A paradigm for vertically integrated curriculum innovation – how curricula were developed for undergraduate, middle and high school students using underwater robotics

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***Abstract* – This paper presents a case study of how an innovative educational engineering project can be developed for multiple skill levels, from middle school to undergraduate. Engineers and educators at Stevens Institute of Technology have collaborated to develop innovative classroom projects that teach a variety of science and engineering principles through the design, construction and testing of underwater robots using simple materials. These materials were first piloted with high school students enrolled in a pre-engineering summer program. Later, the materials were adopted into the undergraduate engineering program. These materials are now being adapted for use in middle and high school classrooms across New Jersey. This vertical integration at the curricula innovation stage is interesting and useful in that it enables two-way feedback. K-12 education can be informed by the knowledge gaps observed at the college level, and undergraduate education can be informed by the innovative teaching methods being pioneered at the K-12 level.**

Index Terms – Underwater, robotics, LEGO, outreach, engineering education, K-12.

INTRODUCTION

Vertical integration at the curriculum innovation stage is useful and necessary. K-12 science education is not only important for creating a scientifically literate and aware society. It is also a vital preparation for students who wish to pursue higher training and careers in Science, Technology, Engineering and Mathematics (STEM). We frequently discover severe shortcomings in the basic knowledge of our engineering undergraduates and it is critical for these observations to be fed back into new K-12 curriculum development. Conversely, educational research has highlighted beneficial teaching methods (e.g. “discovery learning”) at the K-12 level which can often be readily transferred into undergraduate engineering classrooms.

This paper describes a successful example of a set of educational engineering materials being developed at middle school, high school and undergraduate levels. In this case K-12 outreach efforts informed undergraduate curriculum development and lessons learned with undergraduates have informed the adaptation of the materials for middle school classrooms. Additionally, we show that the same classroom activities can be used successfully at all three skill levels, with only small modifications in emphasis and content.

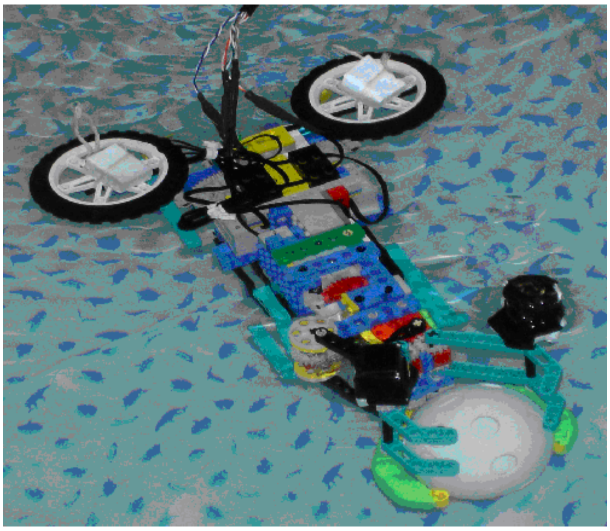

FIGURE 1
REMOTELY OPERATED VEHICLE (ROV) BUILT BY HIGH SCHOOL STUDENTS.

Engineers and educators at Stevens Institute of Technology have collaborated to develop innovative

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classroom projects that teach a variety of science and engineering principles through the design, construction and testing of underwater robot vehicles using a combination of LEGO and other simple materials (e.g. FIGURE 1).

These curricula were initially piloted with high school students as part of a pre-engineering summer outreach program. Based on the successes and lessons learned, the material was then implemented as a short course within the freshman undergraduate engineering program. On the strength of these experiences, a major National Science Foundation (NSF) grant was awarded to feed the material back into the K-12 classroom as projects for middle and high school classrooms across New Jersey.

Year one of the NSF project will disseminate the existing, tried and tested materials to middle and high school classrooms. For year two, new additional curriculum material is to be developed. Once again, this new material will first be piloted in our high school summer program, and then implemented with undergraduates, before being finally adapted and disseminated back to a large number of middle and high school classrooms.

This paper provides an overview of the project, and presents the stages of development from concept to funding and dissemination from undergraduate to middle school classrooms.

PROJECT OVERVIEW

Why build underwater robotic vehicles? When students design, build and program underwater robotic vehicles, they are learning engineering fundamentals which span a wide range of engineering disciplines. Additionally, students are motivated by an exciting and stimulating design scenario.

The underwater environment presents unique design challenges and opportunities which would not be encountered in, for example, a wheeled land vehicle project. The motion of an underwater vehicle in a 3D space is more complex (six degrees of freedom) as compared with the three degrees of freedom of motion of a wheeled vehicle on a 2D planar surface. Additional engineering and science issues include propulsion, drag, buoyancy and stability. Practical construction problems include how to waterproof electrical components.

