Development of a Laboratory Kit for Robotics Engineering Education

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Abstract

This paper discusses the development of a sequence of undergraduate courses forming the core curriculum in the Robotics Engineering (RBE) B.S. program at Worcester Polytechnic Institute (WPI). The laboratory robotics kit developed for the junior-level courses is presented in detail. The platform is designed to be modular and cost-effective and it is suitable for laboratory based robotics education. The system is ideal not only for undergraduate coursework but also may be adapted for graduate and undergraduate research as well as for exposing K-12 students to STEM.

Introduction

As the robotics community celebrates "50 years of robotics" [1], there is no doubt that research and development in the field has evolved drastically since the introduction of the first industrial automation robot, the Unimate. With the advances in enabling technologies (electronics, hardware and computation) and components (sensors and actuators), intelligent vehicles are capable of assisting human drivers in urban environments, vacuum cleaning and lawn mowing robots are becoming a common household appliance, medical and rehabilitation robots are assisting with elder care.

It is also well-known that robotics has become a passion among students of all ages [2]. Robotics provides a new opportunity to capture the interests of students in grades K-12 and to introduce them to engineering and science. Currently, students are exposed as early as K-12 to a growing number of robot competitions such as the FIRST Robotics Competition (http://www.usfirst.org). Strong ties between these competitions, student enthusiasm, research, and education have been observed [3].

Robotics as an engineering discipline is an excellent fit for the undergraduate engineering education of 2020 described in the NAE report titled *Educating The Engineer Of 2020* [4]. Robotics can be used to introduce students to the essence of engineering early in their undergraduate careers; it is an interdisciplinary field of study which can be used to enrich and broaden engineering education; it promotes teamwork, technical competency, innovation and lifelong learning; more importantly, it proves to be an effective tool for improving the recruitment and retention of a diverse range of students [5-7]. The interdisciplinary nature of the field of robotics makes it suitable for incorporating robotics-focused courses into traditional engineering programs such as electrical and computer engineering, mechanical engineering and computer science programs [8, 9].

Growth in the field of robotics, and a perceived need for engineers trained with multidisciplinary skills led the Worcester Polytechnic Institute (WPI) to create a new undergraduate degree program in Robotics Engineering (RBE) in 2007.

As of the fall semester of 2009, the program has grown rapidly to become the the fourth largest discipline at the institution in terms of freshman enrollment. 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 abstract concepts and practical skills from the separate engineering disciplines together 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.

The program has a structure that integrates the foundational concepts from computer science, electrical and computer engineering and mechanical engineering to introduce students to the multidisciplinary theory and practice of robotics engineering. For this purpose, a series of undergraduate courses were created consisting 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). All courses 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 [10], these courses emphasize project-based learning, hands-on assignments, and students' commitment to learning outside the classroom.

RBE 1001 Introduction to Robotics

This course provides a broad overview of robotics at a level appropriate for first-year students. It serves as a stepping stone for students who haven't been involved with high-school level robotics courses and/or competitions. The goal is to capture students' enthusiasm about robotics early in their engineering careers and keep the students engaged. The course also serves as an introduction to Computer Science, Electrical and Computer Engineering and Mechanical Engineering as it is team-taught by faculty from each discipline. The course topics include static force analysis, electric and pneumatic actuators, power transmission, sensors, sensor circuits, C programming and implementation of proportional control in software. The objective is not to cover every topic in depth, but to provide students with a flavor of the subsystems forming a robot. The laboratory assignments use the VEX Robotics Development Kit [11], an off-the-shelf system, supported with the internally developed WPILib C software library for controlling dc motors, reading signals from various sensors including potentiometers, optical encoders, ultrasonic rangefinders, and gyroscopes.

The Unified Robotics I-IV course sequence forms the core of the Robotics Engineering program at WPI. The sophomore level courses, RBE 2001 and RBE 2002, introduce students to the foundational concepts of robotics engineering such as kinematics, circuits, 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.

