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A Unified and Integrated Approach to Teaching a Two-Course Sequence in Robotics Engineering

Taskin Padir, Gregory S. Fischer, Sonia Chernova, Michael A. Gennert

Worcester Polytechnic Institute
E-mail: {tpadir, gfischer, soniac, michaelg}@wpi.edu
[Received 00/00/00; accepted 00/00/00]

This paper presents the details of the curricular content developed for a two-course robotics sequence within the undergraduate Robotics Engineering program at Worcester Polytechnic Institute. The approach focuses on teaching a unified robotics curriculum, incorporating the foundational concepts from computer science, electrical engineering and mechanical engineering, in an integrative manner by emphasizing the whole system design. Outcomes include high student satisfaction, enhanced student learning and a broad engineering education to meet the needs of the growing robotics industry.

Keywords: Robotics engineering education, robotics curriculum, unified robotics, educational robot platform.

1. Introduction

The engineering profession has seen the demand and creation of new disciplines over the centuries. Biomedical, environmental, aeronautical and computer engineering are only a few examples of engineering branches that emerged to meet the growing needs of industry. A recent report by UNESCO [1] provides a new perspective on the importance of engineering in development. According to the report, a new wave of engineering innovation is currently taking place, incorporating concepts such as sustainability, renewable energy, resource productivity, biomimicry and whole system design. It is also emphasized in the report that to be able to meet the growing need for engineers globally, it is important to make an engineer's role more visible within society and better understood by younger generations.

Robotics Engineering is on the verge of becoming the next disruptive engineering discipline. It is by nature a highly multidisciplinary field; application areas are only limited by imagination; it is an all-inclusive field that proved to excite students of all ages; research in the field has been growing exponentially not only in terms of achievements but also based on the number of researchers, funding, centers and programs. Robotics Engineering has the potential of attracting young generations to the engineering profession to meet the global needs for development.

There are many market forecasts predicting a significant increase in the deployment of robotic systems in the next decade. Much of the increase of the robotics volume is expected to be in emergency search and rescue, in health and elderly-care, in the leisure and entertainment market, in the service sector and in the defense industry [12]. It is projected that the growth in the service robotics market to reach more than \$38 billion by 2015 [13] and the personal robotics industry sales are expected to exceed \$19 billion in 2017 [14]. The growth expectations in robotics applications can also be gauged from research spending. According to a recent report, the rest of the world led by Japan, Korea, and the European Union, has recognized the irrefutable need to advance robotics technology and have made research investment commitments totaling over \$1 billion [15].

Robotics Engineering, as a new discipline, also provides opportunities to revitalize science, technology, engineering and mathematics (STEM) education. Considering that engineering students of 2011 will still be professionally active in 2050, their engineering education today should be broad enough for them to generate solutions that meet the new requirements of the global industry and society [2–4]. To achieve a smooth transition from university to industry, there should be agreement between the desired outcomes of engineering curricula and the desired attributes of an engineer defined by industry. In other words, the graduates of engineering programs must have a set of basic skills to meet the needs of industry and society. A good understanding of engineering science, a good understanding of engineering design process, a multidisciplinary perspective, excellent communication skills, high ethical standards, critical and creative thinking, an appreciation of the importance of teamwork, an awareness of economic, environmental and societal issues, and a desire for life-long learning are among the attributes forming the interface between the engineering education and the engineering practice [5].

Robotics, the integration of sensing, computing and actuation in the physical world, can be used to enrich and broaden engineering education. Robotics is a multidisciplinary field; creating a robot requires a whole system design approach; it promotes teamwork, technical competency, innovation and lifelong learning. More importantly, it is proved to be an effective tool for improving the recruitment and retention of students [6–10].

A note on "Robotics" vs. "Mechatronics" as a descriptor is in order here. Although there is some disagreement over the precise distinction, the two terms largely overlap. However, we accept that robotics typically indicates a level of autonomy beyond mechatronics [11]. Insofar as our curriculum features increasing autonomy as courses progress, we adopt "robotics" as the more appropriate term, reserving "mechatronics" for the specific course Modeling and Analysis of Mechatronic Systems.

Motivated by the growing needs of industry, the unstoppable enthusiasm among the current generation of high school students, and the resulting growth in number of students in STEM fields, Worcester Polytechnic Institute (WPI) introduced an undergraduate Bachelor of Science (B.S.) degree program in Robotics Engineering (RBE) in 2007 [18]. The program has grown rapidly to become one of the largest majors at WPI.

This paper presents the details of the development of the robotics curriculum and a companion laboratory platform for a two-course sequence within WPI's Robotics Engineering undergraduate degree program. The courses are titled Unified Robotics III and Unified Robotics IV. They are taught at the junior level and form the bridge between the two sophomore-level courses (Unified Robotics I and II) in the program and the robotics capstone design experience. The unique features of the courses include a unified curriculum covering multidisciplinary robotics topics from computer science, electrical and computer engineering, and mechanical engineering, an emphasis on theory and practice of robotics, project-based learning and an integrated systems engineering approach that builds on prior knowledge to complete level-appropriate yet challenging robotics tasks. For the laboratory experiments and projects in the two-course sequence, a reconfigurable and modular platform was designed and built including a 2 degree-of-freedom (DOF) robotic arm and a differentially driven mobile robot base. Both the arm and base share common design features such as the control electronics, input-output interfaces, and sensors. In the first course, the emphasis is on utilizing low-level programming and hardware integration for the control of a robot arm while the second course builds upon this and focuses on integration with high-level programming and algorithms for autonomous robot navigation. This paper is aimed at providing a detailed description of the Unified Robotics III and IV sequence taught within the new Robotics Engineering program at WPI.

