Robotics as a Learning Medium for Engineering Practice and Team-based Design in Capstone Projects

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In the capstone project courses in Electrical and Computer Engineering at Clemson University robotics projects are used as a medium to teach senior-year undergraduates the tools required for engineering practice and team-based design, qualities essential for their professional success as engineers. The student teams solve technical problems while learning about system design, ethics, safety, hardware and software integration, and technical documentation. The inherent breadth of robotics allows us to control the parameters and skill sets required to execute a project. This model makes it possible to impart specific skills each semester without having to make drastic curricular changes. In addition, evaluation, and feedback from industry members serves to measure student performance from a second viewpoint. This paper documents our experience of using robotics as a learning medium for senior design.

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Introduction

Interdisciplinary skills are necessary for a successful engineer in today's industrial environment, and such skills need to be taught to engineering students as an integral part of their training. For over twenty years robotics design projects have been used in Clemson University's Electrical and Computer Engineering (ECE) capstone design classes as the means to connect classroom learning with practical applications. In this paper, we outline our approach towards satisfying the objectives of teaching the skills and tools of modern engineering practice and team-based design through the medium of robotics. These projects benefit from active industry involvement in evaluating both the design process and the project prototypes.

Representatives from local industry have been involved with our capstone projects in consistent and diverse ways. Industry collaborators i) support evaluation of students on a basic skill set; ii) provide credibility to expectations on professional presentations, skills, etc.; and iii) give presentations on sales, patenting, etc. The close involvement of industry representatives not only provides vital feedback to students regarding the merit of their design, but also provides the instructors inputs on the development of future project ideas.

From a design and control perspective, robotics can be classified as one of the many sub-problems in mechatronics, which has been steadily gaining in importance both as an academic discipline and as a philosophy for engineering education [1] [2]. The wide range of engineering abilities encompassed by robotics makes it an interesting platform for a capstone design class. The versatility and interdisciplinarity of robotics makes it possible for us to manipulate the requirements of projects such that different sets of skills can be developed over the course of the senior year. This idea of *targeted learning* using the medium of robotics is the central contribution of our approach.

Capstone projects [3] provide the prospective engineer an opportunity to learn about the design process. The most favored model for teaching design is currently the paradigm of Project Based Learning (PBL). Dym [4] proposes a definition for design which places emphasis on the technical details of a project as well as the objective of satisfying a client's requirements. With this in mind, our design course gives considerable importance to the project life cycle and sets specific documentation and process requirements for teams to meet during the semester.

Senior design projects in Clemson ECE are spread over two semesters, with students working on a different problem in robotics each semester. To substantiate the process outlined above, we present a set of example first semester design projects from the program, all of which are designed to support assessment of multiple ABET outcomes [5].

Course Philosophy and Rationale

ABET, the accrediting agency for applied science, computing, engineering, and technology programs [5], defines criteria that ensure "programs produce graduates who are ready to enter their professions." Such criteria serve as a good reference point for evaluating the success of our capstone courses. Based on project and individual scores and feedback from external evaluators, students are rated on performance on eleven of the ABET criteria.

To achieve these objectives, Senior Design comprises two two-credit hour courses: ECE 495 and ECE 496. Students implement one project each semester in their senior year. The two projects are not connected by a continuity of the problem to be solved; rather, they are connected by the increased level of expertise required for successful project solution. Generally speaking, the first semester projects are "static" and the second semester projects are "dynamic". Additionally, second semester projects require a top-down design approach as no components are specified a priori while the first semester designs are based on a few given parts, typically a motor and camera. This transitions the teams from previous labs where all components are given and a bottom-up design approach is executed.

Robotic projects specified by the instructor are used to delimit the solution space and to direct training in the tools required for such solutions. Specifically, students must gain expertise in such tools as MATLAB/Simulink, C++ programming, data acquisition, and image processing. The projects hinge on a demonstrable proficiency in technical skills that include closed-loop motor control, real-time control software, electronic circuit design, and systematic design approach.

Students are arranged in teams of five students in order to practice generating and implementing technical solutions in a collaborative manner. Each student completes the Comprehensive Assessment for Team-Member Effectiveness (CATME) survey for their team members three times during the semester [6]. The students complete the design process steps described in [7]. Highlights include the use of the BEES software published by NIST [8], to make a decision regarding material for the project shipping container; use of the Design Failure Modes Analysis (DFMEA) to help analyze the safety of their designs; creation of a Gantt chart to help organize their activities. Each step in the design process is documented as a written report; all of which are then incorporated into a group website at the end of the semester.

