A MULTIDISCIPLINARY APPROACH TO ROBOTICS EDUCATION

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Abstract

This work describes an introductory multidisciplinary mechatronics/computer information systems laboratory course, Robotics with LEGO Mindstorms NXT, and a novel learning environment based on the DARPA Urban Challenge. The course is designed to employ project-based and discovery-based learning of robotics design and programming. A high profile engineering problem, DARPA Urban Challenge, was selected to motivate students. The challenge was modified to fit the LEGO Mindstorms robotic environment available for the course. Student-designed robots were to navigate streets of a miniature city. An easy configurable street-route consisting of modular route segments was developed and implemented. A Mini Urban Challenge competition was organized. The assessment metrics show high student satisfaction and exceeding of the learning objectives set for the course such as the increase in practical knowledge of basic robot controls, multisensor data fusion, and robot programming using a graphical robotic programming language.

Introduction

To learn basics of robotic design and robotic programming, and to promote development of graphical programming skills through project-based learning, discovery-based learning, and learning in a multidisciplinary environment, a Robotics with LEGO Mindstorms NXT course was developed and implemented. This is a two-hour laboratory, one semester, upper division course offered within two programs at the Colorado State University - Pueblo: the Bachelor of Science in Engineering with specialization in Mechatronics program and the Computer Information Systems program.

This course was inspired by an actual robotics competition, the Defense Advanced Research Project Agency's (DARPA) Urban Challenge, a 2007, $2,000,000 prize autonomous vehicle challenge to complete 60 miles in traffic in less than six hours. The challenge took place on November 3rd at Southern California Logistics Airport.

Previous Work and Justification

The major function of the Robotics with LEGO Mindstorms NXT course is to promote knowledge systematization of robotics through discovery-based active learning. Actual robot building is a powerful student motivational tool[1]. Mimicking an actual multimillion-dollar robotic prize competition[2] further enhances student motivation. A set of new tools like LEGO Mindstorms Education Base Set with NXT technology (became available in August 2006) and the National Instruments LabVIEW Toolkit for LEGO Mindstorms NXT (became available for downloads in mid-December 2006) are implemented in this novel robotics design course.

The Robotics with LEGO Mindstorms NXT course is a part of the pedagogical system implemented in the Mechatronics curriculum. This pedagogical system is based on McCarthy's[3] version of the Kolb[4] learning cycle and was motivated in part by work presented by Harb *et al*[5]. New concepts can be learned by following a pattern called the learning cycle exemplified by the questions why, what, how, and what if. Active discovery-based learning is considered an important part of this learning cycle, especially in engineering[6]. Bruner[7] defines discovery learning as a cognitive instructional model whereby students are empowered and encouraged to learn concepts and principles through active hypothesis testing and discovery.

Engineering laboratory courses use active learning. Often, open-ended projects are used as powerful pedagogical tools in discovery-based learning. To minimize the time to build prototypes and to minimize the cost of such projects by using low-cost plastic parts and enforcing reusability of parts, many instructors adopted LEGO bricks and LEGO computerized systems as educational tools. A large body of engineering education research describes the use of LEGO bricks[8]. Most examples use LEGO Mindstorms RCX with the Robolab programming environment (RIS 2.0) based on National Instruments LabVIEW software for various projects and courses like robot competitions[9, 10], programming[11, 12], and project-based learning[13-19]. The literature reviewed shows positive results like increased student enthusiasm towards engineering, perceptual and actual increase in students' knowledge, and development of design and team skills. However, LEGO Mindstorms RCX is restrictive for more advanced robotics projects in both hardware and software. A number of third-party solutions were proposed to increase its flexibility[12, 20].

LEGO's response to a need for an improved microcontroller system is addressed in their current LEGO Mindstorms NXT product. The older LEGO Mindstorms RCX is obsolete. LEGO stopped its production and any further developments in favor of LEGO Mindstorms NXT. While the ideas from literature using old LEGO Mindstorms RCX sets are still valid, the implementations are quickly becoming dated. Hardware and software capabilities of the new LEGO Mindstorms NXT with some new, interesting, and useful features are described elsewhere[21, 22].

