# AC 2009-1161: DESIGNING AN UNDERGRADUATE ROBOTICS ENGINEERING CURRICULUM: UNIFIED ROBOTICS I AND II

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# Designing an Undergraduate Robotics Engineering Curriculum: Unified Robotics I and II


## Abstract

Robotics Engineering (RBE) is a new undergraduate degree program at the Worcester Polytechnic Institute (WPI). As of the fall semester of 2008, the program is the fourth largest discipline at the institution in terms of freshman enrollment. At the core of the curriculum are four signature courses called Unified Robotics I-IV. The goal of these courses is to introduce students to the multidisciplinary theory and practice of robotics engineering, integrating the fields of computer science, electrical and computer engineering and mechanical engineering. The sophomore level courses, RBE 2001 and RBE 2002, introduce students to the foundational concepts of robotics such as kinematics, pneumatics, circuits, electric motors, sensors, signal processing and embedded system programming. The junior level courses, RBE 3001 and RBE 3002, build on this foundation to ensure that students understand the analysis of selected components and learn system-level design and development of a robotic system including embedded design.

This paper discusses the development of a two-course sequence in undergraduate robotics education, Unified Robotics I and II, in detail. Learning outcomes and sample schedules illustrating our approach to designing a new robotics engineering program at the undergraduate level are presented. The paper exemplifies the robotics systems designed by the students within the scope of laboratory experiences and course projects. Finally, we discuss lessons learned, future directions, and student feedback. The initial observations and results are in favor of promoting robotics engineering as a new undergraduate engineering program.


## Introduction

It is well-known that robotics has become a passion among students of all ages[1,2]. In response to this growing interest, institutions of higher education have been introducing robotics courses into their existing curricula[3-5]. Interdisciplinary nature of the field of robotics makes it suitable for incorporating robotics focused engineering courses into engineering programs in one form or another with electrical and computer engineering, mechanical engineering and computer science programs being perhaps the most common of these programs. Indeed, it is very common to find robotics related modules and projects in undergraduate courses on embedded systems, analog electronics, dynamics, algorithms, as well as introduction to engineering. Moreover, robotics projects are frequently encountered in capstone design courses.

Robotics as an engineering discipline requires a strong background in mathematics and sciences as well as in engineering design and programming[5,10]. For this reason, robotics courses have historically been offered at the graduate level and have mostly focused on the study of robot manipulators. Over the past several years, however, robotics has evolved to become a rather diverse field covering a wide spectrum of topics and educational endeavors ranging from assistive technologies to biologically inspired systems, from industrial robotics to humanoids

which provides even more opportunities for incorporating robotics into the undergraduate engineering and even K-12 science curricula.

As described in a companion paper at this conference, Robotics Engineering (RBE) is a new WPI undergraduate degree program introduced in the spring of 2007 and administered by the departments of Computer Science, Electrical and Computer Engineering and Mechanical Engineering. As of the fall of 2008, the program is the fourth largest engineering program (among 11) at the institution in terms of freshmen enrollment. The B.S. program will produce its first graduates in May 2009 and it is planned to seek ABET-EAC accreditation under general engineering criteria in the 2010-2011 academic year.

The RBE program objectives are to educate men and women to:

- Have a basic understanding of the fundamentals of Computer Science, Electrical and Computer Engineering, Mechanical Engineering, and Systems Engineering.
- Apply these abstract concepts and practical skills to design and construct robots and robotic systems for diverse applications.
- Have the imagination to see how robotics can be used to improve society and the entrepreneurial background and spirit to make their ideas become reality.
- Demonstrate the ethical behavior and standards expected of responsible professionals functioning in a diverse society.

These objectives are implemented, in part, through a series of four signature courses called Unified Robotics I-IV. The goal of these courses is to introduce students to the multidisciplinary theory and practice of robotics engineering, integrating the fields of computer science, electrical engineering and mechanical engineering.

In contrast to a theory-driven traditional engineering curriculum, the Unified Robotics courses start with the robot as a design platform and introduce the theory and principles of electrical and mechanical systems as well as programming and algorithms with applications to robotics.

