2006-1905: TEACHING ROBOT DESIGN: STUDENT-DRIVEN, OPEN-ENDED DESIGN PROJECTS

Bradley Bishop, U.S. Naval Academy

BRADLEY E. BISHOP is an Associate Professor in the Weapons and Systems Engineering Department at the United States Naval Academy (USNA). He received the B.S. degree in Electrical Engineering from Michigan State University in 1991, and the M.S. and Ph.D. degrees in EE from the University of Illinois at Urbana-Champaign in 1994 and 1997, respectively. He is the founder of the Mobile Robotics Laboratory at USNA. His research interests include robot swarm control, autonomous surface vessels, and nonlinear control.

Carl Wick, U.S. Naval Academy

CARL E. WICK is a Professor and Chairman of the Weapons and Systems Engineering Department at the United States Naval Academy (USNA). He received the B.S. degree from USNA in 1970, the M.S. degree from the Naval Postgraduate School in 1978, and the D.Sc. degree from The George Washington University in 1993. His research interests include autonomous underwater vehicles, sensor systems, and contemporary microprocessor systems

George Piper, U.S. Naval Academy

GEORGE E. PIPER is an Associate Professor of Systems Engineering at the United States Naval Academy. He holds a B.S., M.S., and a Ph.D. in mechanical engineering from Drexel University. Prior to joining the Naval Academy faculty, Dr. Piper was a senior member of the technical staff at Martin Marietta's Astro Space Division. Dr. Piper is a licensed Professional Engineer. His research interests include space vehicle dynamics and control, robotic aircraft, and control of vibration and noise.

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Abstract

In this paper, we describe an open-ended robot design exercise that focuses on the design process. Students are tasked with defining a set of objectives, developing a solution strategy and constructing a final system. Students undertaking this exercise are working toward a metric based on sound engineering design, in contrast to the victory-based metrics typically associated (in the students' minds) with robotics competitions. The proposed format allows students a truly open-ended experience, since they must develop problem specifications themselves. Instructor support is required to assist in the development of an appropriate problem as well as during the design phase, but a well-prepared instructor can look forward to an extremely beneficial exercise that strongly motivates students and provides substantial dividends for the students in regards to robotics and engineering design in general.

Introduction

Robot design is a challenging topic to teach in a traditional course¹. Most approaches to instruction in robot design focus on subsystem design followed by a common design project (typically involving a competition). While this method provides students with experience in designing a robot to achieve certain objectives, there is often a distinct lack of rigor in the design process itself, with only success in the final competition as the metric by which the students evaluate their overall performance. Due to this 'goal-minded' behavior, students often resort to *ad hoc* methods for design, losing sight of the principles of the discipline.

To alleviate this problem, we provide students with an opportunity to develop their own design project and then carry it out as part of a course on mobile robot design. Student teams (typically comprising three students) complete their design over the course of several weeks and present to their peers both their project concept and the outcomes of their design. Peer evaluations provide valuable insight into the validity of the project and appropriate design methods. In this paper, we lay out the learning objectives and instructional strategies associated with this approach and provide student feedback on their experience. We focus on the pedagogical advantages of the method, including an increased emphasis on design methodology and problem specifications.

Student-directed design provides students with a great deal of flexibility, but also places on them the onus of developing a nontrivial project that involves all aspects of the course and the design process. The project discussed in this work follows several others in the more classical form, involving open-ended but completely specified problems in navigation, design for terrain, etc. Thus, students enter this exercise with several clear examples of appropriate projects as well as graded outcomes from their previous designs.

It is a fallacy common of modern robotics instruction that the discipline is primarily a vehicle for instruction in basic engineering principles. In fact, robotics is an important and robust discipline in its own right. As such, a key component of this design project is to synthesize a complete design based on previous experiences in the course, providing students with added experience

and insight into their craft as roboticists. This exercise is also extremely beneficial in other ways, especially for students who are about to undertake a capstone senior design project. Students are frequently asked to develop and carry out a novel design project as part of their capstone experience without ever having an opportunity to do so on a smaller scale. This project is intended to provide experiential support for these future capstone efforts.