Curriculum Context of Robotics with LEGO Mindstorms NXT Course

Robotics with LEGO Mindstorms NXT is a two-hour laboratory one-semester junior/senior-standing course available within the recently offered, ABET accredited, Bachelor of Science in Engineering with specialization in Mechatronics (Mechatronics) program at the Colorado State University – Pueblo. The course is also cross-listed under the Bachelor of Science in Computer Information Systems (CIS).

To increase the practical knowledge of basic robot controls, multisensor data fusion, and robot programming using a graphical robotic programming language (introduced in a previous course on mechatronics) through project-based and discovery-based learning, a course, Robotics with LEGO Mindstorms NXT, is designed and implemented. A special, inexpensive, modular, and configurable environment mimicking streets, intersections, turning lanes, and parking lots was designed for this course.

In their first year's Introduction to Engineering course, students were exposed to an older LEGO Mindstorms RCX environment allowing them to transfer some of the experience to the new system. CIS students are currently in, or finished with, an advanced programming course and are already familiar with programming structures. Course grading is based on fulfilling criteria from the actual DARPA Urban Challenge announcement [2], progress reports, and a final presentation with report.

Laboratory Assignment

This laboratory course is designed to develop student robotic design and graphical programming skills, and to specifically provide practical experience with basic robotic controls and robot interaction with its surroundings. The inspiration for the experiment comes from DARPA's Urban Challenge. The experiment requires one LEGO Mindstorms NXT set per team with additional sensors available if desired.

Laboratory Task:

A robot is to be constructed and equipped with a sufficient number of sensors to be able to navigate the streets of a miniature city. The robot should include at least two types of sensors: a number of light sensors for detecting curbs, stop lines, no-passing and passing lines, and turning lanes, as well as at least one ultrasonic sensor for sensing other traffic on the road like parked cars, cars waiting to turn, cars coming from the opposite direction, etc. A portion of a city model with modular sections consisting of various street types and intersections including START and FINISH positions will be provided. A description of the desired route will also be provided. The robot is to operate as follows:

1. An executable NXT program based on the route description should be created and stored into the robot memory.
2. After placing the robot at the START position the robot should be turned on.
3. Then, the robot should follow the prescribed route based on the route description. The choice of type and number of sensors is open.
4. When the robot reaches the FINISH position, it will execute a parking maneuver resulting in the robot being parked in a parking spot.

Hardware and software designs are not further specified.

The rules for the Mindstorms NXT DARPA Urban Challenge are constructed from a subset of the DARPA Urban Challenge rules, specifically from the Required Behaviors Section: Basic Navigation and Basic Traffic[2]. If it is assumed that an average car is about 4m long and the designed Mindstorms NXT robot is about 0.2m long, than the ratio of lengths between the two is about 20:1. Therefore, the original DARPA Urban Challenge rules are scaled down at least 20 times for distances.

1. Required modified basic navigation rules are as follows.
   a) Robot stays entirely within its travel lane around corners.
   b) Robot stops within 0.05m of stop lines.
   c) At an intersection, robot exhibits less than 10 seconds of delay when intersection is clear.
   d) Robot completes passing maneuver around a stationary obstacle (of similar size to robot) within the modular section maintaining a safety buffer of 0.1m in front of and behind obstacle.
   e) Robot perpendicular parks in a designated parking spot.
2. Required modified basic traffic rules are as follows.
   a) Robot stops between 0.1m and 0.25m behind a stopped lead vehicle.
   b) Robot travels at least half its maximum speed on straight-aways.
3. Optional modified basic navigation rules are as follows.
   a) Robot stops within 0.05m of stop signs.
   b) Robot completes passing maneuver around a moving obstacle within the modular section(s) maintaining a safety buffer of 0.1m in front of and behind obstacle.
   c) Robot parallel parks in a designated parking spot.
4. Optional modified basic traffic rules are as follows.
   a) Robot exhibits correct precedence order at an intersection, i.e. the first vehicle to reach a stop line is the first to leave.
   b) Robot maintains a safety buffer of 0.3m when traveling.

LEGO Mindstorms NXT Specifications are summarized in literature[21, 22].

