2006-78: DISCOVERY BASED LEARNING IN THE ENGINEERING CLASSROOM USING UNDERWATER ROBOTICS

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Discovery based learning in the engineering classroom using underwater robotics

Abstract

Underwater robotics projects offer an excellent medium for discovery based engineering and science learning. The challenge of building underwater robotic vehicles and manipulators engages and stimulates students while encompassing a very broad spectrum of engineering disciplines and scientific concepts.

This paper describes the successful design and implementation of student projects, building wire guided remotely operated underwater vehicles (ROVs) with motorized grabbers. This work is part of an ongoing effort to incorporate innovative, hands on projects into our freshman engineering curriculum. These projects help expose students to practical design issues in the freshman year, foster creative problem solving skills and may aid student retention on engineering programs. These projects have also been successfully piloted in pre-college programs, aimed at generating interest in engineering careers among high school students.

We describe ongoing work to extend these projects to include computer control and sensory feedback, allowing students to develop autonomous underwater vehicles (AUVs). Further, we outline ongoing work to assess the effectiveness of these modules.

1 Introduction

This paper describes an ongoing effort, at Stevens Institute of Technology, to develop a set of educational modules, which will teach fundamental engineering principles through the design, construction, programming and testing of underwater robotic vehicles using simple materials. These modules emphasize discovery based learning, creative problem solving, collaborative team work and provide hands on exposure to the iterative engineering design process.

This paper provides an overview of the proposed educational module, presents the results of a pilot implementation project during which students successfully constructed remotely operated underwater vehicles and discusses methodologies by which the effectiveness of such modules might be assessed.

1.1 Why build underwater robotic vehicles?

When students design, build and program underwater robotic vehicles, they are learning engineering fundamentals which span virtually every engineering discipline. Additionally, students are motivated by an exciting and stimulating design scenario.

The use of projects based on small robotic vehicles is now widespread in engineering curricula, however these are predominantly wheeled, terrestrial vehicles. Such projects often reduce to little more than exercises in applied programming, losing valuable opportunities to present substantial mechanical challenges or to incorporate real interdisciplinary engineering design. In contrast, the
underwater environment presents unique design challenges and opportunities. The motion of an underwater vehicle, through a three dimensional space with six degrees of freedom, is more complex. Additional engineering issues include propulsion, drag, buoyancy and stability. Practical construction problems include how to waterproof electrical components. The challenge of creating a robot which can be sent to explore a hostile and inaccessible environment is also motivating and stimulating to many students.

1.2 Why use LEGO?

Our students work with a combination of LEGO and additional simple materials. LEGO is particularly suited to discovery based learning due to its ease and speed of assembly (Portsmore et al., 2004)\(^1\), (Wang et al., 2004)\(^2\). This speed reduces the time between conception of an idea and its implementation, enabling students to discover through trial and error, rapidly test a range of alternative designs and evolve their designs iteratively by observing the relationship between structure and function. In contrast, when students use conventional materials, the construction process is lengthy and frustrating. Time constraints prevent students from evolving their designs through multiple iterations of testing and modification. Often there is no time allotted for the students to fail, analyze the failure and then modify their design. In contrast “We know that students will learn most deeply and profoundly when they…have an opportunity to try, fail and receive feedback on their work” (Bain, 2005)\(^3\).

1.3 Retention and recruitment

Enrollment rates in undergraduate engineering programs are in decline (Engineering Trends Quarterly Newsletter, 2005)\(^4\) and several studies have found a drop out rate for undergraduate science and engineering students of greater than fifty percent (National Science Board, 2004)\(^5\). Student feedback suggests that there is a shortage of genuine opportunities for creative invention within engineering courses and that this can frustrate many talented and motivated students, discouraging the completion of engineering training or the pursuance an engineering career.

The teaching methods described in this paper are intended to provide students with more opportunities to invent and create. Additionally, they enable students to see how their theoretical studies relate to practical engineering problems. Incorporating this hands on, discovery learning project early in the freshman year is part of an ongoing effort to improve student retention rates. We have also incorporated the project into pre-college courses for high school students to help stimulate interest in engineering careers and boost engineering enrollment rates.

Studies at other institutions (e.g. Pomalaza-Ráez, 2003)\(^6\) have indicated that hands on mobile robot projects using simple materials such as LEGO with undergraduate students, may significantly improve retention rates.

1.4 Cost

The wire-guided ROV project described below is relatively inexpensive to implement. Start-up costs for materials to enable a team of five students to complete the project are approximately $200. These materials can then be re-used by successive student teams. The main replenishment
costs are batteries (unless rechargeable batteries are used) and small items such as string and duct tape.

Ongoing work includes extending the projects to include computer control and sensory feedback. This will involve additional expense, however the programmable controllers used will be relatively small and low cost, re-usable and flexible, providing students with a valuable tool which they can make use of in many other applications.