Why use LEGO? LEGO is particularly useful for discovery based learning due to its ease and speed of assembly [1, 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 often lengthy and frustrating. Time constraints prevent students from evolving their designs through multiple iterations of testing and modification.

DISCOVERY BASED LEARNING

Discovery learning [3] 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 [4]. 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 [5].

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/Build/Test/Modify. In contrast, surprisingly little of the conventional engineering curriculum is devoted to this design process, with the learning experience of engineering students often bearing little resemblance to the activities of professional engineers in industry.

HISTORICAL DEVELOPMENT OF THE PROJECT

The underwater robotics project was originally developed and pilot tested as part of Stevens' ECOES (Exploring Career Options in Engineering and Science) Program. ECOES is a summer residence program for high achieving high school sophomores and juniors interested in pursuing a STEM career. The students participated in a 12 hour design project unit delivered during the two week ECOES session. During the 2005 summer program, 30 ECOES students participated in building remotely operated underwater vehicles as their engineering design project.

Based on the success of the ECOES project, the decision was made to offer the project to Stevens undergraduates through the Engineering Experiences program beginning the Fall semester of 2005. The primary objective of the Engineering Experiences program is to provide incoming freshman students with an opportunity to learn more about engineering as a profession and to explore the various engineering disciplines for which programs are available at Stevens. The underwater robotics unit is a natural addition to the program due to the multidisciplinary nature of the unit.

The undergraduate version of the course is offered as a series of four laboratory afternoons with an additional, voluntary evening lab session for each team.

The continued success of the program with students led to the development of a proposal to the National Science Foundation's Information Technology Experiences for Students and Teachers (ITEST) program. The proposal was funded in September 2006 and Build IT, a LEGO-based underwater robotics project is now being used in a comprehensive outreach program to provide pre-engineering experiences to over 2000 New Jersey middle and high school students from diverse backgrounds.

The original project involved student teams building Remotely Operated Vehicles (ROVs), human controlled, wire guided underwater vehicles. The second year of the Build IT project will involve extending this work to included programmable, computer controlled vehicles which respond to sensor stimuli to carry out autonomous activities. Once again, these new materials will be developed and piloted with ECOES summer students, will then be trialed with undergraduates, before being repackaged and disseminated to a large number of middle and high school classrooms.

It is interesting to note that the same classroom activities can be used with a wide range of skill levels from middle school to undergraduate level. With only small modifications to the emphasis and content, these projects can be made challenging, informative and engaging to students regardless of previous knowledge or ability.

LEGO ROV MATERIALS

Students are provided with a selection of LEGO including several motors, battery boxes and leads, gearing, structural and mechanical components. Also provided, are a selection of plastic propellers (obtainable from hobby stores) mounted on LEGO axles (FIGURE 2).

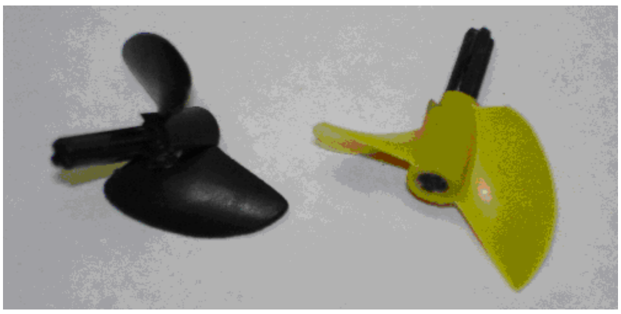

FIGURE 2
PROPELLERS MOUNTED ON LEGO AXLES.

Additional materials include Styrofoam, modeling clay, a selection of weights (nuts and bolts work well), rubber bands, string and duct tape. A 30 inch deep inflatable pool is used to test the designs. Wiffle balls are specified as the objects to be retrieved and manipulated by the ROVs.

Students are issued with a variety of electrical components, with which to create a control system and have the opportunity to learn soldering and simple circuit design and debugging. Long control cables are pre-assembled for the students. These cables contain eight wires (enough to control four independent motors) and are terminated with four LEGO compatible end connectors (FIGURE 3).