Route configuration:

To provide a variety of navigational situations, a set of miniature route segments was constructed for this course to allow construction of configurable routes in a matter of seconds. These segments are assembled in different configurations, thus creating different routes and tasks for robots. Figure 1 depicts some of the route segments used to assemble a route for testing the navigational capabilities of robots. Clockwise from top-left, the segments shown are a three-way intersection, a street with a passing lane, a straight street, and a four-way intersection[22]. Developed here are the new modules including a straight street segment with parallel parking, a perpendicular parking lot, and a 90-degree curve, depicted in Figure 2. Both figures show all segments separated slightly to indicate cut lines. Obstacles simulating other vehicles may be placed at any point to obstruct traffic. An actual configuration used to test the robots is shown in Figure 3. It consists of a straight street segment, a passing lane, a three-way intersection, a 90-degree curve, another straight street segment, a four-way intersection with an obstacle, and a perpendicular parking lot.

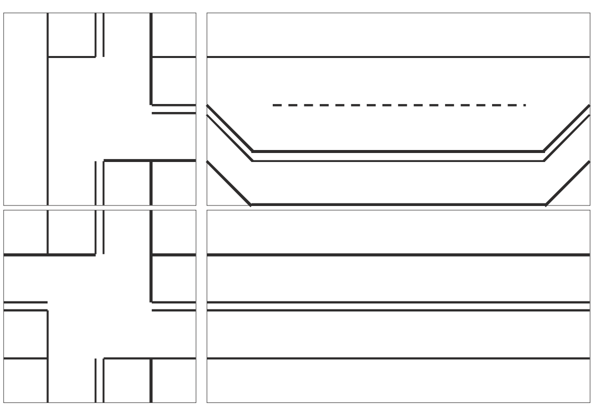

Figure 1: Route segments for testing navigational capabilities of robots[22].

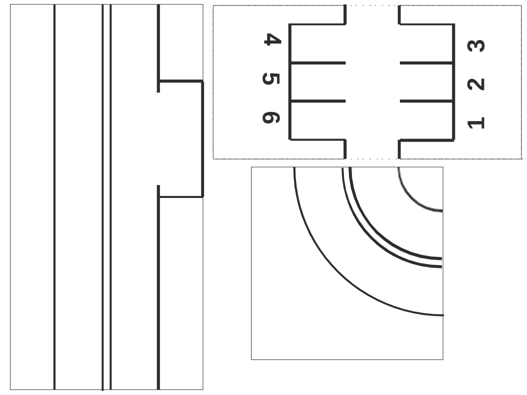

Figure 2: Route segments for testing turning and parking capabilities of robots.

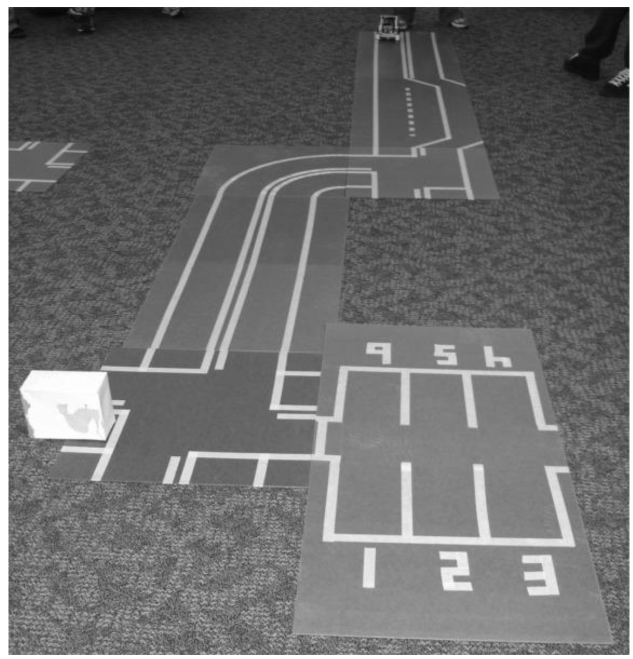

Figure 3: One route configuration.

Assessment and Evaluation

Mechatronics and computer information systems students of sophomore, junior, senior, and graduate standings took the course. Students constructed and programmed robotic vehicles to traverse a miniaturized route using LEGO Mindstorms NXT sets. Some final hardware robot designs are shown in Figure 4. They all use three available actuators, two to power the wheels and one to rotate an ultrasonic sensor in search of road obstacles. Other two (or three) light sensors pointing down are used to sense the road.