2 Discovery based learning

Discovery learning (Bruner, 1966) is a cognitive instructional model in which students are encouraged to learn through active involvement with concepts and principles, and teachers encourage students to have experiences and conduct experiments that permit them to discover principles for themselves.

Although discovery learning is frequently employed in an early childhood development setting, the instructional model offers several advantages to a high school or undergraduate setting. It arouses students’ curiosity, motivating them to continue to work until they find answers (Berlyne, 1965). Students also learn independent problem solving and critical thinking skills because they must independently analyze and manipulate information.

Students often benefit more from being able to engage in active learning by “seeing” and “doing” things than from passive learning by listening to lectures. Tackling material from several perspectives and persevering with unresolved problems improves students’ core intellectual skills—they learn how to learn independently. Cognitive development is not the accumulation of isolated pieces of information; rather, it is the construction by students of a framework for understanding their environment. Teachers should serve as role models by solving problems with students, explaining the problem solving process and talking about the relationships between actions and outcomes. Observing students during their activities, examining their solutions and listening carefully to their questions can reveal much about their interests, modes of thought and understanding or misunderstanding of concepts (Slavin, 1994).

Discovery based learning is a particularly effective means of teaching the iterative approach to engineering design. Students are encouraged to approach engineering problems through an iterative sequence of steps: Design/Test/Modify (figure 1). In contrast, surprisingly little of conventional engineering curricula are devoted to this design process, with the learning experience of engineering students often bearing little resemblance to the activities of professional engineers in industry.

![Figure 1: The iterative design process](image-url)
3 An overview of the Stevens underwater robotics student project program

Educators and engineers at Stevens Institute of Technology are currently engaged in developing a set of educational modules, which will teach fundamental engineering principles through the design, construction and testing of underwater robotic vehicles. The strategies incorporated into our underwater robotics projects foster an active, discovery learning environment that integrates many mathematical, scientific and engineering principles and will support conceptual and skill-based learning, application of principles to novel situations, collaborative learning and cooperative group skills.

Students begin with a mechanical design project, creating stable vessels which support the weight of motors, controllers and batteries at near to neutral buoyancy. They investigate underwater propulsion, running a series of experiments to optimize thrust based on gearing and propeller design. They also investigate ways of controlling vertical motion in the water. They build controllers for the LEGO motors and evolve their designs into ROVs, underwater vehicles controlled remotely by a human operator via connecting wires.

Future work will involve students adding a variety of sensors and small microcomputers to their vehicles, eventually programming the machines to respond to sensor stimuli with intelligent motion. The ultimate design challenge will be to develop a vehicle which will perform simple, unaided, autonomous tasks. Students will test their designs by entering their robots in a competition to complete an assortment of challenges.

We are investigating the use of various different kinds of control systems and programming languages. Students may benefit from starting with simple control systems and accessible graphical programming languages before progressing to more sophisticated controllers and advanced syntactical languages.

4 Building remotely operated underwater vehicles – a pilot project implementation

4.1 Background

We have successfully implemented pilot student projects, building wire guided ROVs. These pilots have included freshman undergraduate projects and similar projects with teams of senior high school students. With freshmen, the course can be completed in as little as four 90 minute contact sessions with additional periods of unsupervised laboratory time. High school seniors have completed the same tasks comfortably in 12 contact hours over five sessions. Some flexibility with laboratory sessions and contact time is desirable to accommodate different ability levels.

4.2 Materials

Students were provided with a selection of LEGO including several motors, battery boxes and leads, gearing, structural and mechanical components. Also provided, were a selection of plastic propellers (obtainable from hobby stores) mounted on LEGO axles (figure 2). Additional materials included Styrofoam, modeling clay, a selection of weights (nuts and bolts work well),
rubber bands, string and duct tape. A 30 inch deep inflatable pool was used to test the designs. Wiffle balls were specified as the objects to be retrieved and manipulated by the ROVs.

Students were issued a variety of electrical components, with which to create a control system and had the opportunity to learn soldering and simple circuit design and debugging. Long control cables were pre-assembled for the students. These cables contained eight wires (enough to control four independent motors) and were terminated with four LEGO compatible end connectors (figure 3). To build a control system, several three position switches were supplied. Each switch can control a single motor with three possible states, Forward/Off/Reverse. Pre-drilled aluminum boxes were supplied for mounting the switches. Additional supplies included 9-volt batteries, battery connectors, wire, solder, electrical tape, shrink wrap, soldering irons, solder suckers, wire snips and strippers and safety glasses. A digital multimeter was useful for debugging circuits.