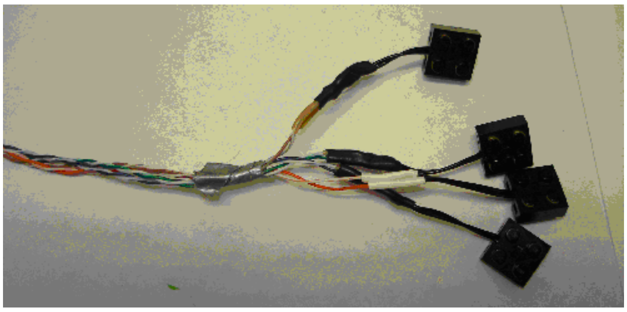

FIGURE 3
CONTROL CABLE WITH LEGO COMPATIBLE END CONNECTORS.

To build a control system, several three position double throw switches are supplied. Each switch can control a single motor with three possible states, Forward/Off/Reverse. Pre-drilled aluminum boxes are 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, safety glasses and a digital multimeter.

LEGO ROV PROCEDURE

Students are divided into five person teams. The project consists of (usually) five laboratory sessions, of around two hours each. Greater or lesser numbers of contact hours can be used, depending on the ability and age of the students. In each design session, 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 with 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 straight line speed.
2) Design a surface vessel with controlled steering, using two independently controlled motors. The challenge involves negotiating a figure 8 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.

In each laboratory session, instructors deliver short, interactive lectures or “Tech-Talks”. These are limited to around 10 minutes each. On occasions where two Tech-Talks are delivered in the same session, it is best to separate them by periods of practical work. Tech-Talks employ the concept of “just in time learning”, to convey the underlying scientific and engineering principles which are necessary to complete each successive stage of the design challenge. Tech-Talk subjects include:

1) Gearing mechanisms, torque, speed and thrust.
2) Ways to achieve two degrees of freedom of motion.
3) Electrical circuits and control panel design.
4) Buoyancy, Archimedes principle and vertical motion.
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.

RESULTS FROM ECOES AND ENGINEERING EXPERIENCES

To date, all student teams have succeeded in creating remotely operated underwater vehicles which successfully completed the final design challenge. Several important and encouraging features of the student’s work have been observed:

- Every student team arrives at original and creative solutions to the design problems. Each team’s solutions are significantly distinct from those of other teams.
- The iterative engineering design process is highly apparent in each team’s work, with solutions evolving through successive cycles of designing, testing and modification.
- Design solutions are 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 induces positive teamwork habits to develop within each team.
- Students are highly engaged in the work, enjoy experiencing the challenges and want to do more.
- Students take pride in their creations and in their ability to solve significant engineering problems.

The following page shows examples of student solutions to each of the intermediary design challenges of the project. Additional pictures, information and some student team’s final presentations can be viewed on the project web site: http://www.ciese.org/ecoes2005/ecoes1.html

BUILD IT

As mentioned, the success of the proof of concept exercise led to the development of a successful proposal to the National Science Foundation’s Information Technology Experiences for Student and Teachers (ITEST) program.

So began the Build IT project. Build IT will directly impact 2,625 students, or 875 students in each of three years via a substantial, three-week in-class interdisciplinary project. Classroom teachers, grades 7 – 12, will be prepared to implement this project through a two-year, 144-hour professional development program, encompassing two one-week summer institutes, four days of school-year workshops over two years, and in-class support. The remotely operated vehicle (ROV) and autonomous underwater vehicle (AUV) curriculum materials, teacher support materials, online technical support, video library, library of student presentations, and IT and STEM career information will be made available on the project web site for use by students and teachers all over the world.

Build IT will introduce teachers and students to programming and computer controlled machinery by using an accessible icon based programming language, based on LabVIEW, and LEGO robotics materials. Using computers to control real devices can be more engaging and meaningful for students than stand alone, abstract programming exercises. The project will foster IT and engineering career awareness among students, teachers, guidance counselors, administrators and parents.

To accomplish the project goals, a set of compelling, project-based educational modules that integrate information technology, science, mathematics, and engineering knowledge and skills will be adapted for middle and high school, piloted, and shared with participating teachers to be implemented in middle and high school science classrooms. Further, the project aims to create and implement an infrastructure of using technology as a tool within the context of existing STEM curricula. This will enable students and teachers to gain hands-on skills, expertise, and understanding of IT tools and concepts consistent with national education standards [6,7,8] including programming, communications, and experimental design and techniques.

Stevens will host participating classroom teachers for a two week summer program. In order to enable teachers to absorb and assimilate a significant amount of new material, a scaffolding approach will be implemented, focusing in Summer ‘07 on mechanical design of wire guided ROVs and on programming in Summer ’08 to create Autonomous Underwater Vehicles (AUVs). It is extremely important to ensure the teachers’ comfort level with the materials. If the teachers feel overwhelmed by the content, actual project implementation will decrease and overall sustainability of the project after the funding cycle will be minimal. For this reason, the project materials are delivered over three years, with significant online and classroom support to provide continuous assistance during the school year.