Experience has shown that this sort of student-driven, open-ended project requires a great deal of instructor flexibility, deep familiarity with available components, and ready suggestions for potential projects. But, for instructors who are willing to undertake the effort, a student-driven design project can provide a significant experience in problem specification and engineering design while simultaneously reinforcing core concepts of robotics. Note that there are many well designed robotics competitions, from Trinity College's famous Fire Fighting Home Robot Contest² to the high-level Intelligent Ground Vehicle Competition³, and that the authors do not intend to suggest that these competitions are not valuable. Rather, we propose that the exercises discussed in this paper provide a valuable ramp-up educational experience for students who wish to pursue a capstone design experience involving robotics competition, and that the techniques developed serve to better reinforce basic concepts than do simplistic in-class competitions.

Preparation

The project discussed in this paper is part of a Mobile Robot Design course, taught as a senior-level elective in the Systems Engineering Department at the United States Naval Academy. Students are not expected to be able to handle a complete design experience without some guidance, which is provided in the course through a sequence of increasingly complex, but still well-defined, tasks. The course includes one hour of lecture and four hours of laboratory each week for a total of three credit hours. This course focuses on robot design and hands-on experience, with the following taking place before the project that is the main focus of this paper:

- Students are first reminded of basic statics and dynamics. This is accomplished through a single-lab experience involving building a hill-climbing robot (see Figure 1). In one two-hour period, they design and construct a *differentially-driven* vehicle⁴ to climb a smooth slope at the maximum possible angle, touching only the climbing face of the slope (i.e., no grabbing onto the edges). Parts provided are standard LEGO Mindstorms⁵ kits, with each team being allotted an identical number of gears of various sizes, and an equal selection of tires, hubs and rubber track pieces from which to select. This project emphasizes stability, torque, traction, and vehicle kinematics. It sets the stage for the study of dead reckoning and differential drive control.

Figure 1: Hill-climbing robot samples

- Students study dead reckoning using a simple differentially-driven vehicle of their own design (see Figure 2), built from the same set of available parts as the hill climber⁶. Students must carefully design the vehicle to provide stability in motion as well as agility for turning. Low resolution shaft encoders (16 counts/rev) are used as feedback to allow the vehicle to traverse a fixed course on a smooth floor. The programming language for the LEGO RCX is Visual NQC, a version of the standard Not-Quite-C⁷ created by Dave Baum.

Figure 2: Examples of poorly designed (left) and well designed (right) differentially driven vehicles for dead reckoning

- The two previous exercises are combined into a challenge lab in which the students must design a vehicle to overcome a wide array of terrain challenges as it traverses a course (see Figure 3)⁸. Students have been taught concepts in terrain compliance⁹ as well as very basic terradynamics and wheel-soil interaction, and have viewed a wide array of fielded rough-terrain vehicles. Again, only a limited and equal selection of parts is available for the task.

Figure 3: Examples of robots designed for the terrain challenge. The left hand vehicle has a torsion-compliant frame and a vertically actuated wheel that allows low radius turns. The vehicle on the right sports a compact design with high gearing and an active undercarriage.

- Students are next introduced to alternative robot control concepts through a behavior-based robot programming laboratory (see Figure 4). Students develop a robot that searches an area for a ‘food’ item while avoiding bright light and obstacles. Typically, subsumption-based methods are used¹⁰. This so-called ‘Robo-Roach’ project requires that students develop a very fast and agile system with well-designed behaviors to achieve the goals of finding as much ‘food’ as possible while simultaneously avoiding collisions, entanglements and susceptibility to capture (by avoiding bright areas).

Figure 4: Robot roaches preparing for the demo in the behavior-based programming assignment

These assignments vary in complexity and depth, but provide students with substantial experience in mobile robot capabilities as well as design and construction methods. Every student views the performance of every project and has an opportunity to discuss novel aspects of the various approaches to the tasks at hand. This process provides each student with a wide array of tools for the upcoming project and exposes students to many different approaches to solving problems.