The paper is organized as follows. Section 2 provides the context for the two courses within the program. The details and practical content of the courses are presented in Section 3. The key features of the custom, modular robotics development platform are introduced in Section 4. Finally, Section 5 provides a discussion of the lessons learned and our findings on student learning.

2. Context

The Robotics Engineering program at WPI integrates 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 an introductory engineering class with a robotics focus at the freshman level and a four-course Unified Robotics sequence at the sophomore and junior levels. Figure 1 provides a visualization of the RBE curriculum. All courses are offered in 7-week terms with 4 hours of lecture and 2 hours of in-laboratory instruction per week. WPI students are expected to spend approximately 17 hours per week per course within the 7-week term structure. The typical student course load is 3 courses per term. Furthermore, in keeping with the long history of the WPI Plan [16], all courses emphasize project-based learning in small teams, hands-on and open-ended assignments, and students' commitment to learning outside the classroom. Project-based learning is an integral part of the educational experience for all students under the WPI Plan [17] and robotics courses provide an excellent opportunity for implementing this instructional approach by incorporating open-ended projects with detailed timelines and milestones.

The sophomore-level courses, Unified Robotics I and II, emphasize the foundational concepts of robotics such as mechanisms, position and velocity analysis, stress and strain, pneumatics, circuits, operational amplifiers, electric motors and motor drive circuits, sensors, signal conditioning and embedded system programming using the C programming language. 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 the relationship among the electrical engineering, mechanical engineering and computer science disciplines as they apply to robotics.

The 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 sophomore-level courses. It is in these courses that the students actually begin to understand and appreciate the details underlying their earlier experiences. These junior-level courses provide a much deeper theoretical coverage of robotics, including: coordinate systems and frame transformations, manipulator kinematics and dynamics, modeling and control, sensors, signals, reasoning with uncertainty, navigation, mapping and path planning. In these courses students no longer have closed pre-packaged hardware and software components; they now are introduced to interrupt-based programming, software system architecture, object-oriented design, in-circuit debugging, and probabilistic algorithms. In this article, we focus on these courses because, in our opinion, they reinforce the set of skills a robotics engineer needs to have by providing depth of knowledge. Furthermore, the two-course sequence can

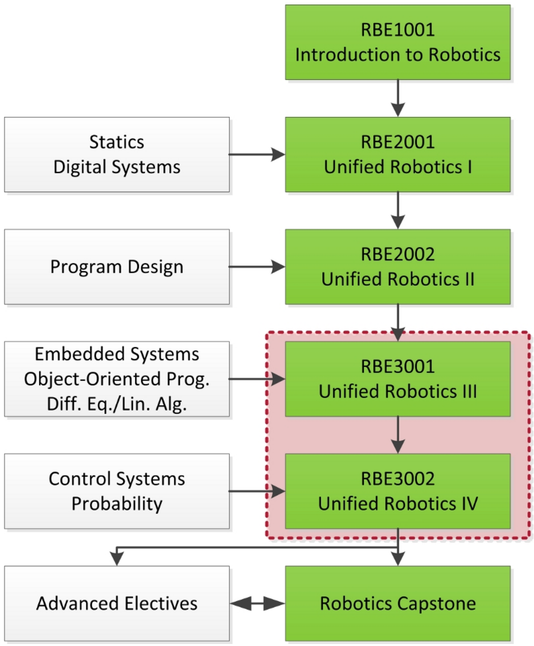

Fig. 1. Robotics Engineering program at WPI is structured around a core curriculum comprising an introductory course followed by four unified robotics courses. This paper presents the details of the junior level courses, RBE 3001-2 Unified Robotics III-IV.

be adopted and implemented within similar programs by minor modifications provided that students gain the expected background in their prior courses.

3. An Overview of the Two-Course Sequence

Based on the coursework students are expected to complete prior to taking Unified Robotics III and IV, a set of expected skills at the interface of Unified Robotics III and IV and courses prior to them in the curriculum have been developed. This set can be summarized as follows:

1 Topics covered in Unified Robotics I and II.

- Position, velocity, and acceleration analysis,
- Kinematics of simple mechanisms,
- Concepts of stress and strain,
- Basics of hydraulic and pneumatic systems,
- DC and AC circuit analysis,
- DC motor principles and selection,
- C programming,
- Modular code design,

2 Foundations of embedded systems,

3 First and second-order linear differential equations,

4 Topics from controls; Laplace transforms, linear systems,

5 Basic linear algebra; matrix addition, multiplication, transpose, inverse, determinant,

6 Familiarity with Maple & MATLAB,

7 Familiarity with CAD (Pro/E or Solidworks),

8 Topics from probability; expected value, Gaussian distribution, mean, variance.

This set of expected skills not only describes the technical background students are expected to have as prerequisites, but also serves as a guide for the instructors to design and develop the course content. The design and development of content for Unified Robotics III-IV has been motivated by and attempts to address the following questions:

1 What comprises a meaningful laboratory experience in an undergraduate robotics course?

2 What is the appropriate level of robotics education for undergraduates?

3 How do we ensure that students can reach a level of robotics theory and practice to accomplish a reasonable yet satisfying course project?