Directly following each summer’s one week Teacher Institute, the teachers will lead a small group of their classroom students in a one week pilot implementation of the materials, with support from Stevens project staff and undergraduate assistants. These one-week institutes will serve as an educational laboratory experience for the teachers to increase their comfort level with the materials, to develop confidence for school year implementation, and to simply figure out what works with their students.

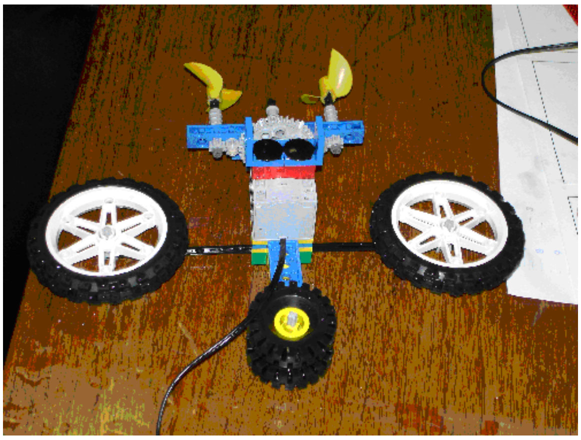

FIGURE 4
CHALLENGE 1: STRAIGHT LINE MOPTION WITH A SINGLE MOTOR.

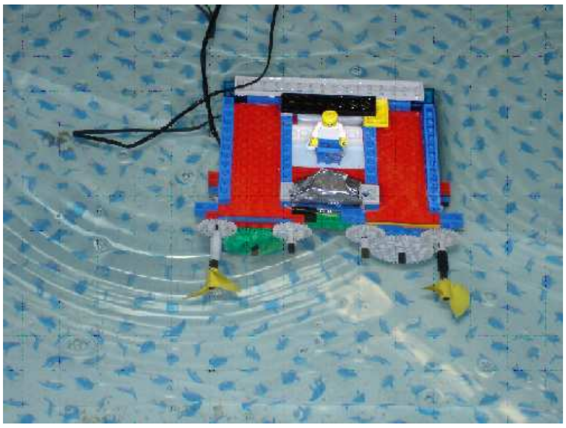

FIGURE 5
CHALLENGE 2: SECOND MOTOR FOR STEERING ON A 2D PLANE.

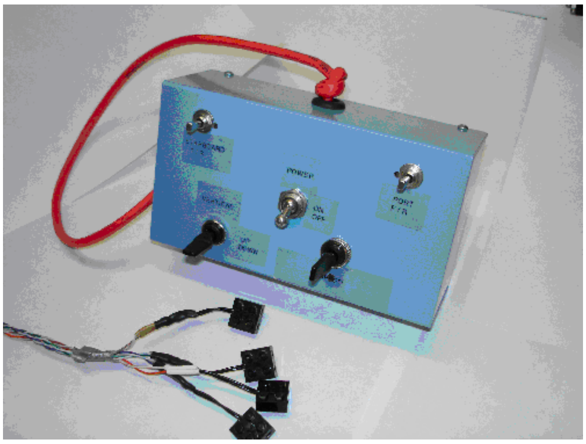

FIGURE 6
CHALLENGE 3: BUILD AN ELECTRICAL CONTROL SYSTEM.

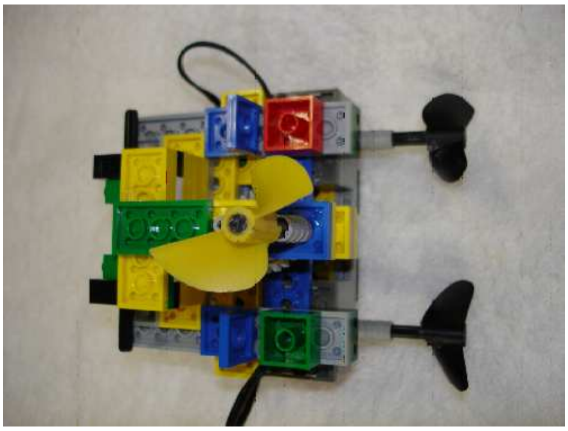

FIGURE 7
CHALLENGE 4: ADD A THIRD MOTOR FOR VERTICAL MOTION.