RBE 2001-2002 Unified Robotics I-II

The sophomore-level courses, Unified Robotics I and II (RBE 2001 and RBE 2002), emphasize the foundational concepts of robotics engineering including kinematic linkage analysis, stress and strain, pneumatics and hydraulics, dc circuits, operational amplifiers, electric motors and motor drive circuits, sensors and sensor signal conditioning and embedded system programming using the C language [6]. The goal is to introduce students to the analysis of electrical and mechanical systems as well as the principles of software engineering. In both courses, the emphasis is on robotics applications, project-based learning and on the relationship among the electrical engineering, mechanical engineering and computer science disciplines as they apply to robotics. In combination, RBE 2001 and RBE 2002 provide a study of the foundations of robotics by integrating the fields of computer science, electrical engineering and mechanical engineering and prepare students for the advanced robotics courses.

Providing such a broad foundation in the 2000-Level robotics courses necessarily requires making compromises in the number of topics covered and the depth coverage in any one topic. It is simply not possible, given practical constraints on class time and student load to introduce students to everything they might require to engineer a robotic system. To balance these conflicting constraints, certain compromises are made in the delivery of the material to the students and in the exercises performed in the laboratory.

The first compromise relates to the material that is selected. Rather than attempt to teach all of the material that might normally be associated with a 2000-level course in any one discipline, the choice was made to pare the material to that which is essential to provide sufficient depth for the students to understand the related laboratory exercises. In this context, the emphasis in the classroom is on the most commonly encountered concepts rather than interesting special cases. In determining curriculum content, every topic is scrutinized to ensure that it is actually used for some significant purpose in the classroom, on homework, in exams and in the laboratory.

A second compromise relates to the laboratory exercises. In the laboratory students largely work with pre-packaged hardware and software elements which, while sufficient to reinforce concepts introduced in the classroom, hide many of the lower-level details of the devices they use in the laboratory. This provides a stable environment which allows students to focus on electrical, mechanical or computer science concepts introduced in class without worrying about these lower-level details. The result of these compromises is that students at the 2000 level have enough theoretical knowledge to "mostly" know how to approach a laboratory problem, and have a set of tools in the laboratory which allow them to rapidly prototype their solution. Many of these solutions fail on their initial attempt, which tends to prompt the students to stay engaged, revisit their errors and iterate on their designs. The result is a reinforcement of classroom theory, the development of better intuition from seeing ideas that don't work, and an increase in their willingness to iterate towards a better design.

RBE2001-2002 laboratories continue to use the VEX Robotics Development Kit supplemented by our WPILib software library. The lab assignments are designed to emphasize the theoretical background, such as simple linkage analysis, dc motor parameter identification, and sensor signal amplification [6].

RBE 3001-3002 Unified Robotics III-IV

Junior-level courses, Unified Robotics III and IV (RBE 3001 and RBE 3002) build upon the intuition that the students began to develop in the 2000-level courses [7]. It is in these courses that the students actually begin to understand and appreciate the details underlying their

2000-level experience. These junior-level courses provide a much deeper theoretical coverage of robotics, including: frame transformations, forward kinematics and inverse kinematics, manipulator dynamics, control systems, sensors, signals, reasoning with uncertainty, navigation, world modeling and path planning. In these courses students no longer have pre-packaged hardware and software components; they now are introduced to interrupt-based programming, software system architecture, object-oriented design and in-circuit debugging, and probabilistic algorithms.

The focus in RBE 3001 is on developing a deeper understanding of the types of devices they encountered in RBE 2001 and 2002. The course begins with an introduction to the Atmel AVR series of 8-bit microcontrollers which provide the computational platform for all of the experiments done in the laboratory. These experiments involve topics such as: real-time interrupt-based programming; control of a single axis robot arm; control of a multiple link robotic manipulator; characterizing encoders, accelerometers and magnetometers; characterizing infrared and ultrasonic rangers; and developing a simple, but complete, pick and place robotic system.

The focus in RBE 3002 is on integrating the information in the previous three courses into a complex robotic system. This course begins with an introduction to object-oriented programming and development of a framework based on a communication protocol between a PC and a robot. By incorporating hardware and software components developed in RBE 3001, the students perform experiments which involve topics such as: hardware/software partitioning; control of a mobile platform; multi-sensor data fusion, motion planning, world modeling and reasoning in the presence of uncertainty.