4 How do we maintain student interest and learning active as the courses progress?

5 What is the required content for these courses that will lead into a comprehensive robotics capstone experience?

The approach adopted by the faculty within this framework can be described by the following features common to both courses:

1 A systems level approach to design has been adopted in each course. In this approach, designing a robot for a specific functionality requires an understanding of the user requirements, developing a set of design specifications, an integrated design effort to meet the specifications, and a design validation process.

2 Lectures and homework assignments are designed to support the individual lab experiments and eventually the course projects (See Appendix A for detailed lecture plans).

3 Structured and well-defined lab exercises provide students with the necessary in-depth knowledge and practice to prepare them for the course project.

4 Each course culminates with a comprehensive course project that directly builds on the hardware and software modules and experience from the previous lab experiments.

What is unique about these courses is that they are an important part of the core curriculum for the Robotics Engineering program at WPI and they have been developed and delivered by a multidisciplinary team of instructors

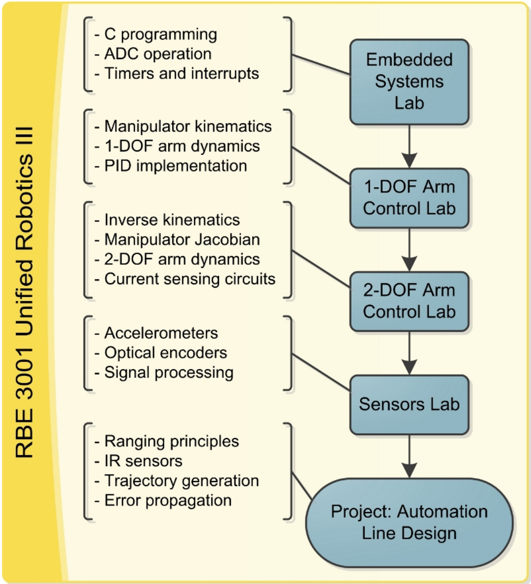

Fig. 2. Laboratory assignments and lectures are designed in an integrative and unified manner to enable students to design and implement an automated production line in RBE 3001.

from Computer Science, Electrical and Computer Engineering and Mechanical Engineering Departments [18]. This unified and integrative approach to teaching robotics at the undergraduate level makes it possible to provide the students with a meaningful educational experience in robotics. The remainder of this section provides details of the content for the two-course sequence.

3.1. RBE 3001: Unified Robotics III

The focus in RBE 3001 is on developing a deeper understanding of the types of devices encountered in Unified Robotics I and II, such as sensors, actuators and controllers. The course begins with an introduction to low-level microcontroller programming. In this course, the Atmel AVR series of 8-bit microcontrollers serves as the computational platform for all of the laboratory experiments due to their prevalance, capabilities, and broadly supported open development environment. These experiments involve topics such as: real-time interrupt-based programming; joint-level modeling and control of a single axis robot arm; forward and inverse kinematics to control a multiple link robotic manipulator; characterizing encoders, accelerometers and infrared rangers; and ultimately incorporating into a simple, but complete, pick-and-place robotic system.

3.1.1. Course Objectives

Upon successful completion of this course, students will be able to:

1 Demonstrate knowledge of different types of actuators used in robotic systems.

2 Analyze the position and velocity kinematics of robot arms.

3 Analyze and simulate the dynamics of robot arms.

4 Analyze sensor signals to implement real-time control algorithms.

5 Demonstrate knowledge of error propagation in electrical, mechanical and computational systems.

6 Write moderately involved programs in C to perform a specified task with a robotic system in real-time on a microcontroller.

7 Construct, program, and evaluate the operation of a complete integrated robotic system to perform a specified task.

The course objectives are an integral part of the course assessment process. They provide a measurable set of outcomes expected from the students completing the course.

3.1.2. Lab Assignments and Course Project

In order to fulfill the course objectives outlined above, four laboratory assignments and a multi-week course project have been developed with individual homework assignments along the way to support learning the necessary material. Each lab and the project builds upon the work completed in previous labs. Students work in teams of 2 or 3 on all lab and project assignments, and students typically remain in the same team for the duration of the course to maintain continuity across assignments. The content of the labs and project are as follows:

1 **Lab: Microcontroller Programming–**Unified Robotics III emphasizes embedded programming skills expected from a Robotics Engineer while introducing manipulator kinematics and dynamics for common robot arm configurations found in applications, such as a SCARA arm. This lab has an overall goal of exploring the microprocessor architecture and developing the C functions that will become the building blocks for the robotics applications that will be used in the course. Students become familiar with programming and debugging the ATmega644PA microprocessor, identify its features, ports, and registers. They configure interrupts, read from the ADC, and develop a serial communications and logging interface between the microprocessor and the PC.