The sophomore-level courses Unified Robotics I and II (RBE 2001 and RBE 2002) emphasize the foundational concepts of robotics such as kinematics, stress and strain, pneumatics, electrical circuits, operational amplifiers, electric motors and motor drive circuits, sensors, signal conditioning and embedded system programming using C language. The goal is to introduce students to the analysis of electrical and mechanical systems as well as the principles of software engineering.

It should be noted that both RBE 2001 and RBE 2002 are offered in 7-week terms with 4 hours of lecture and 2 hours of laboratory session per week. Further in concept with the long history of the WPI Plan[18], these courses emphasize project based-learning, hands-on assignments, and students' commitment to learning outside the classroom.

Below, RBE 2001 and RBE 2002 will be discussed in detail.

**Unified Robotics I**

The focus in RBE 2001 is the effective conversion of electrical power to mechanical power. The course also provides a hands-on introduction to embedded systems programming as well as the analysis of mechanisms and electrical circuits within the context of robotics engineering. Course topics and laboratory experiences include position, velocity, acceleration and force analysis of simple mechanisms, electric motors, H-bridges and motor drive circuits, an introduction to control systems and PID controllers, C programming and software engineering.

Learning outcomes for RBE 2001 are:

- Describe basic terminology related to the field of robotics.
- Formulate the position and velocity kinematics of a mobile robot in 2D.
- Determine power system requirements and structural requirements using force analysis.
- Specify DC motor requirements that meet a specified locomotion or manipulation task.
- Write moderately involved programs in C to perform a specified task with a robotic system in real-time.
- Specify appropriate electrical system design to convert battery energy into a controllable power drive signal to a specified DC motor.
- Construct, program, and test the operation of a mobile robotic system to perform a specified task.

RBE 2001 was first offered in the spring of 2008. The recommended background for this course includes our first year introduction to robotics course, basic digital circuits and statics. Although not discussed in detail in this paper, we note that RBE 1001 Introduction to Robotics, serves as the first-year engineering course within the RBE program and is required for the robotics engineering majors. As might be expected, RBE 1001 attracts students from a wide range of disciplines including computer science, electrical and computer engineering, mechanical engineering, biomedical engineering, civil engineering and so forth.

| ***Declared Major*** | ***Number of Students*** |
|---|---|
| Robotics Engineering | 54 |
| Mechanical Engineering | 6 |
| Computer Science | 5 |
| Electrical and Computer Engineering | 4 |
| Other | 3 |
| **Total** | **72** |

**Table 1: Students enrolled in RBE 2001 Unified Robotics I according to their majors in the fall of 2008.**

In the fall of 2008, 72 students were enrolled in RBE 2001, a 300% increase from the first offering in the spring of 2008. A breakdown of the students according to their majors is presented in Table 1. While it is clear that the course attracted students from diverse backgrounds the vast majority of the students considered themselves RBE majors even though their declared major (with the registrar) may have indicated otherwise.

As summarized in Table 2, majority of students come with a background appropriate for a sophomore level class; e.g. a completed calculus sequence, knowledge of mechanics and electricity from Physics, and some but not sufficient programming skills. It should be noted that more than one third of students reported that they had not taken differential equations and a majority lacked linear algebra. In view of this observation, it has been a challenge to design a course which will both cover the foundations of mechanical and electrical systems, embedded systems programming and control systems while keeping all the course material relevant to robotics and within the course foundation of the students.

| ***Courses Taken*** | ***% of students*** |
|---|---|
| Calculus I-IV | 94-98 % |
| Differential Equations | 64 % |
| Linear Algebra | 16 % |
| Physics I-II (Mechanics, Electricity) | 94-98 % |
| Statics | 79 % |
| Introduction to Robotics | 85 % |
| ***Software Packages*** | |
| TKSolver | 0 % |
| MathCAD | 6 % |
| MATLAB | 19 % |
| Excel or equivalent | 96 % |
| ***Computer Programs*** | |
| Scheme | 66 % |
| C/C++ | 43 % |
| Basic | 17 % |
| Visual Studio | 11 % |
| Other | 49 % |
| I cannot write computer code. | 13 % |

**Table 2: Background and skill sets for students enrolled in RBE 2001 Unified Robotics I in the fall of 2008 (53 respondents).**

***Structure:***

In planning the lectures and laboratory experiments for RBE 2001, a typical robot task is the design problem and all the relevant theory and practice are presented within the context of solving this task. 53 students responded to a survey administered in RBE 2001 at the beginning of the fall of 2008 and the results revealed that the common ground for the course was not too broad (See Table 2 for survey results).