Laboratory Kit for RBE 3001-3002

Laboratory experiences are an essential part of any undergraduate or graduate robotics course. By completing the laboratories, students are able to design and build robotic systems to perform pre-specified tasks, demonstrate the ability to collect, analyze, and interpret data, identify the sources of error in a physical system, demonstrate appropriate levels of creativity in solving real-world problems, work effectively in teams and communicate effectively about laboratory work, both orally and in writing [12]. Successful implementation of laboratory experiences for robotics courses rely on the availability of robust, low-cost and modular robotic platforms suitable for design and experimentation.

When students complete the 2000-level Unified Robotics courses, they have developed a basic theoretical understanding of robot-related topics, good intuition related to mobile robot platforms, actuators and sensors, and considerable experience designing simple robots to complete relatively well constrained tasks. At this level, however, they don't necessarily understand how the hardware and software components they are using actually work. Their access to the hardware and software details of the equipment they are using is limited, as is their ability to manage real-time constraints.

Upon entering the junior-level unified robotics courses, students begin to explore topics they were able to take for granted at the sophomore level. In these courses, students are provided a number of components designed and custom-built by WPI's Robotics Engineering faculty and staff as shown in Figures 1 and 2, which include:

- A custom-designed 2-axis robotic arm (the "EduArm") which is composed of modular joints powered by DC motors with incorporated optical joint encoders and potentiometers for feedback,
- The "EduBot" compact, modular mobile robot platform with rear differential drive by dual encoded DC motors, omnidirectional front wheels, battery power, and a modular frame allowing attachment of standard components including the EduArm,
- Embedded controller hardware including an AVR microcontroller, analog and digital inputs and outputs, linear and switching motor amplifiers, power distribution and communications,
- Software libraries with varying levels of abstraction for embedded control of the system with varying levels of abstraction,
- Programming and debugging connections between the robot and a PC,
- Wired and wireless communications with a PC for hierarchal/supervisory control of the micro-controller and data logging,

The STK-500 development system for Atmel's AVR microcontrollers provides a basic platform which allows serial I/O, provides LED indicators, pushbutton switches and header connectors for accessing the I/O ports of the ATmega644 processor (located underneath the custom-made expansion daughter card). Students can purchase the

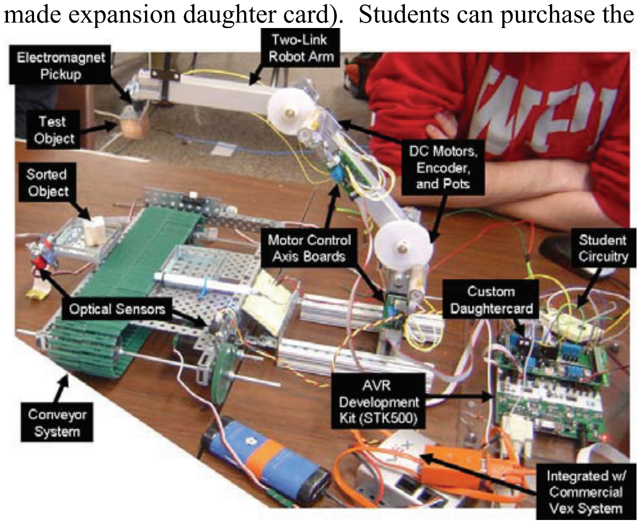

Figure 1: Prototype EduArm system including the 2-Link arm with DC motors, encoders, potentiometers, gear trains, magnetic gripper, sensors, control circuitry, and microcontroller.

STK-500 boards at a discounted price, which allows them to develop software outside of the laboratory. Development tools consist of AVR Studio 4 or the Eclipse environment and WinAVR which are freely downloadable, but which provide the features necessary to upload and debug programs written in C/C++ or AVR assembly language. This combination provides students with a low-cost way of obtaining a fairly powerful programming environment. In the laboratory students also have access to JTAG MKII interfaces for in-circuit debugging.