2 **Lab: Single-Link Robot Arm–**Students get acquainted with the robotic manipulator designed for the course and its control circuitry. Specifically, they study and model a linear motor control circuit with motor current sensing and implement a PID controller on the microcontroller for the position control and velocity of the single-link arm. DC motor and single-link robot arm dynamics are also introduced. Students gain insight into PID control tuning, system step-response, and DC motor current sensing for

calculating torque output. This lab assignment also requires students to understand DAC operation and establish SPI communication.

3 **Lab: 2-Link Serial Manipulator–**Building on the previous lab, students are introduced to a two-link planar manipulator. Students learn about the forward kinematics and dynamics of serial manipulators. The lab assignment involves the calculation of forward kinematics based on the joint angle readings from potentiometers, calculation of the robot workspace, derivation of the robot dynamics, implementation of point-to-point Cartesian motion, and real-time integration of the robot platform with MATLAB running on a PC.

4 **Lab: Non-Ranging Sensors–**Students develop the computer interfaces to, and determine the characteristics of, a number of sensors commonly found in robotic systems. Specifically, they explore a 3-axis accelerometer and 2-channel optical encoders. The lab assignment requires students to implement bi-directional SPI communications between the accelerometer module and the AVR microprocessor, and become familiar with the counter chip LS7366R for reading the encoder data. Students also experience the characteristics of various sensors that can be used to determine robot configuration. They compare the joint angle measurements from potentiometers, encoders and the accelerometer mounted on the last link.

5 **Course Project: Automated Production Line–**Students combine all the knowledge gained in Unified Robotics III to automate a production line using the 2-link robotic manipulator, sensors, and a conveyor belt. The assignment is to locate a block on a moving conveyor belt, move the 2-link arm to pick up the block, grasp the block with a gripper, and sort the block based on its weight as inferred from motor currents. The solution is left rather open-ended; students are only provided a set of user requirements and some guidelines.

The task for the course project is as follows: Objects are placed one at a time onto one end of the conveyor belt. The exact placement is random. Two types of objects are used, each with a different weight. Students are asked to instrument and program an automation system to:

- Detect the relative position of each object on the belt with respect to the robot base,
- Use inverse kinematics to determine the corresponding joint positions,
- Determine the correct timing for pick up,
- Pick up the object,
- Identify the objects based on weight,
- Sort the objects by placing them in two different bins.

As can be seen, all the knowledge and practical experience gained by the students in the lab assignments is applicable in completing the course project. The project typically covers a duration of three weeks during which the progress of each project team is monitored by weekly design reviews. The first design review begins with a design document detailing their proposed solution. The open-ended course project allows students to think outside the box and tackle the problem from a whole system design point of view. Given that the course is taken by third-year RBE students, the course project proves to be a rather challenging task. However, since the project builds upon modules developed in prior lab exercises, groups have a very high success rate. The final report, in the form of an conference paper, allows the students to reflect on their efforts and demonstrate what they have learned.

3.1.3. RBE 3001 Summary

Unified Robotics III has been offered four times to date. It is now known as a hard, yet very rewarding, course among our students. In the labs and course project, some students have implemented out-of-the-box solutions, such as simple gripper mechanisms acting as switches to distinguish between different weight payloads, added degrees of freedom at the robot base for increasing the robot workspace and sensor fusion to improve the performance of the automation line.

3.2. RBE 3002: Unified Robotics IV

Once students complete Unified Robotics III, they have gained experience in low-level microprocessor programming, robot kinematics and dynamics as well as actuators and sensors. The focus in Unified Robotics IV is on integrating the information students acquired in their prior courses into a complex robotic system. The emphasis shifts to higher-level programming, intelligence and algorithms, and the robotic device shifts from a manipulator arm to a mobile platform based on the same electronics hardware. This course begins with an introduction to object-oriented programming and development of a software framework based on a communication protocol between a PC and a robot. By incorporating hardware and software components developed in RBE 3001 on the robot, 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.

3.2.1. Course Objectives

Upon successful completion of this course, students will be able to:

1 Compute mobile robot kinematics.

2 Develop a model for mobile robot platform dynamics.

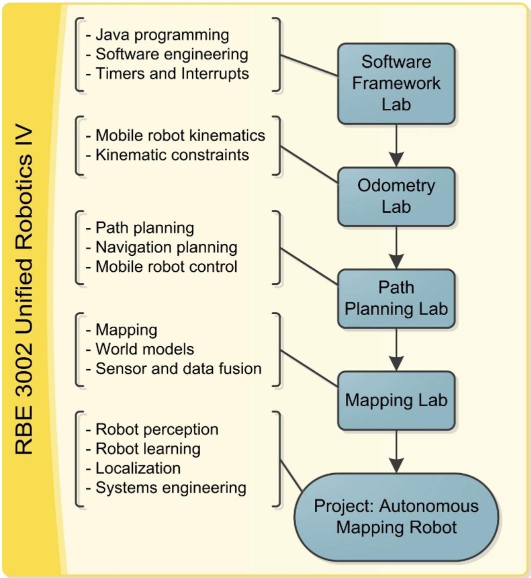

Fig. 3. Laboratory assignments and lectures are designed in an integrative and unified manner to enable students to design methods and program an autonomous mapping robot in RBE 3002.