Based on the expected background of students and learning outcomes developed for the course, the lectures are structured in a modular way to cover foundational topics in robotics. Moreover, the laboratory experiences are designed to complement the course material. . The course was team-taught by three faculty members from computer science, electrical and computer engineering and mechanical engineering departments.

Table 3 provides an outline of the lectures and laboratories for RBE 2001. In addition to *C++: How to Program* by Deitel[14], a custom textbook which combined selected chapters from *Design of Machinery* by Norton[15] and *Fundamentals of Electrical Engineering* by Rizzoni[16] is used for the RBE 2001-2002 sequence.

| ***Class/Lab*** | ***Topic*** |
|---|---|
| 1-4 | Introduction to Kinematics, Steering Mechanisms, Position Analysis |
| Lab 1 | Constructing and Testing a Basebot |
| 5-6 | Introduction to Embedded C programming |
| 7-8 | Introduction to Electric Circuits and Measurement |
| Lab 2 | Applied Kinematics: Steering the Basebot |
| 9-10 | Introduction to Control Systems, PID controller |
| 11-12 | Electric Motors and Drives |
| Lab 3 | Implementation of a PID Controller for Basebot |
| 13-15 | More Kinematics, Velocity and Acceleration Analysis |
| Lab 4 | DC Motor Drive Circuit: Steerable Basebot |
| 16-18 | Software Engineering |
| 19-21 | Dynamic Force Analysis, Virtual Work, Lumped Parameter Models |
| Lab 5-7 | Term Project: Bringing all together |
| 22-23 | More C programming |
| 24-26 | Electric and Mechanical Power, Batteries, DC-DC converters, |

**Table 3: Lecture and laboratory outline for RBE 2001.**

It should be noted that a 7-week term allows 28 lectures and the schedule presented in Table 3 reserves 2 lectures for the in-class examinations. While in a traditional college quarter or semester, 26 lectures may not seem like sufficient time to cover the requisite material, WPI has been pioneering this approach for more than 35 years with great success. The fundamental requirement for success is significant student learning that takes place outside the classroom[18].

***Laboratories:***

The laboratory assignments have been completed using the VEX Classroom Lab Kits[17]. Each lab group consisted of 2-3 students and teams are provided with a robotic design kit at the beginning of the term. As needed, additional DC motors, H-bridge motor drive chips, and custom made mechanical parts are also provided.

The final laboratory project which spans three weeks mainly has two parts. First, project teams are required to design a mobile robot that can autonomously navigate to a set location from a base by using a steering mechanism and implementing a PID controller for DC motor position control. Second, the project becomes open-ended in the sense that students are given the freedom of choosing an additional functionality for their robot. Figure 1 illustrates examples of robots designed within the scope of RBE 2001 final project.