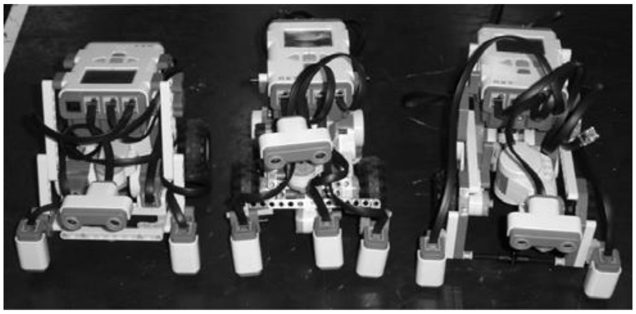

Figure 4: Some final robot hardware designs.

Appropriate assessment instruments are developed. Their goals are to re-evaluate widely-known results from literature as the instruments are applied in this particular case (motivation, learning perceptions, quality of learning experience) as well as the specific laboratory objectives such as the degree of increase in practical knowledge of basic robot controls, multisensor data fusion, and robot programming.

Both formative and summative assessment evaluation techniques are addressed. Formative evaluations are based on informal student interviews, topic discussions, questions raised, and bi-weekly progress reports discussing milestones met. Summative evaluations are based on final robot performance measures (degrees to which the robots satisfy criteria stated in the Laboratory Task Section), a final team presentation with report, a survey (student perceptions of lab effectiveness, suitability, and motivational value), and university-standard student evaluations of teaching for the entire course.

During the official DARPA Urban Challenge on Saturday, November 3rd, 2007, the students held their own mini Urban Challenge in the lobby of the student dorm. Although it was interesting for onlookers, results were not as hoped due to the early date. In one case, the robot traversed the entire route, but didn't detect another vehicle at an intersection. The obstacle was placed at such an angle that it didn't reflect the ultrasound back to the robot's sensor. In another case, results were inconsistent; the robot performed differently each time through the route, possibly due to varying lighting conditions.

At the end of the semester, the final testing or robotic designs and robot capabilities was performed using a rout in the laboratory in which the students developed the robots. The results were all positive. All robots were able to satisfy the required modified basic navigation and traffic rules as stated in the Laboratory Assignment Section. Among the optional navigation rules, parallel parking was well specified and the easiest. However, the robot passing maneuver around another moving robot was not well defined in the task, so the results depended on the speed of the other moving robot. If the robot to be passed moved to fast, the passing lane was not long enough to complete the maneuver. Thus, the speed of the robot to be passed was limited to a tenth of its full speed. Not all groups were able to accomplish this task. Stop signs were not implemented since they required additional sensors and were somewhat redundant to stop lines. The optional traffic rules where interpreted in such a way so they were relatively easy to implement. The correct robot precedence at an intersection was implemented by checking for obstacles (other robots) at an intersection at the robot arrival. The arriving robot would go through the intersection (or turn) if no other robots were present. Otherwise it would wait until all is cleared. While traveling through the intersection the robot would not check for other robots. Finally, when traveling, robots maintained a safety buffer of 0.3m by using their ultrasonic sensors to check for other robots in front of them. When another robot was detected at the threshold distance of 0.3m the robot traveling behind the slow robot would just stop and wait for the slow robot to move away.

Besides igniting interest in robotics for the students in the class, there was an unintended effect of exciting a group of about 24 preschool children who came to participate in a final testing stage.

A survey was administered to students at the conclusion of the course. It was adapted from a Drexel University form[23]. The survey with average student responses is shown in Table 1. The scale used for the survey was 1 to 5. Where 1 indicates 'Not at All', 2 indicates 'To a Limited Extent', 3 indicates 'To a Moderate Extent', 4 indicates 'To a Great Extent', and 5 indicates 'To a Very Great Extent'.

Table 1: Survey with Average Student Responses.