3 Develop a distributed architecture mobile robotic system.

4 Implement navigation algorithms based on sensor fusion and environment representation.

5 Write moderately involved programs in Java to control real-time tasks with a robotic system.

6 Construct, program, and test the operation of a robotic system to perform a specified task.

The course objectives are an integral part of the course assessment process. They provide a measurable set of outcomes expected from the students completing the course.

3.2.2. Lab Assignments and Course Project

We have developed four laboratory assignments and a multi-week course project in order to fulfill the course objectives outlined above. Each lab and the project builds upon the work completed in previous labs. As in the previous course, students work in teams of 2 or 3 on all lab and project assignments. The content of the labs and project are as follows:

1 **Lab: Software Framework–**Students are introduced to Unified Robotics IV software framework and begin to develop a distributed, object-oriented software system for the mobile robot platform which is used throughout the course. The software framework enables students to communicate with their robots from a PC by sending and receiving command packets. This lab serves as a building block for the following lab assignments and the course project. Part of the assignment require students to develop their own documentation for the communication protocol they are given.

2 **Lab: Kinematics and Odometry–**Students develop a kinematics model for their mobile robot platform and implement methods for differential drive motion, simple trajectory generation (drive along a straight-line or a circular arc) and odometry calculation. The lab objective is to demonstrate the ability to follow a pre-planned trajectory and to track the robot's position based on odometry readings.

3 **Lab: Path Planning–**Students implement an occupancy grid based path planning algorithm and path traversal through waypoint navigation. The lab objective is to demonstrate the robot's ability to plan and follow a path through a predefined environment. Students also develop a Graphical User Interface (GUI) to visualize the occupancy grid, the planned path and current robot position.

4 **Lab: Mapping–**Students implement mapping algorithms based on occupancy grid and line map representations, as well as a visualization tool to display the map data. The lab objective is to demonstrate the ability to generate a local map using the robot's turret-mounted IR and ultrasonic range sensors and to update the map as the robot moves through the environment.

5 **Course Project: Autonomous Mapping Robot–** Students program a mobile robot to autonomously navigate in an unknown environment while mapping its environment. The focus is on high-level mapping and navigation tasks to create a world model of a maze and then travel through it. Students gain considerable amount of experience with low-level programming and sensor interfacing in RBE 3001. RBE 3002 project emphasizes mobile robot motion control, obstacle avoidance and navigation planning at the high-level and complements the projects student complete in the previous RBE courses. Once again, students are only provided with a set of requirements:

- Robot must operate fully autonomously within the experimental environment setup in the lab.
- Robot must effectively avoid obstacles and walls within its environment.
- Robot must generate a dynamic local map of its environment.
- Robot must generate a dynamic global map of its workspace.
- Robot must be capable of planning an admissible trajectory to move within its workspace.
- Robot must be capable of estimating its position and orientation in world coordinates.
- Robot must be capable of navigating to a given waypoint with an accuracy of 3*in*. The waypoints

will remain stationary within robot's workspace and will be clearly marked. Robot must navigate at least 4 out of 5 waypoints.

- Robot must return to the starting point (base) by planning a path. The robot must update the world map while returning to the base. Note that the location of the obstacles on the return trip may change and the robot must adjust the map and plan accordingly.
- Programming must demonstrate a wireless communications link between the robot and a control center.

Similar to Unified Robotics III, all the knowledge and practical experience gained by the students in the Unified Robotics IV lab assignments is applicable to completing the course project. The project typically covers a duration of three weeks during which the progress of each project team is monitored by weekly design reviews. The first design review begins with a design document detailing their proposed solution. The open-ended course project allows students to think outside the box and tackle the problem from a whole system design point of view. Given that the course is taken by third-year RBE students, the course project proves to be a rather challenging task. Again, the projects are typically considered rewarding by the students and have high success rates due to the way they builds upon the foundation built in previous labs.

3.2.3. RBE 3002 Summary

Unified Robotics IV has been offered four times to date. It is now known as a hard, yet very rewarding, course among our students. In the labs and course project, students successfully implemented rather complicated autonomous robot navigation algorithms including probabilistic occupancy grids, extended Kalman filters and various path planning methods. Of the 10 teams participating in the last offering of the course, 9 teams were able to successfully navigate to all five waypoints and return to the starting location within a single run. The remaining team was able to perform both the waypoint navigation and the return trip, but in separate trials.

3.3. Evaluation

Each lab and project assignment includes a grading rubric that identifies the standards and criteria for grading the assignment. The rubric simplifies grading, ensures consistency and allows students to make informed decisions about how to prioritize their work. The following is an example grading rubric for the autonomous mapping final project in Unified Robotics IV:

- (10 points) The team delivered an effective, complete and preliminary design review.

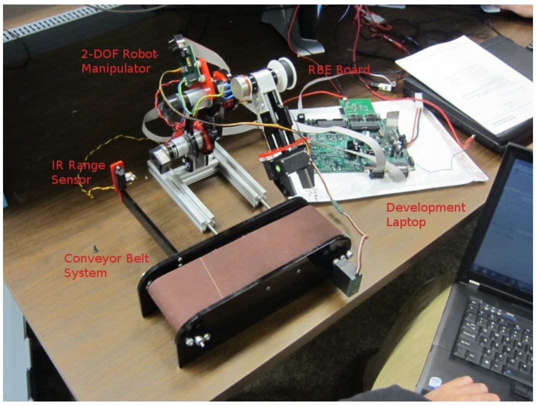

Fig. 4. In Unified Robotics III, the lab experience is centered around a two-link robot manipulator. Students implement sensor integration, motor drives, low-level microprocessor programming in C language, and robot control.