4.3 Procedure

Students were divided into five person teams. The project typically requires four to five sessions with instructors plus additional time for students to work on their projects. In each session the student teams are given progressively more complex, intermediary design challenges. Intermediary challenges initially involve developing simple motorized surface vessels, progressing to fully controllable, submersible vehicles and motorized grabbers. As a final challenge, each team has to use their ROV to retrieve and manipulate objects on the bottom of a pool of water.

The intermediary design challenges include:
1) Design a surface vessel with a single motor and various propeller options, optimizing gearing ratios to maximize speed in a single direction.

2) Design a surface vessel with steering, using two independently controlled motors. The challenge involved negotiating a figure eight course, around two buoys, in the least amount of time.
3) Develop an electrical control system for four independent motors.

4) Add a third motor to the vehicle, enabling vertical motion in the water column.

5) Design a motorized mechanical manipulator which can grasp specified objects.

6) Combine the products of stages 3, 4 and 5 to produce a vehicle which can retrieve the greatest number of objects from the bottom of the pool within a five minute period. Retrieved objects must be deposited in bins at various depths in the water in order to score points.

Many of these challenges have a variety of solutions. For example, challenge 2 can be solved using twin propellers, a single propeller plus rudder or a single propeller with variable direction.

At some stages during the project, specific roles are assigned to each team member including:
- Propulsion engineers
- Electrical control system engineers
- Grabber designers

Students are encouraged to rotate through different roles in order to maximize the breadth of their experience. The allocation of different roles is also intended to maximize student participation, by preventing too many students trying to work on the same part of their design at any one time.

In each laboratory session, instructors deliver short, interactive talks. These are limited to around 10 minutes each. On occasions where two talks are delivered in the same session, they are separated by periods of practical work. These short talks are designed to convey the underlying scientific and engineering principles which are necessary to complete each successive stage of the design challenge. Additionally, these talks are designed to show students how the theory that they are studying in mathematics and physics classes relates in tangible ways to the real, practical engineering problems which they are tackling. Talk subjects include:

1) Gearing mechanisms, torque, speed and thrust.
2) Different ways to achieve two degrees of freedom of motion.
3) Electrical circuits and control panel design.
4) Buoyancy, Archimedes principle and how to move up and down.
5) Grabbers, graspers and manipulators

Students receive handouts containing supplementary information including:
- Photographs and descriptions of industrial and research ROVs and AUVs.
- Notes on important aspects of submarine design.
- Notes on circuits and electrical design issues.
4.4 Results

All student teams succeeded in creating remotely operated underwater vehicles which successfully completed the final design challenge. Several important and encouraging features of the student’s work were observed:

- Every student team arrived at original and creative solutions to the design problems. Each team’s solutions were significantly distinct from those of other teams.
- The iterative engineering design process was highly apparent in each team’s work, with solutions evolving through successive cycles of designing, testing and modification.
- Design solutions were achieved through invention, experimentation and discovery and not through didactic, prescribed instructions.
- The structure of the course and the nature of the design challenges successfully induced positive teamwork habits to be developed within each team.
- Students were highly engaged in the work, enjoyed what they were doing and wanted to do more.
- Students took pride in what they created and in their ability to solve significant engineering problems.

4.4.1 Student survey results

To gain preliminary insight into the likely effectiveness of these projects, students were asked to complete anonymous assessment questionnaires. These consisted of a combination of Likert scale and open ended questions. More comprehensive assessment studies are planned and a discussion of possible assessment methodologies is included later in the paper (section 5.2). The following is a summary of the student questionnaire responses. The number of students is inserted in each box. A total of 13 students completed the survey.

Question 1. On a scale of 1 to 5, with 5 representing very easy, how easy did you find the following?

<table>
<thead>
<tr>
<th></th>
<th>1 Very difficult</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5 Very easy</th>
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<td>6</td>
<td>1</td>
<td></td>
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<td>6</td>
<td>6</td>
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<td>5</td>
<td>3</td>
<td>2</td>
<td><strong>3.3</strong></td>
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</table>
Question 2. On a scale of 1 to 5, with 5 representing very effective, how helpful did you find these aspects of the project in learning about mechanical engineering?

<table>
<thead>
<tr>
<th></th>
<th>1 Not at all effective</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5 Very effective</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3.5</td>
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<tr>
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<td>3</td>
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<tr>
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<td>3</td>
<td>6</td>
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<td>4.2</td>
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<tr>
<td>Buoyancy and Stability</td>
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<td>3</td>
<td>5</td>
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<tr>
<td>Grabber Design</td>
<td></td>
<td>4</td>
<td>3</td>
<td>6</td>
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<tr>
<td>Problems associated with</td>
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<td>4.6</td>
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<tr>
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</tbody>
</table>

Question 3. On a scale of 1 to 5, with 5 representing very interesting, how interesting did you find these aspects of the project?