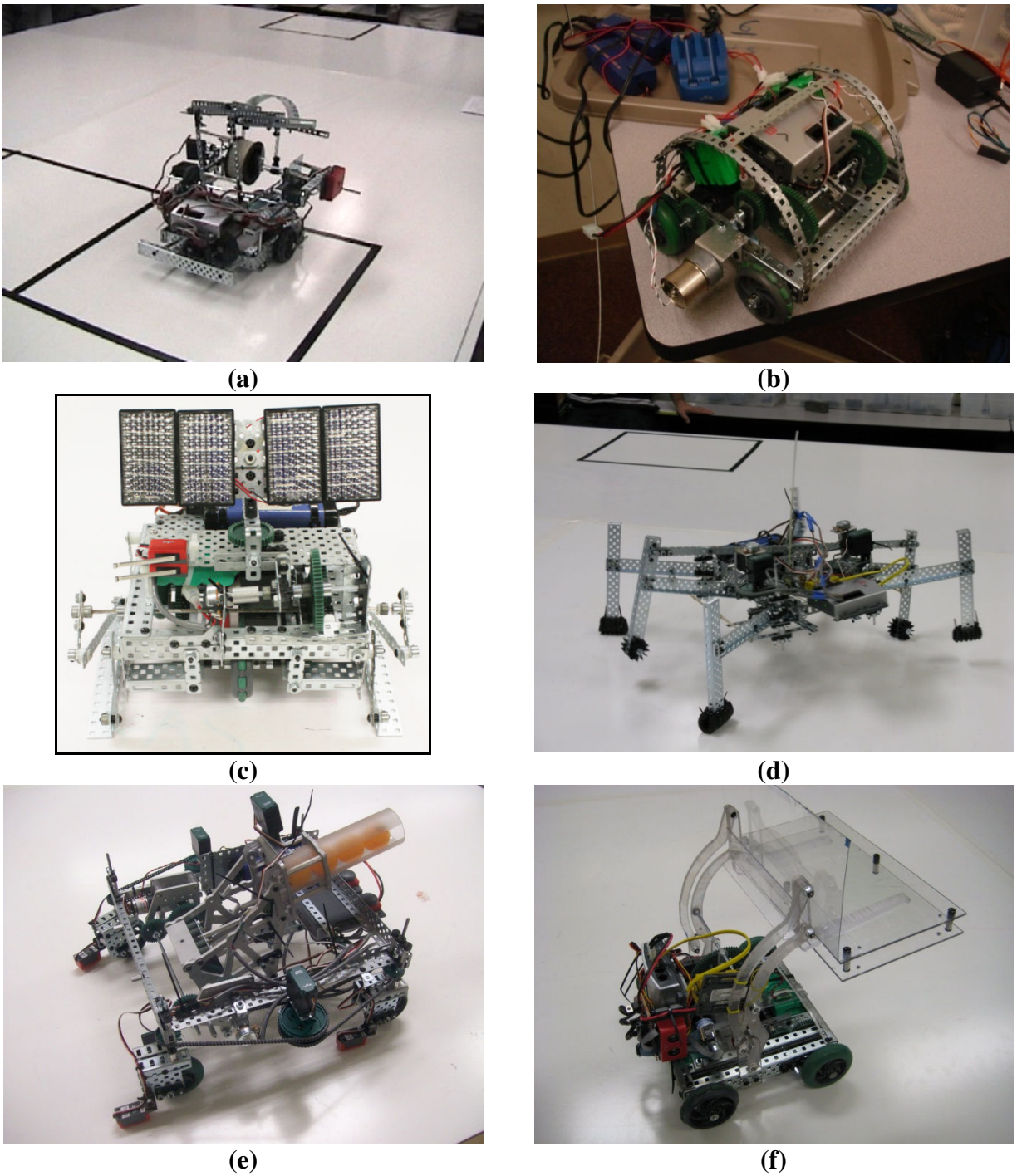

**Figure 1: Robots designed by RBE 2001 students as their final project: (a) Rappelling robot that uses fishing line to lower itself from the table to the floor. (b) Somersaulting robot – name says it all. (c) Light-seeking robot that turned towards the brightest spot in the room. (d) A hexapod that used 3 PID controlled DC motors. (e) A ping-pong ball shooting robot with a custom made shooter mechanism. (f) A fork-lift robot with a fourbar linkage design.**

***Observations and Outcomes:***

Based on course evaluations and faculty feedback following observations can be reported about RBE 2001 Unified Robotics I:

- Although the course is designed for the Robotics Engineering B.S. degree program, it attracts students from various departments.
- The course is designed to cover the foundations of mechanical engineering, electrical engineering and computer science relevant to the study of robotics while keeping the focus on applications of robots.
- One common problem students encountered in the course was to grasp the material fully in all three fields comprising the course content. It was common to observe students doing quite well in one or two of the areas while struggling in the third. It is our observation that especially during the lab activities, one student would do all the programming while the other worked on the mechanical assembly.
- According to course evaluations completed by the students in the fall semester of 2008,
  - 68% said that they learned more from the course relative to other courses.
  - 74% found the organization of the course very good or excellent.
  - 68% ranked the educational value of the assigned work as very good or excellent.
  - 87% said that they put more effort into the course relative to other courses.
  - 64% reported that they spent 17 hours or more per week on all activities related to the course. 88% reported 13 hours or more.
- At the end of the term, the grade distribution was as follows (72 students total):
  A : 22 students; B : 33 students; C : 10 students; NR (No Record)[19] : 8 students.
- Despite the heavy work load, the quality of the final projects was a clear indicator of the passion and commitment of the students in the RBE program.