- (60 points) The requirements outlined in the project handout are validated by clear demonstrations, visuals, data collection, and documentation.

  1. Robot effectively avoids obstacles: 5pts
  2. Robot generates a dynamic local map: 5pts
  3. Robot generates a dynamic global map: 5pts
  4. Robot plans a trajectory to move within its workspace: 5pts
  5. Robot estimates its position and orientation in world coordinates: 10pts
  6. Robot navigates to waypoints with an accuracy of 3in: 20pts
  7. Robot returns to the starting point while updating the map: 10pts

- (10 points) The team delivered an effective oral presentation supported by slides, videos, etc as the critical design review. The points are equally distributed among the quality of the presentation, technical content and effective communications by the team members.

- (20 points) The team submitted a lab report OR a multimedia presentation to communicate the project to the course staff and external reviewers. The report is graded based on the effectiveness and clarity of the introduction, methodology, results and discussion.

Students are evaluated using the above grading rubric as a team and receive a single team grade for the 2–3 team members. Additionally, students are asked to complete a peer review form evaluating the level of contribution made by each team member. Although very rarely necessary, a student with consistently poor peer reviews receives a grade reduction for the lab portion of the course based on the percent effort as reported by the team.

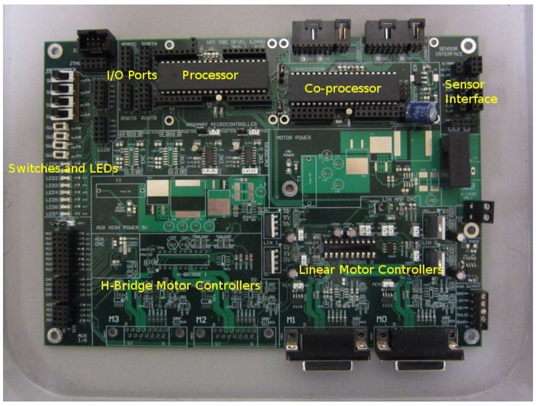

Fig. 5. A highly configurable custom robotics development board has been developed at WPI for the course laboratories. The board houses an 8-bit ATmega644PA microprocessor and a second co-processor, two linear motor drives, two H-bridge motor drives, motor current sense circuits and sensor interfaces. The same electronics hardware is used for a robot arm in Unified Robotics III and for a differential drive mobile robot in Unified Robotics IV.

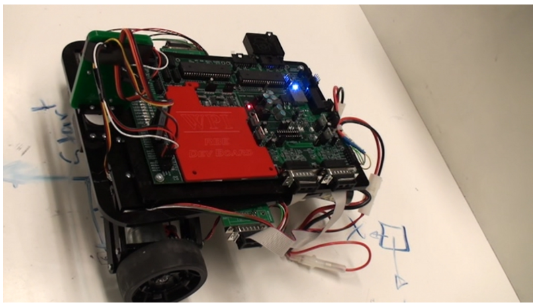

Fig. 6. In Unified Robotics IV, the lab experience focuses on autonomous mobile robot navigation. Students write high level programs in Java to implement odometry, path planning, world mapping and navigation algorithms that interfaces with the previously developed low level C microcontroller hardware interface.

4. Robotic Development Platform

Students who are in Unified Robotics III and IV are provided with a number of components and platforms designed and custom-built by WPI's Robotics Engineering faculty and staff. These components include:

- A custom-designed 2-axis robotic arm (Figure 4) which is composed of modular joints powered by DC motors with incorporated optical shaft encoders and potentiometers for feedback,
- A compact, modular mobile robot platform (Figure 6) with front differential drive by the same DC motors used in the robot arm, omnidirectional rear wheel, battery power, and a sensor turret including an IR and an ultrasonic range finders,
- Embedded controller hardware (Figure 5) including a primary and secondary AVR microcontroller, analog and digital inputs and outputs, switches, LED indicators, linear and switching motor amplifiers, current sensing circuitry, 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 hierarchical/supervisory control of the microcontroller and data logging.

One of the key components of this lab kit is the RBE Development Board which is described in more detail in [19]. It incorporates a primary AVR microcontroller with in-circuit programming and debugging, two independent differential linear motor control channels, four independent motor control channels with H-Bridge outputs, motor drive current sensing, two 4-channel, SPI 12-bit digital-to-analog converters (DAC), four SPI encoder counter interfaces, dual serial ports for communication and debugging, a co-processor primarily preconfigured for PWM servo control, high configurability using on-board jumpers, support for up to four axis control boards, support for one ultrasound sensor interface board, support for multiple infrared sensor modules, support for one compass/accelerometer board. In addition, custom hardware for controlling each motorized axis, ultrasonic range sensing, accelerometers and a magnetic compass is included in the kit. The custom platform provides the openness, expandability, and reconfigurability to enable the instructors to provide students with a lab experience which includes reviewing schematic diagrams, reviewing component datasheets as necessary, developing mathematical 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. The platform has been developed as open-source, and open-hardware platform. .