The expansion daughtercard board provides the following features:

- 2 independent linear motor control channels
- 2 independent motor control channels with H-Bridge outputs
- Motor drive current sensing
- 4 channel, 12-bit digital-to-analog converter (DAC)
- Highly configurable using on-board jumpers
- Support for two axis control boards
- Support for one ultrasound interface board
- Support for one infrared sensor module
- Support for one compass/accelerometer board.

In addition, custom hardware was developed for control of each motorized axis, ultrasonic sensing, accelerometers and a magnetic compass.

Given these tools, students are now required to handle all of the low-level details they were able to ignore at the 2000-level. A typical laboratory exercise consists of:

- Reviewing schematic diagrams of the expansion card (and other cards used),
- Reviewing component datasheets as necessary,
- Developing math models based on the theory,
- Developing code to implement the derived math models,
- Developing code to measure and record real-time data as the system operates,
- Transferring data from the system under test to a PC for subsequent analysis, and
- Analyzing results using tools such as Matlab to compare their implementation to theory.

Software Framework

In order to facilitate the implementation of the high-level obstacle avoidance, path planning and navigation algorithms, such as Dijkstra or A* algorithms, a software framework is designed to accompany the hardware described above. The computing platform consists of two parts. The device computing platform resides on the robot and uses the Atmel AVR644P processor. The client computing platform runs on a workstation, usually a Microsoft® Windows PC or a Linux system. The device platform interfaces directly with the hardware components on the robot and communicates with the client via a serial, wireless connection. The client performs the bulk of the complete system's computation.

The library provides the functionality needed for an application program on the client to access the activators and sensors on the robot in a well-defined, uniform manner. The library can be extended to easily accommodate new hardware components. Figure 3 illustrates the UML representation of an API developed by students. Figure 4 demonstrates the world map generated by a student team using the EduBot platform and the software framework.

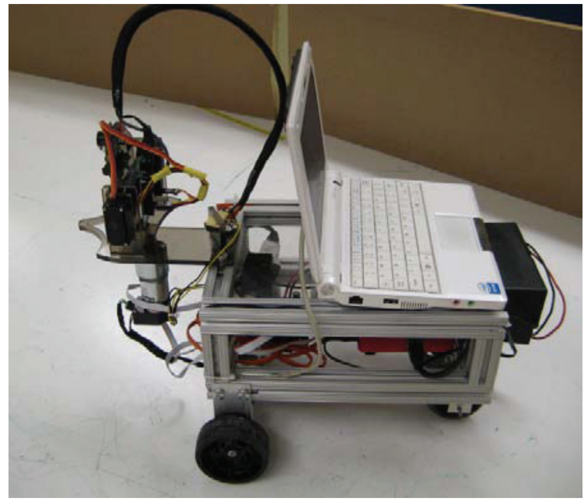

Figure 2: Prototype EduBot system with obstacle avoidance and navigation capabilities.

Evaluation

Students are surveyed at the completion of each course and data is compiled for the courses in the core curriculum. The data are reviewed by the RBE faculty during the Annual Retreat. As a result, each course in the Unified Robotics sequence has gone through revisions at least once based on this review process. Sample data collected from the student course evaluations is presented in Appendix A.

We have gathered extensive formal and informal input from these courses and while the overall student satisfaction has been high, the feedback has unearthed issues involving expected workload and integration. These have lead to several modifications in the courses and an observable increase in student perception of quality.

Conclusion

In conclusion, although 2008/09 marks the first offering of the entire four-course sequence, it appears that our approach is leading to an effective way of teaching multidisciplinary skills to engineering students based on robotics education and the laboratory platform developed at WPI is transforming the way in which robotics engineering is taught. To date, the implementation of the Unified Robotics sequence appears to be having the desired effects of a spiral curriculum. In some sense, everything the students do in the laboratory in RBE 3001-3002 is directly related to something they have done in the previous RBE 2001-2002 courses.