**Unified Robotics II**

***Overview:***

RBE 2002 emphasizes the interaction of a robotic system with its environment through sensors and feedback. Concepts of stress and strain in the context of force sensing, material properties and operational principles of sensors used in robotics, basic signal conditioning such as amplification and filtering, as well as programming strategies for integrating multiple sensors are introduced. Learning outcomes for RBE 2002 are:

- Apply concepts of stress and strain as related to sensing of force in robotics applications.
- Demonstrate the knowledge of physical properties of materials used to design sensors for robotics applications.
- Analyze sensor signals and design electronic circuits and/or implement algorithms for signal conditioning.
- Perform transient and AC circuit analysis applied to robotics.
- Develop programming strategies for a robot with multiple sensors to perform a specified task.
- Construct, program, and test the operation of a robotic system to perform a specified task.

RBE 2002 was first offered in the spring of 2008. RBE 2001 Unified Robotics I and introduction to program design make up the recommended background.

In the fall of 2008, 54 students were enrolled in RBE 2002, a 260% increase from the first offering in the spring of 2008. For this course, 45 out of 54 students enrolled listed themselves as RBE majors.

Table 4 provides an outline of the lectures and laboratories for RBE 2002.

| ***Class/Lab*** | ***Topic*** |
|---|---|
| 1-3 | Properties and Mechanics of Materials |
| Lab 1 | Motor Current Sensing and Mechanical Force Analysis |
| 4-5 | Instrumentation for Sensors |
| 6-8 | Embedded C Programming: Structures and Pointers |
| Lab 2 | Strain Gauges and Instrumentation Amplifiers |
| 9-10 | Stepper Motors and Drive Circuits |
| 11-12 | Sensor Classification and Sensor Characteristics |
| Lab 3-4 | Basebot Design with Multiple Sensors |
| 13-14 | Signal Conditioning |
| 15-17 | Sensors for Mobile Robots I |
| 18-21 | More Programming in C: Sensing Strategies |
| Lab 5-7 | Term Project: Fire Fighting Robot |
| 22-23 | Hydraulic and Pneumatic Devices |
| 24-26 | A Survey on Sensor Technologies |

**Table 4: Lecture and laboratory outline for RBE 2002.**

***Laboratories:***

In a manner similar to RBE 2001, the laboratory assignments are completed using the VEX Classroom Lab Kits[17].

The final laboratory project which spans three weeks has, to date, been a variation of the Trinity College Fire-fighting Robot Contest[9,11]. Specifically, project teams are required to design a mobile robot that can autonomously navigate on a field to detect the entry to a room, locate a candle simulating a fire inside the room and put it out. The project requires a well-thought design process and developing sensing and navigation strategies for successfully completing the task. The project is open-ended as students are not provided specific instructions on the mechanical or electrical design. Rather, they are only provided a set of design criteria. Each robot performance is evaluated based on how fast it locates the doorway, how fast it makes entry to the room, how fast it locates the fire, how fast it puts out the fire and how fast it returns to the base. Then each robot design is evaluated based on mechanical, electrical, and software design, as well as design tradeoffs, and project documentation. Figure 2 illustrates examples of robots designed for RBE 2002 final projects.