5. Results and Discussion

As part of the program assessment process, at the end of every term students evaluate the course and instructor for every course in which they are registered. Faculty members receive an electronic report of their evaluation. These evaluations cover a variety of topics related to the course and instructor and provide a tool to track student experience in the courses. Table 1 provides a summary of student responses from the last offerings of both courses.

The following observations can be made about the two-course sequence:

	RBE3001	RBE3002
My overall rating of the quality of this course is	4.3	4.7
The educational value of the textbook and/or assigned reading was	3.9	4.1
The educational value of the assigned work was	4.3	4.5
The amount I learned from the course was	4.8	4.5
The intellectual challenge presented by the course was	4.7	4.7
The exams and/or evaluations were good measures of the material covered.	4.4	4.5
	$n = 23$	$n = 20$

Table 1. Student evaluation of Unified Robotics III and IV (Fall 2010). (Scale: 5.0 (Excellent/Strongly Agree))

- Robotics in nature is a multidisciplinary engineering field, therefore it needs to be taught in a unified and integrated manner.
- Robotics is a complicated subject to be taught at the undergraduate level. The course content needs to be carefully designed and supported to ensure that the students receive adequate breadth and depth.
- Student experience can be summarized by the following statement from a course evaluation: *"We work hard, the courses are hard, but we learn a lot. So, it is worth it."*. Nearly 100% of the students reported that they spent more than 17 hours on their coursework. Moreover, they ranked the amount that they learned and the intellectual challenge presented by the course as 4.8 out of 5.0 which is an indicator for student satisfaction.
- Previous observation quantifying the student effort is partly because the final projects are rather challenging. The instructors' subjective assessment of the project success has shown that more than 75% of the project teams successfully completed the given task. The project teams are comprised of 2-3 students.
- One indicator for student learning in this project based approach is the individual grades assigned in the course projects. Approximately, 50% of the course projects received a grade of A in both courses.
- It should be noted that the curriculum includes three other robotics courses and a comprehensive capstone design project. This provides ample opportunities for instructors to emphasize the mechanical, electrical and software design concepts throughout the program.
- Because the teaching approach presented here is unique in unifying and integrating multidisciplinary subjects around a complete robotics system, there is no one textbook that can be adopted; therefore, instructors must supply the effort to prepare complete lecture notes and other supplementary material to support student learning.
- Anecdotal student feedback demonstrates that the skills learned in the two course robotics sequence are valued highly by the prospective employers and helped the students to find robotics jobs and summer internships. To date, all 17 graduates of the program are either admitted to graduate school or employed full-time.

6. Conclusion

The paper presented the details of a unified and integrated teaching approach for a two-course sequence developed within the new Robotics Engineering program at Worcester Polytechnic Institute. The courses are designed to provide the theoretical and practical knowledge required for a foundational robotics education. The student interest in robotics is evident in both courses and lead to high success rates. The positive feedback from the students, graduates and instructors, student grades and formal evaluation results are indicators for measuring the effectiveness of the approach. Our future work includes continuous development of the Unified Robotics course sequence and introduction of new robotics courses at the undergraduate and graduate levels to educate engineers to meet the needs of the growing robotics industry.

Acknowledgements

The authors wish to thank the more than 100 students who successfully completed Unified Robotics III and IV since 2009 for their feedback in creating new content and updating the existing content. We would also like to thank the course TAs and the RBE Lab Manager, Joe St. Germain, for dedicating countless hours in developing and maintaining the laboratory kits for Unified Robotics III-IV.

Appendix A. Lecture Plans

Tables 2 and 3 present the outline of the lecture and laboratory sessions for Unified Robotics III and IV.

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1.	AVR Control Architecture
2.	Encapsulation and Problem Decomposition
3.	Real-Time Programming, Interrupts
L1	AVR Programming
4.	A Review of Control Systems
5.	Software Implementation of Controllers
6.	Motor Control Electronics
L2	Single-Link Robot Arm
7.	Dynamics of a Single Link Arm
8.	Numerical Operations in Embedded Systems
E1	Embedded Systems, Single-Link Arm, Motors
9.	Kinematics & Dynamics of Multiple Link Arm
L3	Two-Link Serial Manipulator
10.	Representations in 3D Space/Transformation
11.	Serial Manipulator Kinematics
12.	Analog Output Sensors and Sampling
13.	Digital Output Sensors
L4	Non-Ranging Sensors
14.	Digital Communications (SPI and IIC)
15.	Principles of Ranging
16.	Sensor Signal Processing
17.	Differential Motion & Manipulator Jacobian
18.	Inverse Position Kinematics
19.	Inverse Velocity Kinematics
E2	Jacobian, dynamics, signal conditioning
20.	Computed Torque Control
L6	Final Project: Automated Production Line
21.	Path and Motion Planning
22.	Error Propagation in Computational Systems
23.	Error Propagation in Electrical Systems
24.	Error Propagation in Mechanical Systems
E3	Inverse Kinematics, Range Sensing, Errors
25.	Final Project Demos