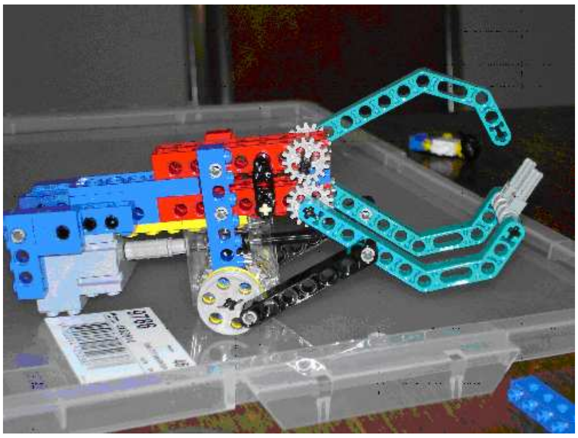

FIGURE 8
CHALLENGE 5: BUILD A MOTORIZED GRABBER.

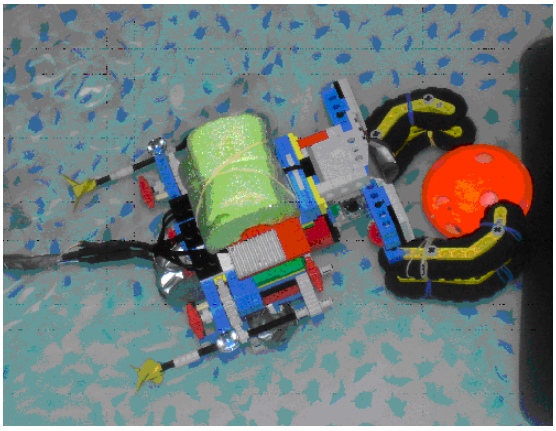

FIGURE 9
FINAL CHALLENGE: RETRIEVE BALLS FROM BOTTOM OF POOL.

At the conclusion of the summer institutes, formative evaluation data will be collected from teachers, students, and project staff to guide project staff and teachers on refinements necessary for both the materials and the classroom implementation.

By involving teachers in the decision making process, their sense of empowerment is increased and long-term participation will be enhanced [9]. Summative evaluation data will be collected from teachers and students during and at the conclusion of the school year.

ADDITIONAL BUILD IT ACTIVITIES

Beyond classroom and summer institute experiences for teachers and students, two additional forums will be conducted to cultivate and nurture participants' interest in developing IT skills and pursuing IT careers:

IT Symposia: Participating students, teachers, guidance counselors, and parents will be invited to an IT Symposium at Stevens. Leading Stevens researchers will be featured via a variety of hands-on lab tours, guest lectures, and similar activities. Women and minority faculty and industry presenters will be selected for these presentations, whenever possible. Undergraduates will serve as hosts and facilitators for a minimum of 350 students and 35 guidance counselors invited to participate over the three years of the project.

A *Workshop on IT and STEM related career opportunities:* will be held for guidance counselors, teachers, and parents. The workshop will focus on IT workforce issues, educational pathways to pursue IT careers, and showcase alumni who are women and underrepresented minorities in prominent IT careers. After the workshop, the information will be available via the project web site and actively disseminated to school districts, both statewide and nationally.

FUTURE WORK - 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. The LEGO NXT controller, LEGO robotics sensors and an icon based programming language may provide a suitable basis for creating this additional functionality.

We envisage a project split into two parts. The first part will center on the mechanical challenges of creating a stable wire guided ROV capable of bearing a payload equal to the weight of an NXT controller and batteries. A second part of the project will see the human controlled ROVs evolving into self-guided AUVs. Sensors and a waterproofed NXT controller will be added to the vehicles, and the NXT will be programmed to produce simple autonomous behaviors.

Alternative controllers and programming languages will also be considered. The NXT controller and simple, icon based programming languages may prove to be valuable stepping stones towards more complex languages and control systems, especially for students with little prior experience of computers and programming.

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. Efforts to simultaneously create innovative educational materials at a variety of different skill levels mean that this is an interesting example of vertically integrated curriculum development, with mutually beneficial lessons learned at the middle school, high school and undergraduate levels.

In a successful pilot implementation, 30 high school students succeeded in creating remotely operated underwater vehicles, electrical control systems and motorized grabbers. Following this success, two groups of undergraduates per semester, over a two year period have undertaken the same project activities, with equally positive feedback. Now these materials are being adapted for mass dissemination in middle and high school classrooms across New Jersey.

A second stage to the project work is being developed, in which students will use sensors and programmable controllers to create autonomous robotic capabilities in their vehicles. Following our developmental model, these new materials will also be piloted at Stevens, first with high school seniors during a summer program and then undergraduates as part of our Engineering Experiences program, before being tailored for mass dissemination to middle and high school classrooms.

ACKNOWLEDGEMENTS

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