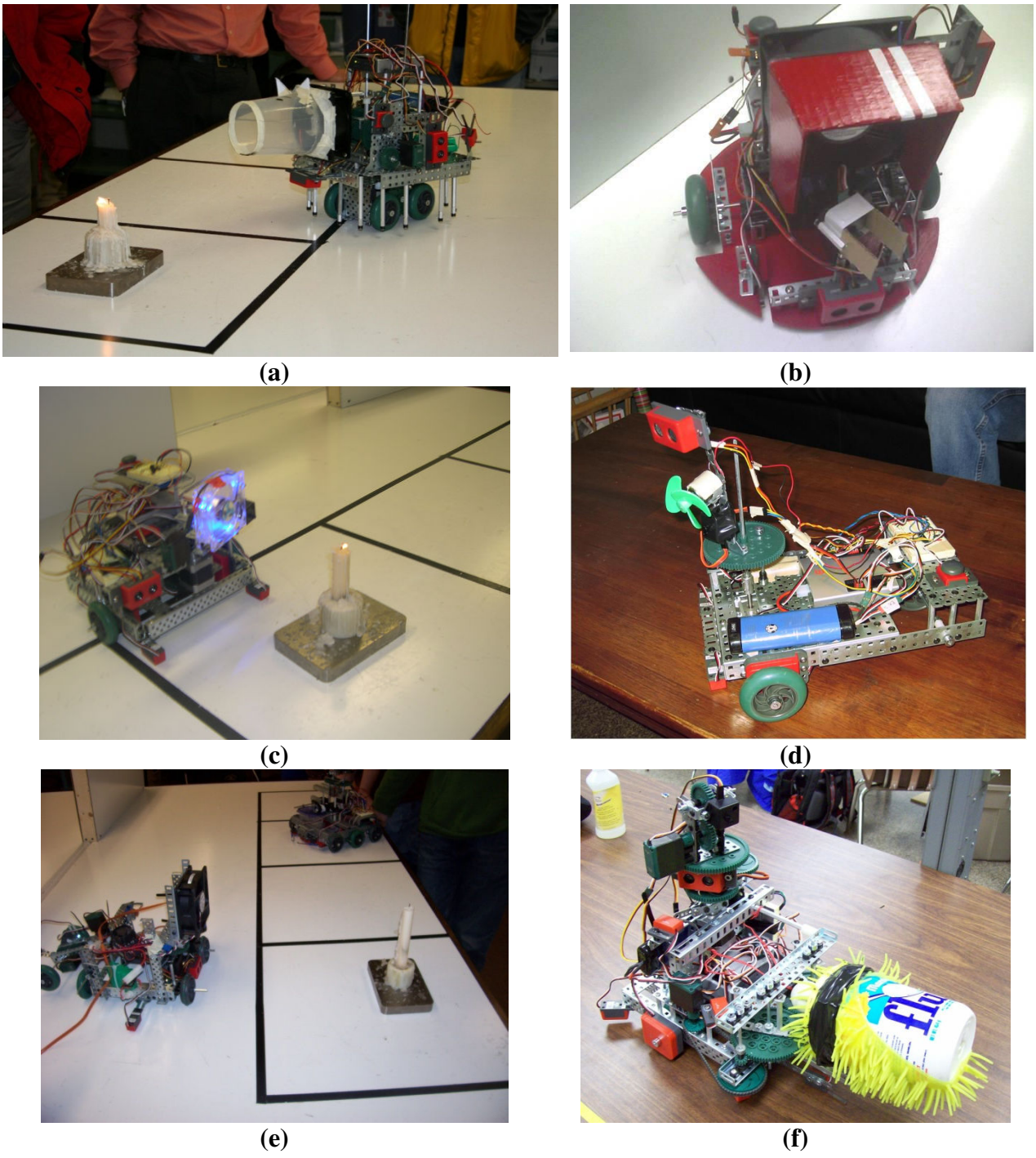

**Figure 2: (a)-(f) Fire-fighting robots designed by RBE 2002 students as their final project.**

***Observations and Outcomes:***

Based on student and faculty feedback following observations can be made about RBE 2002 Unified Robotics II:

- According to course evaluations completed by the students in the fall semester of 2008,
  - 86% said that they learned more from the course relative to other courses.
  - 91% found the organization of the course very good or excellent.
  - 79% ranked the educational value of the assigned work as very good or excellent.
  - 91% said that they put more effort into the course relative to other courses.
  - 51% reported that they spent 17 hours or more per week on all activities related to the course. 84% reported 13 hours or more.
- At the end of the term, the grade distribution was as follows (54 students total):
  A : 24 students; B : 25 students; C : 3 students; NR (No Record)[19] : 3 students.
- Despite the heavy work load, the quality of the final projects was a clear indicator of the passion and commitment of the students in the RBE program.

## Conclusion

This paper has presented an overview of a two-course sequence in undergraduate robotics education, Unified Robotics I and II. The planning of these courses illustrates the approach adopted by the faculty at the Worcester Polytechnic Institute to design a new robotics engineering program at the undergraduate level. Although most student learning take place outside the classroom by enforcing hands-on assignments and independent study, students remain passionate about robotics and are highly committed to the new RBE program.

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