	Item	**Avg.**
1	Analytical Skills *Applies logic in solving problems and analyzes problems from different points of views. Translates academic theory into practical applications using appropriate technical techniques, processes, and tools.*	5
2	Communication Skills *Articulates ideas in a clear and concise fashion and uses facts to reinforce points. Written materials flow logically and are grammatically correct. Plans and delivers oral presentations effectively. Uses technology and graphics to support ideas and decisions.*	4.5
3	Creative Problem-solving *Develops many potential solutions to problems while discouraging others from rushing to premature conclusions. Suggests new approaches and challenges the way things are normally done.*	4.75
4	Life-Long Learning *Learns independently and continuously seeks to acquire new knowledge. Exceeds basic requirements of an assignment and brings in relevant outside experiences to provide advanced solutions to the problems at hand*	4.5
5	Project Management *Sets goals, prioritizes tasks and meets project milestones. Seeks clarification of task requirements and takes corrective action based upon feedback from others. Creates action plans and timetables to complete assigned work.*	4.5
6	Research Skills *Uses computer based resources effectively thus acquiring information from multiple sources and organizes and interprets data appropriately. Designs and conducts experiments to validate theories.*	4.25
7	Systems Thinking *Understands how events interrelate and demonstrates an ability to take new information and integrate it with past knowledge. Integrates and uses knowledge from various courses, including Engineering, CIS, Physics, Mathematics, and Social Sciences, to solve technical problems.*	5
8	Teamwork *Each member contributes a fair share to the completion of the project. Everyone participates, listens and cooperates with other members. Members share information and help reconcile differences of opinions when they occur.*	4.5
9	Do you have a better understanding of mechatronics from this course?	4.25
10	Do you have a better understanding of computer information systems from this course?	3.75
11	Did you understand the objectives of your project?	4.5
12	Did your team meet the objectives of the project?	4.25
13	Did your team meet the milestones?	4
14	Do you feel your technical writing skills have benefited from the course?	3.25
15	Do you feel your oral communication abilities have improved by taking the course?	3.75

16	Have your computer skills improved by taking the course?	2.25
17	Do you understand the process of solving an engineering/programming problem?	4.5
18	Did you ask for help when or if you did not understand something?	3.75
19	Do you feel you contributed greatly to the project?	4.75
20	Did you enjoy working on a team?	4
21	Did your participation on the team help or hinder your performance and the end result of the project?	3.75
22	Do you understand the importance of having a planning/design phase before an implementation phase?	4.25
23	Do you feel that expectations were too high?	3.75
24	Do you feel like there was too much work?	3.5
25	Was the course relevant to your interests?	4.75
26	Did the course stimulate your interest in engineering/CIS/robotics?	5
27	Do you understand various aspects of hardware/software integration	3.75
28	Are you able to develop criteria for the selection, justification, and implementation of selected technology methods and processes to perform a design task	4.25
29	Are you capable of using commercially available hardware/software tools for robotics	4
30	Are you able to build and program robots for independent research in robotics	4

Results were positive with an overall average of 4.17 on a scale of 1 to 5. The points with the highest average scores, 4.75 or higher, were:

- Was the course relevant to your interests?
- Did the course stimulate your interest in engineering/CIS/robotics?
- Do you feel you contributed greatly to the project?
- Systems Thinking
- Creative Problem-solving
- Analytical Skills

This indicates a high level of interest and effort in the class throughout the semester.

Robotics projects are an effective educational tool for learning robotics. While all students were enthusiastic about the course, they felt that the material was overwhelming for a one-credit course, and that they needed more structure. A considerable amount of unscheduled laboratory time is needed to complete the project. It was found that while easy to use for simple tasks, the LEGO Mindstorms NXT software is somewhat cumbersome for more complicated programs. In the future, based on these comments and our own observations, the course will be implemented as a two credit hour course containing one lecture hour in addition to the two lab hours per week.

Conclusions

In this work, a robotics laboratory design course implementing a new hardware/software environment, the LEGO Mindstorms NXT, is presented. A novel set of route segments was designed to enable quick construction of configurable routes. Miniaturization of the DARPA Urban Challenge is used as a novel motivational tool. The course laboratory task combines robotic navigation tasks coupled with obstacle detection and avoidance tasks. Project-based learning objectives dealing with robot controls and simple multisensor data fusion are satisfied. Student comments are positive. The project setup is cost-effective (about $300 per setup). Based on student responses and an evaluation of student work, this research confirms that robotics projects are an effective educational tool for learning robotics.

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