In addition to the common learning elements described above, project specifications are defined each semester such that one specific skill from this set is highlighted. This is consistent with the paradigm of Project Based Learning [4], the objective of which is to define a problem such that the process of solving it leads to acquisition of certain skills. In the following section, we outline some of the tenets and skills of engineering practice and design, and use selected projects from ECE 495 in previous semesters [9] to explain how robotics plays a central role in educating students in these areas.

Engineering Practice

Systems Integration – The Laparoscopy Surgery Robot

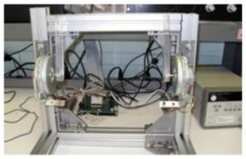
The difference between conventional system design and mechatronics design is that the latter requires, as outlined in Isermann's work [10], "simultaneous engineering" to take place. That is, the project must be considered in its totality right from the beginning, rather than as a collective of components designed by different kinds of engineers. Thus, the idea of systems integration can hardly be separated from the notion of a robotics or mechatronics system design.

To emphasize the multidisciplinary practices associated with systems integration, students were asked to design a low-cost joystick-controlled laparoscopic surgery leader-follower robot. The motivating idea for this project came from the widespread use of laparoscopic surgery tools in medicine, and the rapidly growing usage of teleoperated laparoscopy robots.

To make this project work, groups had to simultaneously address the challenges of adhering to client specifications for the user interface, interfacing multiple motor-encoder pairs, developing software to work smoothly with the electronics, and design a mechanical master device which was safe to handle and functionally complete.

Customer Requirements – Haptic Virtual Manipulatives

Interaction with a real customer is beneficial for a senior design class in two ways – it provides the students a chance to deliver technology which potentially satisfies real social or industrial requirements and it gives them a chance to practice their design and implementation constrained by strict requirements imposed by the customer.



The designer of Math Out of the Box® [11], a K–5, inquiry-based math curriculum, served as the project customer for this system. The task assigned to the groups was to design haptic virtual manipulatives for K-12 students to learn about symmetry and equivalence (heavy vs. light, for example). As a result of low student performance in K-12 mathematics, experts recommend the development of new tools for teaching such topics as number sense, fractions, algebra, and geometry and measurement. One of the most efficient methods currently available for such instruction is the use of manipulatives [12], using real-world objects to teach abstract concepts. Haptic virtual manipulatives [13] are computer generated objects or shapes whose interactions can be felt by users through a simple haptic device.

Groups were provided with an OpenGL interface template which displayed either the Symmetry or the Balance virtual environment. The hardware to be designed was a simple haptic interface to allow tactile interaction with the virtual world seen on the monitor by delivering a specific torque profile. Additionally, it was necessary to have enhanced safety features for the device, since it was to be handled by young schoolchildren. A panel of practicing engineers evaluated the final designs. For this project, the class was awarded a 2010 NCEES (National Council of Examiners for Engineering and Surveying) Engineering Award for Connecting Professional Practice and Education [14].

Computer Vision – Ping Tac Toe

In industrial systems, the use of cost-effective yet powerful sensors is a pivotal requirement for commercial viability of a product. Computer vision, which uses the camera as a low-cost sensor, fulfills this requirement. In this project, computer vision was used as the sensing system for robots capable of autonomously playing a game of tic-tac-toe with ping-pong balls of two different colors.

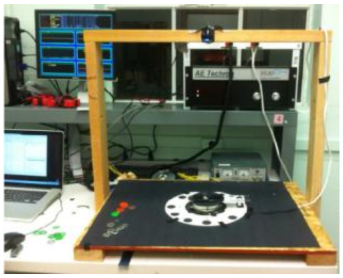
Groups are introduced to image processing by way of in-class tutorials covering image processing concepts from elementary to intermediate levels of complexity, examples include color spaces, image storage, pixel access (all elementary), PCA-based region description, background subtraction, morphological operations, edge detection (all intermediate). Both MATLAB, which has an extensive image processing toolbox, and OpenCV, which is a widely used C++ library for image processing, are introduced as options for the implementation software.