The Project: Assignment and Assessment

At the sixth to seventh week of the semester, student teams (typically comprising three members) are asked to develop their own project, which is to include robot design and programming. The basic toolset remains the same: LEGO Mindstorms with Visual NQC. Limitations on numbers of various parts, however, are lifted (to the extent that parts are available). Students are also permitted to use a wide array of electronics and additional parts from the course or departmental stock where necessary, and are encouraged to use machine and wood shop facilities to construct test areas or devices for the project.

Students are given a set of sample projects that display sufficient complexity and depth for the project. The project comprises three weeks of laboratory time (12 in-class hours) and includes a formal presentation and report. A key component of the entire process is a peer evaluation that

represents a significant portion of their grade (adjusted by the instructor if necessary). The following rubric is provided to students as they develop their design projects:

Analysis Key:

Project Difficulty:	1	2	3	4	5	Most Difficult (<u>Average = 4</u>)
Performance:	1	2	3	4	5	Fully Functional
Presentation:	1	2	3	4	5	Excellent
Teamwork:	1	2	3	4	5	All members contributed equally

The total score for the project (1 – 5) is given by the formula:

$$(2*(\text{Performance}) + (\text{Presentation}) + (\text{Teamwork}))/4 + (\text{Project Difficulty} - 4)$$

Thus, students know that they may attempt a more challenging project without undue penalty, but adopting a very straightforward project could cause a significant grade reduction. Because the difficulty rating is evaluated by their peers, students have a strong incentive to select an appropriate project. The instructor retains the right to adjust a difficulty rating (or any other score) to avoid collusion or accidental misconceptions regarding the sophistication of projects. This right has never been exercised in the five year history of offering this project.

In addition to peer evaluations, the instructor grades each team's formal project report. The two grades are combined to provide an overall score for the project, which constitutes 24% of the student's final grade in the course. The rubric used to evaluate project reports was:

Component	Values
Problem Statement	0 – 3 None: 0 Fully defined with assumptions and setup details: 3
Code	Included: 0 – 2 Documented: 0 – 1 Discussed: 0 – 2
Robot/Devices	Images: 0 – 1 Design History: 0 – 2 Details: 0 – 2
Analysis	Performance Discussion: 0 – 3 Problem Analysis: 0 – 2 Potential Solutions: 0 – 2

Sample Projects

To get students started, the following project ideas (in very rough form) are presented:

- **Stair-navigating robot:** Design, construct and program a robot that can climb or descend any of the stairs in the building, or any stair of a lower height and longer depth.
- **Gauntlet:** Your robot must make its way across a minefield and return the path generated to a second robot that must navigate without mine-sensor feedback. Get the second robot

across the minefield. Mines will be detected via a simulated magnetic sensor (using photosensors). Any contact with a mine results in a failed attempt.

- Artillery Bot: A small rover robot searches an area for a target, moves to a safe location, and calls in a strike on the target from an automated turret.
- Ladder-climber: Robot is designed to autonomously climb ladders with known rung spacing, starting from the floor.
- ‘Morphing’ robot, designed for various modes of locomotion. For example (many others are possible):
  - Robot is designed with a mobile cg that can be used to autonomously:
    - i) Cross wide gaps
    - ii) Adjust wheel contact force for climbing/descending steep slope
    - iii) Detect and react to these obstacles in any combination and order
    - iv) Achieve agile turning
- Cooperative Mapping Project¹¹: Two or more robots are designed to search an area for obstacles and provide a cell-based map of open floor space for further navigation.

Some students select projects from this list, but most develop their own. Even if they select a project from the list, they must flesh out the assumptions, objectives and metrics for success for their specific version, all of which must be submitted to the instructor before the first day of laboratory for the project. The instructor provides feedback on achievability and a rough difficulty rating, or rejects the proposal and requests a new one. Once a suitable proposal has been provided, the students begin work. Some examples of student-developed projects from the past few years include:

- Stair-rail climber: A robot designed to autonomously mount a ramp to a railing in a spiral staircase, clamp down on the rail and traverse it to a different floor:

Figure 5: The stair-rail climber

- Bridge-laying robot: robot autonomously detects gaps and places a bridge across them to provide a stable transition platform. After crossing the gap, the robot removes the bridge to prevent enemy combatants from using it.
- Automatic Transmission: a mobile robot with an automatically-adjusting transmission that will maintain control and speed regulation over wide changes in slope:

Figure 6: The automatic transmission

- Dual-track vehicle: system with two sets of linear tracks at 90° with respect to one another, one set of which is actuated vertically to allow the vehicle to move in Cartesian space without steering. The vehicle was used as part of a search-and-remove ‘hazardous waste’ removal system. When this vehicle had located a target for removal, a second bot was sent to the location to pick up the target:

Figure 7: Cartesian-bot

Student Feedback

The 43 students in the 2005 offering of this course were polled on the impact that it had on their abilities in a variety of areas, on a scale consisting of ‘Greatly Improved,’ ‘Somewhat Improved’ or ‘Not Improved.’ While some students felt that their abilities in some of these areas could not be improved, or did not need improvement, the overall consensus was that the project provided strong support of the primary objectives of the course:

Ability	Number of students giving the rating		
	Greatly Improved	Somewhat Improved	Not Improved
Ability to develop specifications and problem statements	25	17	1
Ability to manage time on large projects	13	25	5
Ability to divide tasks and work in a team	12	26	5
Ability to troubleshoot	28	13	2
Coding or mechanical design ability (as appropriate)	34	9	0
Understanding of mobile robotics	28	14	1
Understanding of the design process	25	16	1

Students were next asked to rate the value of the entire project from several perspectives:

Area	Number of students giving the rating		
	Extremely Valuable	Somewhat Valuable	Not Valuable
[Preparation for and completion of] Senior design projects	27	13	3
Education as a systems engineer	32	11	0
Appreciation of the complexity of real problems	33	10	0
Confidence as an engineer	25	18	0

Conclusions

Students clearly and overwhelmingly find this project beneficial for their education in robotics and robot design as well as for their overall growth as engineers. They also find the exercise to be of great benefit as preparation for their senior design projects (in the proposal phase as this project ended, to be completed the following semester).

This project was designed to provide students with an open-ended design experience with clear evaluative metrics beyond “victory,” which students often associate with a competition (regardless of the actual grading metrics used). Feedback from students demonstrates that this project was successful in meeting all of the goals that were set out. Furthermore, students find this experience worthwhile and fulfilling.

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Bibliography

- ¹ Piepmeier, J. A., Bishop, B. E., and Knowles, K. A., “Modern Robotics Engineering Education,” *IEEE Robotics and Automation Magazine*, Vol. 10, No. 2, June 2003, pp. 33 – 37.
- ² URL: <http://www.trincoll.edu/events/robot/>, “Trinity College Fire Fighting Home Robot Contest,” accessed 12 Jan 2006.
- ³ URL: <http://www.igvc.org/deploy/>, “The Annual Intelligent Ground Vehicle Competition,” accessed 12 Jan 2006.
- ⁴ Dudek, G., and Jenkin, M., *Computational Principles of Mobile Robotics*, Cambridge University Press, Cambridge, MA, 1999.
- ⁵ URL: <http://mindstorms.lego.com/eng/>, “LEGO Mindstorms,” accessed 12 Jan 2006.
- ⁶ Bishop, B. E. and Wick, C. E., “Educational Control Studies of a Differentially Driven Mobile Robot,” *Proceedings of the 2003 Southwest Symposium on Systems Theory*, March 2003, pp. 308 - 312.
- ⁷ URL: <http://bricxcc.sourceforge.net/nqc/>, “Not Quite C,” accessed 12 Jan 2006.
- ⁸ Bishop, B. E., “Teaching Robot Design: Locomotion Beyond Differential Drive,” *Proceedings of the 2005 ASEE Annual Conference, CD-ROM, June 2005*.
- ⁹ Sandin, P. E., *Robot Mechanisms and Mechanical Devices Illustrated*, McGraw Hill, New York, 2003.
- ¹⁰ Arkin, R. C., *Behavior-based Robotics*, The MIT Press, Cambridge, MA, 1998.
- ¹¹ Bishop, B. E., “Design of a Cooperative Autonomous Mobile Robot System at the Undergraduate Level,” *Computers in Education Journal*, Volume XI, Number 2, April-June, 2001, pp. 44 – 49.