<table>
<thead>
<tr>
<th></th>
<th>1 Not at all interesting</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5 Very interesting</th>
<th>Average</th>
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</thead>
<tbody>
<tr>
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<td>4</td>
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<tr>
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</table>

Question 4. Overall, are you satisfied with this project?
1. Yes, it was interesting yet challenging and informative.
2. Yes, but not with my performance.
3. Yes, because we went from last place, to second, then first.
4. Yes, because we improved in standing.
5. Yes
6. Yes
7. Yes, I learned quite a bit and it was fun.
8. Yes, I thought it was a fun and instructional experience
9. Yes, upon completion of this project, I had a much better understanding of the forces at work under water.
10. Yes, although more time would be sufficient.
11. Yes
12. Very. If this class replaced engineering design, it would be awesome to go to class rather then a chore.
13. Yes
Question 5. Would you recommend this project to other students?
1. I already have, it was a lot of fun.
2. Yes, it teaches short-time interval problem solutions.
3. Yes, it enhances your knowledge on ROV’s and buoyancy. As well, it is greatly interesting.
4. Yes
5. Yes.
6. Yes.
7. Yes, it is enjoyable and informative.
8. Yes.
9. Yes, definitely it was a great experience.
10. Yes.
11. Yes.
12. Yes, it was interesting and fun.
13. Yes.

Question 6. Did you find the project as a whole helped you understand the practical mechanical engineering applications and related tools and skills? If so, please explain how.
1. Yes, buoyancy and trim were highlighted in this project.
2. Helpful because we were made to think up new ideas.
3. Yes, it helped me understand the weight and buoyancy ratios.
4. Yes. It was cool to see how all the gearing worked and propulsion.
5. I learned that floats must be significantly above weights.
6. Yes. Floats need to be at the highest point of the vehicle and weights at the lowest point-also they need to be evenly distributed left to right and front to back.
7. Yes. Learned about propulsion, gearing, grabbing, buoyancy and electrical.
8. Yes, because I saw the problems that engineers in this field face and how they solve these problems.
9. Yes, as a group we solved many problems throughout the entire design process, including the problems associated with underwater vehicle operation. Specifically, the principles of gears and buoyancy were greatly stressed.
10. Yes, learning how to balance an underwater vehicle.
11. Yes, it showed how Mech Eng concepts are used in real life.
12. Gear ratios and how water affects mechanical design in a whole different way.
13. Yes, gear ratios and such.

4.4.2 Examples of student project work

The figures on the following page illustrate the evolution of the student designs over the course of the five laboratory project sessions. Additional pictures, information and the student team’s final presentations can be viewed on the project web site:
http://www.k12science.org/ecoes2005/ecoes1.html
Figure 4. Straight line motion with single motor. Figure 5. Steering with two motors.

Figure 5. A grabber design. Figure 6. An electrical control system.

Figure 7. Final designs. Submersible vehicles with grabbers.
5 Future work

5.1 From ROVs to AUVs

The original intention of this work was to enable students to develop fully autonomous robot vehicles, which could respond to sensor stimuli with intelligent motion. The pilot implementation reported above goes partway toward achieving this goal.

So far, student projects have involved creating wire guided ROVs, controlled by a human operator. To develop truly autonomous behavior, the underwater vehicles will need to be equipped with sensors and a programmable controller.

Ongoing work is investigating appropriate choices of autonomous robotics challenges. These need to be intellectually substantial, meaningful enough to engage students, yet realistically achievable by freshman students in a short space of time using relatively simple components.

Various choices of controllers, programming languages and sensors are being considered. Students with little prior experience of computers and programming may benefit from a gentle introduction to simple controllers and graphical programming systems, before progressing to more sophisticated controllers and syntactical programming languages.

5.2 Proposed studies to assess educational impact

The intention is to undertake more formal evaluations of the educational merit of the project with successive student teams. Aspects of the project that could usefully be investigated include: the impact of hands on, discovery learning projects on undergraduate retention; the impact on student enrollment following pre-college participation in the project; the impact of the project on future academic performance of participating students; and pre and post tests to assess engineering and scientific knowledge learned during the project. The project would also make an interesting environment within which to investigate gender differences and or bias in approaches to engineering problem solving and teamwork.

6 Summary

Educators and engineers at Stevens Institute of Technology are collaborating to create discovery based educational materials, teaching a wide range of engineering skills and scientific principles through student projects involving underwater robotics.

In a successful pilot implementation, students succeeded in creating remotely operated underwater vehicles, electrical control systems and motorized grabbers.

It is intended to add a second stage to the project work in which sensors and programmable controllers will be used to develop autonomous robotic capabilities in the vehicles.

The discovery based learning approach to science and engineering education has proven effective, engaging and stimulating. It is particularly compatible with student projects which
emphasize the iterative engineering design process. LEGO components have substantially facilitated the design process by reducing the time between conception of an idea and its implementation.

**Bibliographic Information**