The robotic system had to then use the camera input as raw sensor data and process it using image processing techniques to identify the game state. The game state would then be used to plan and execute the next move in accordance with the game strategy. An additional element of complexity was introduced by placing lights at the side of the board for the system to automatically identify which robot was supposed to make a move. The game had to be played by completely autonomous robotic systems which would be able to identify a winning configuration and stop shooting.

Closed-Loop Control – Puzzle Solving Robot

Closed-loop control is at the heart of all senior design projects at Clemson ECE. Students are introduced to the theory of linear control via a senior level course, ECE 409. However, implementing a practical robotic system with one or more PID-controlled degrees-of-freedom serves to strongly reinforce their conceptual understanding of control systems. One such practical system is the puzzle solving robot, in which a single-DOF rotary robotic arm with quadrature encoder feedback is controlled.

Earlier in the semester, teams were asked to implement a PID-controller using encoder feedback to mimic a clock-hand with a variable, user-defined step-size. This provided experience with understanding how to implement a closed-loop PID control MATLAB Simulink model, and to tune the individual gains to obtain the desired step response. Further, students used this project to understand how to interpret the quality of their controller using plots and graphs in addition to the visual quality of the response.



This intermediate mini-project was useful training for their final project, which was the design and implementation of a puzzle solving robotic arm using computer-vision as the sensor. The robot was required to move washers on a ring-shaped game board from their start position to a desired end position inside hollow wells located at known locations around the ring. Strict restrictions were placed on what constituted successful placement of washers (partially inside the ring counted as failure) to place greater emphasis on the performance of their closed-loop controller in this project.

Discussion

An ongoing challenge is to fully determine whether students learned what we expected. Many of the technical and nontechnical aspects are evaluated through the course grading; however, the real difficulty lies in determining if we have reshaped the student's attitude about their imminent future as a practicing engineer. In particular, have they taken two important steps: i) realized that they must draw on a variety of sources and experiences to solve real problems (i.e. the solution is not in the preceding chapter of the textbook) and ii) gained confidence in applying what they have learned to this point in their undergraduate program out of the context of the course in which they learned it. To this end, we administer an anonymous, on-line survey through Blackboard at the end of each semester using questions proposed by the University to assess instructor effectiveness and by the ECE Department and the Instructor to assess learning outcomes.

Results from the Fall 2011 course survey suggest some success in our approach to the class. Specific student responses to the essay question where students are asked to describe the strengths of the course include "The course allows lots of freedom in how the projects are done so you actually have to think about what you are doing" and "… it was nice to be turned loose and told to work on projects rather that regurgitate formulas on examinations". This is captured quantitatively in the response to the scaled agreement item (1= "Not at all" through 5= "Very much") question that the course emphasized "Applying knowledge to solve real-world or realistic problems" which received a 4.6 rating compared to 4.1 for all students in all classes in the same major. The question that the course emphasized "Exercising my creativity in the discipline" received a 4.6 rating compared to 3.5 for all students in all classes in the same major. Instructor supplied questions, which don't have a comparison to other course responses, include a 4.7 response to the question that "The course emphasized that teamwork skills are important to an engineer and the class/lab created an opportunity to solve a challenging problem as part of a team." and a 4.7 to the question "The course emphasized that professional development and continuous learning are important to an engineering career."

The survey tool suggests a possible weakness in our implementation of the approach in that the response to the question "The judges from IEEE helped reinforce that the design project has relevance to the real-world" received only a 4. This response is somewhat surprising as anecdotally the response of the students to comments and criticism from practicing engineers is very reverent. This seems to point to the need for more involvement of the jury members with the students during the semester. The students are often skeptical about course elements such as safety, ethics, and life-cycle and so these topics can be targeted as an opportunity to increase interaction and increase the credibility of these elements.

One class of responses that is hardest to interpret is that the course is "disorganized", even though lectures, schedule, and detailed grading criteria are posted at the start of the course. This criticism may originate from frustration at solving an open-ended problem with the inherent uncertainties of our customer-vendor interaction model; however, it merits investigation. We are always walking a thin line between over specifying the solution and creating an intractable problem for the given time and resources.

Conclusions

We have used robotics in the first semester design course in order to dictate technical and nontechnical learning outcomes and used collaboration with industry partners to evaluate the results. We believe this targeted learning approach can provide consistency between projects and team experiences while providing the design freedom expected in a capstone design course. We continue to work towards quantifying the outcomes of this approach as feedback to improving the course.

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