Table 2. Lecture schedule for Unified Robotics III

1.	Introduction to Java
2.	Java Inheritance and Interfaces
L1	Introduction to RBE3002 Software Framework
3.	Java Exceptions, Arrays and Threads
4.	Mobile Robot Kinematics
5.	Odometry
6.	Kinematic Wheel Constraints
L2	Kinematics and Odometry
7.	Java GUI Programming
8.	Task Planning
9.	Path Planning
10.	Robot Maneuverability
L3	Path Planning
11.	Mobile Robot Motion Control
12.	Mapping
13.	Localization
14.	World Models
L4	Mapping
15.	Uncertainty in Robotics
16.	Recursive State Estimation
E1	Midterm
17.	Sensor and Data Fusion & Kalman Filter
18.	Sensor and Data Fusion & Kalman Filter
19.	Uncertainties in Robot Perception
L5	Final Project: Autonomous Mobile Robot
20.	Decision Making
21.	Robot Learning and Multi-Robot Systems
22.	Mobile Robot Localization
23.	Mobile Robot Localization
24.	Systems Engineering
25.	Systems Engineering
E2	Final Exam
26.	Final Project Demos

Table 3. Lecture schedule for Unified Robotics IV

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Name:
Taskin Padir

Affiliation:
Electrical & Computer Engineering Department
Worcester Polytechnic Institute

Address:
100 Institute Rd., Worcester, MA 01609, USA

Brief Biographical History:

Dr. Padir is an Assistant Professor of Electrical and Computer Engineering at Worcester Polytechnic Institute. He holds Ph.D. and M.S. degrees from Purdue University both in electrical engineering. He received the B.S. degree in electrical and electronics engineering from the Middle East Technical University, Ankara, Turkey. He teaches the undergraduate unified robotics courses offered within WPI's Robotics Engineering Program. He is the Director of WPI's Robotics and Intelligent Vehicles Research (RIVeR) Laboratory. Dr. Padir's research interests include robot control, adaptive robotic systems, and intelligent vehicles.

Membership in Learned Societies:

• IEEE, AAAI, AUVSI, Sigma Xi

Name:
Gregory S. Fischer

Affiliation:
Mechanical Engineering Department
Worcester Polytechnic Institute

Address:
100 Institute Rd., Worcester, MA 01609, USA

Brief Biographical History:

Dr. Fischer is an Assistant Professor of Mechanical Engineering with appointments in Biomedical Engineering and Robotics Engineering at Worcester Polytechnic Institute. He received the B.S. degrees in electrical engineering and mechanical engineering from Rensselaer Polytechnic Institute, Troy, NY, in 2002 and the M.S.E. degrees in electrical engineering and mechanical engineering from Johns Hopkins University, Baltimore, MD, in 2004 and 2005. He received the Ph.D. degree from The Johns Hopkins University in 2008. Dr. Fischer worked to develop and teaches undergraduate and graduate courses in WPI's Robotics Engineering program. He is also Director of the WPI Automation and Interventional Medicine Laboratory, where his research interests include development of robotic systems for image-guided surgery, haptics and teleoperation, robot mechanism design, surgical device instrumentation and MRI-compatible robotic systems.

Membership in Learned Societies:

• IEEE, ASME

Name:
Sonia Chernova

Affiliation:
Computer Science Department
Worcester Polytechnic Institute

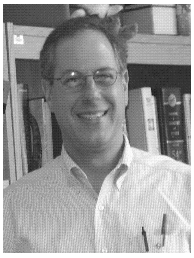
Address:
100 Institute Rd., Worcester, MA 01609, USA

Brief Biographical History:

Dr. Chernova is an Assistant Professor in the Department of Computer Science at Worcester Polytechnic Institute. She received her Ph.D. in computer science from Carnegie Mellon University in 2009, following which she held a postdoctoral associate position at the MIT Media Lab. Dr. Chernova teaches undergraduate unified robotics courses offered within WPI's Robotics Engineering Program. Her research interests include autonomous systems, interactive robot learning and human-robot interaction.

Membership in Learned Societies:

• AAAI



Name:
Michael A. Gennert

Affiliation:
Computer Science Department
Electrical & Computer Engineering Department
Worcester Polytechnic Institute

Address:
100 Institute Rd., Worcester, MA 01609, USA

Brief Biographical History:

Prof. Michael A. Gennert is Director of the Robotics Engineering Program at Worcester Polytechnic Institute, where he is Associate Professor of Computer Science and Associate Professor of Electrical and Computer Engineering. He has worked at the University of Massachusetts Medical Center, Worcester, MA, the University of California/Riverside, General Electric Ordnance Systems, Pittsfield, MA and PAR Technology Corporation, New Hartford, NY. He received the S.B. in Computer Science, S.B. in Electrical Engineering, and S.M. in Electrical Engineering in 1980 and the Sc.D. in Electrical Engineering in 1987 from the Massachusetts Institute of Technology. Dr. Gennert is interested in Computer Vision, Image Processing, Scientific Databases, and Programming Languages, with ongoing projects in biomedical image processing, robotics, and stereo and motion vision.

Membership in Learned Societies:

• IEEE, ACM, Sigma Xi