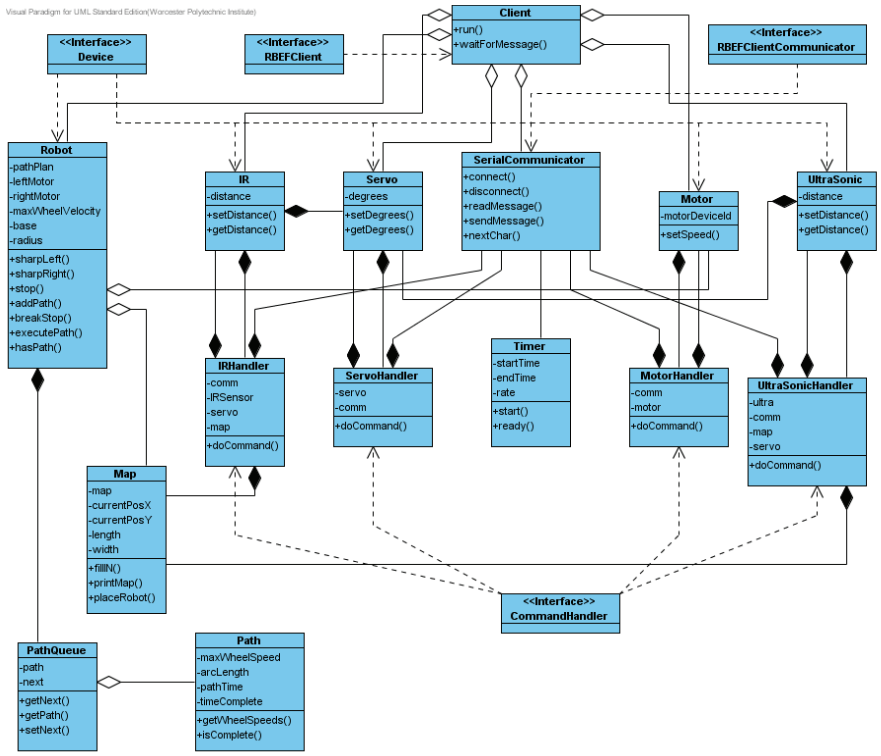

Figure 3: UML representation of the Application Programming Interface (API) developed by RBE 3002 students using the software framework.

Figure 4: World map generated by a student team using the EduBot platform and the software framework.

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Appendix A: Summary of Student Responses to Course Evaluations

RBE 2001 Unified Robotics I (A-term 2008)
- 54 responses
- 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.

RBE 2002 Unified Robotics II (B-term 2008)
- 45 responses
- 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.

RBE 3001 Unified Robotics III (C-term 2009)
- 21 responses
- 82% said that they learned more from the course relative to other courses.
- 73% found the organization of the course very good or excellent.
- 83% ranked the educational value of the assigned work as very good or excellent.
- 100% said that they put more effort into the course relative to other courses.
- 100% reported that they spent 21 hours or more per week on all activities related to the course.

RBE 3002 Unified Robotics IV (D-term 2009)
- 28 responses
- 72% said that they learned more from the course relative to other courses.
- 37% found the organization of the course very good or excellent.
- 71% ranked the educational value of the assigned work as very good or excellent.
- 88% 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. 96% reported 13 hours or more.

RBE 2001 Unified Robotics I (A-term 2009)
- 30 responses
- 80% said that they learned more from the course relative to other courses.
- 83% found the organization of the course very good or excellent.
- 80% ranked the educational value of the assigned work as very good or excellent.
- 86% said that they put more effort into the course relative to other courses.
- 43% reported that they spent 17 hours or more per week on all activities related to the course. 82% reported 13 hours or more.

RBE 2002 Unified Robotics II (B-term 2009)
- 33 responses
- 72% said that they learned more from the course relative to other courses.
- 91% found the organization of the course very good or excellent.
- 81% ranked the educational value of the assigned work as very good or excellent.
- 74% said that they put more effort into the course relative to other courses.
- 43% reported that they spent 17 hours or more per week on all activities related to the course. 62% reported 13 hours or more.