduate capstone projects and graduate research projects,
- An Advisory Board, composed of industry representatives and committed alumni, that provides strategic advice and resources to the program, and
- Membership in industry organizations, including the Advanced Robotics for Manufacturing Institute, Massachusetts Technology Leadership Council Robotics Cluster, National Advanced Mobility Consortium, National Defense Industry Association Robotics Division, and the Robotics Industry Association.

6. Conclusions

6.1. Lessons Learned

10 years of experience in Robotics Engineering have led to many valuable lessons.

- Robotics Engineering is not only a highly viable major, it is one of increasing importance.
- The top-down program design has led to a fundamentally well-designed curriculum that admits evolutionary change.
- The curriculum, courses, equipment, hardware, and software require constant attention and updating to remain vigorous and relevant.
- Students will work extraordinarily hard in robotics classes and labs, as well as co-curricular activities such as competitions.
- Strong industry connections lead to enhanced opportunities for students before and after graduation.
- Robotics Engineering has proven to be a boon for the university and a source of pride for the students in it.

6.2. Recommendations to Further Robotics Engineering Education

To further Robotics Engineering education, we recommend the following:

- Robotics Engineering should soon become a recognized branch of engineering.
- Development of a set of robotics-specific criteria by ABET, following identification of a lead and cooperating societies from among ASME, CSAB, IEEE, and possibly others.
- Enhanced robotics and mechatronics education community-building activities, including IEEE Robotics & Automation Society education materials [17] and the Mechatronics Educators Community forum [18].

Finally, we encourage additional colleges and universities to develop programs in Robotics and related fields to both spur and tap into interest in STEM education.

ACKNOWLEDGEMENTS

The Robotics Engineering program could only have been created through the hard work of many faculty, staff, and administrators at WPI. The authors wish to extend special thanks to Profs. N. Bertozzi, M.J. Ciaraldi, E.C. Cobb, D. Cyganski, G.S. Fischer, F.J. Looft, W.R. Michalson, T. Padır, K.A. Stafford, G. Tryggvason, Robotics Resource Ctr. Assoc. Dir. B.A. Miller, Lab Managers J. St. Germain and K. Harrington. Data collection and analysis by the WPI Career Development Center's Allyson Bernard and David Ortendahl in is gratefully appreciated.

REFERENCES

[1] W.H. Gates, "A Robot in Every Home", Scientific American, pp. 58-65, Jan. 2007.

[2] M.A. Gennert and T. Padir, "Robotics Engineering as an Undergraduate Major: A 5 year Retrospective," ASEE Annual Meeting, Atlanta, GA, Jun. 2013.

[3] J.M. Esposito, "The state of robotics education: proposed goals for positively transforming robotics education at postsecondary institutions," *IEEE Robotics & Automation Magazine* 24, no. 3 (2017): 157-164.

[4] M.A. Gennert, W.R. Michalson, M.A. Demetriou, "A Robotics M.S. Degree," *ASEE Annual Meeting*, Louisville, KY, Jun. 2010.

[5] M.J. Ciaraldi, et al., "The New Robotics BS Program at WPI," *ASEE Annual Meeting*, Pittsburgh, PA, Jun. 2008.

[6] G. Tryggvason and D. Apelian. "Re-Engineering Engineering Education for the Challenges of the 21st Century," Commentary in *JOM: The Member Journal of TMS*, Oct. 2006.

[7] ABET. http://www.abet.org/.

[8] T. Padir, G. Fischer, S. Chernova, M.A. Gennert, "A Unified and Integrated Approach to Teaching a Two-Course Sequence in Robotics," *J. Robotics and Mechatronics*, Vol. 23 No. 5, 2011.

[9] T. Padir, M.A. Gennert, G. Fischer, W.R. Michalson, E.C. Cobb, "Implementation of an Undergraduate Robotics Curriculum," *Computers in Education J. special issue on Robotics Education*, Vol. 1, No. 3, pp. 92-101, July-Sep. 2010.

[10] M. Prince, "Does active learning work? A review of the research," *J. Engineering Education*, 93 (3), 223-231, 2004.

[11] T. Padir, G. Fischer, W.R. Michalson, G. Pollice, "Development of a Laboratory Kit for Robotics Education," *Association for the Advancement of Artificial Intelligence Spring Symposium on Educational Robotics and Beyond: Design and Evaluation*, 2010.

[12] NeuronRobotics https://github.com/NeuronRobotics.

[13] Willow Garage, "TurtleBot," http://turtlebot.com/.

[14] G. Yetter, K. Capaccioli, "Differences in responses to Web and paper surveys among school professionals," *Behavior Research Methods*, 2010, 42 (1), 266-272

[15] G. Tryggvason, M.A. Gennert, F.J. Looft, T. Padir, L.E. Schachterle, Robotics: Assessing an Interdisciplinary Program," *ASEE Annual Meeting*, Louisville, KY, Jun. 2010.

[16] ABET. http://www.abet.org/blog/news/announcing-the-2016-abet-award-recipients/.

[17] IEEE Robotics & Automation Society. http://www.ieee-ras.org/educational-resources-outreach/educational-material-in-robotics-and-automation.

[18] Mechatronics Education Community. https://www.mechatronicseducation.org/.