Using Multi-Robot Systems for Engineering Education:

Teaching and Outreach with Large Numbers of an Advanced, Low-Cost Robot

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Abstract

This paper describes the experiences of using an advanced, low-cost robot in STEM education. It presents three innovations: it is a powerful, cheap, robust and small advanced personal robot; it forms the foundation of a problem-based learning curriculum; and it enables a novel multi-robot curriculum while fostering collaborative team work on assignments. The robot design has many features specific to educators: it is advanced enough for academic research, it has a broad feature set to support a wide range of curricula, and is inexpensive enough to be an effective outreach tool. The low cost allows each student to have their own robot for the semester, so they can work on activities outside the classroom. This robot was used in three different classes in which it was the foundation for an innovative problem-based learning curriculum. In particular, the robot has specialized sensors and a communications system that supports novel multi-robot curricula, which encourage student interaction in new ways. The results are promising; the robot was big success in graduate, undergraduate and outreach activities. Finally, student assessments indicate a greater interest and understanding of engineering and other STEM majors, and class evaluations were consistently above average.

Index Terms

Engineering problem-based learning, multi-robot systems, outreach, robotics education.

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I. INTRODUCTION

There are many good reasons to use robotics in the classroom: they are excellent examples of engineered systems, they can be used to motivate a student towards a wide variety of science, technology, engineering, and mathematics (STEM) topics, and they can cut across gender and race gaps to excite a large population of students. This paper presents the results with a new platform, the Rice r-one mobile robot [1]. The r-one is an advanced, low-cost robot designed for teaching, outreach and research. This paper presents the three innovations that make the r-one particularly effective at STEM education and outreach. First, the robot is designed to be an *advanced personal robot*: a design that has powerful sensors and abilities, but is cheap enough, robust enough, and small enough to survive many semesters in a student's backpack. Second, the robot forms the foundation of a problem-based learning curriculum emphasizing *hands-on homework assignments and design-challenges* that engage students more fully than traditional homework. Third, multi-student assignments become *multi-robot assignments*, which enables the authors to cover a novel multi-robot curriculum while fostering collaborative team work on assignments.

In this paper, results are presented from using the platform in three semesters of classes. It is the foundation of Rice University's freshman Introduction to Engineering Systems course, which helps recruit more students to STEM majors. The platform is an excellent outreach tool that has been used to give many outreach demonstrations, including an all-day interactive exhibit at the Museum of Science and Industry in Chicago for National Robotics Week. These results show that the r-one robot, and the curriculum it supports, are an effective way to recruit, retain, and train students in STEM topics.

This paper is divided as follows. After reviewing the relevant engineering and educational literature in Section II, an overview of the r-one design is provided in Section III. Section IV presents the undergraduate and graduate curriculum based on the r-one, and presents data showing that the robot accomplished its mission. Section V focuses on the new multi-robot curriculum concepts that have been introduced with this new platform. Section VI describes outreach activities: demos and exhibits. Finally Section VII describes future work: the open-

Robot	Source	Wheel Encoders	Radio	Neighbor Position	Robot ID Beacon	Visible Light sensor	IR Range	Ultrasonic Range	Accelerometer	Gyro	Bump Sensor	Cliff Detector	Temperature Sensor	Camera	Microphone	Remote Programming	Gang/Self Charging	Other features	Retail Price ($)	Parts Cost ($)
Khepera III	K-Team	•	•				•	•				•							2000	-
Create	iRobot	•									•	•							220	-
Scribbler	Parallax		•			•	•												198	-
Finch	Finch					•	•		•				•						99	-
robomote	USC	•	•				•				•							compass	-	150
3pi	Pololu																	IR line(x5)	99	-
CostBots	Berkeley		•						•									NEST sensor boards	-	200
Mindstorms	LEGO	•	•			•		•			•								249	-
e-puck	EPFL	•	•				•		•					•	•				979	-
e-puck + IR	EPFL	•	•	•			•		•					•	•				1388	-
kilobot	Harvard					•	•									•	•		-	14
r-one	Rice	•	•	•	•	•	•		•	•	•	•1	•			•1	•1		-	250

1 = Currently in development

TABLE I: Comparison of existing multi-robot platforms.

source release of the robot and curriculum, and a high-school robot summer camp underway for summer 2012.

II. RELATED WORK

While there are many off-the-shelf robots available, Table I, as well as a great deal of robot curricula [2], [3], [4], current educational robots have very limited hardware, especially sensors. Furthermore, there are almost no multi-robot curricula available [5], as robots that can interact with each other are not readily available to the public. The r-one brings the cost of deploying a classroom-sized, multi-robot system within the reach of middle and high schools. This is proposed as a novel way to motivate the next generation of engineers and computer scientists.

Multi-robot systems have great potential for many practical applications; exploration, mapping, search and rescue, surveillance, manipulation, construction and supply chain logistics are all applications where multi-robot systems can have a large impact [6], [7]. In particular, *large populations* of robots (100 – 10,000) can produce breakthrough solutions by providing greater efficiency, accuracy, and robustness, with lower cost and lower overall system complexity, as evidenced by the Kiva warehouse management system [8]. However, current understanding of the coordination and control of large populations of robots is incomplete. The gaps between theory, simulation, and reality make it difficult to transition research from theory to experiments to deployment. A key missing component is an advanced, low-cost multi-robot platform that can bridge the gap between simulation and implementation[9]. This paper describes the authors' experiences developing and using their new **r-one** mobile robot platform, which they believe can make efficient experiments with large populations a practical reality.

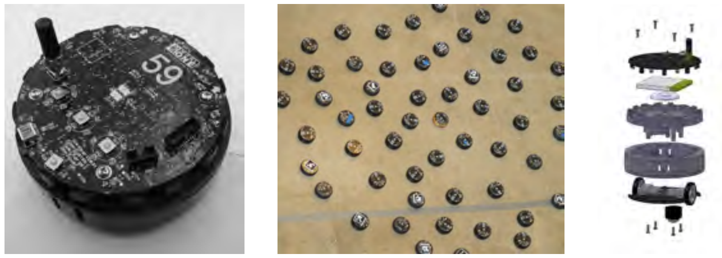
III. AN ADVANCED PERSONAL ROBOT

This section presents an overview, framed in an educational light, of the r-one robot's hardware and software design. It discusses the design decisions taken to produce a platform that, for a number of reasons, fits perfectly into an educational environment.

A. Hardware Design for Education

The three target applications for the r-one robot shown in Fig. 1(a) are teaching, outreach, and research. Each of these applications share three critical requirements: **1. Low Cost:** Tertiary education requires this to support a pedagogical model of one robot per student; outreach programs require it if they are to fit a robot system within their budget, and research programs require it if they are to be able to scale to large robot populations. **2. Advanced Design:** The basic sensor suite needs to be comprehensive, complete, and useful for all three of the above applications. In particular, specific multi-robot sensors for communication and localization need to be built-in. **3. Useability:** Basic operations, like programming, charging, and debugging, need to be automated and have a hands-free centralized user interface. This is required for efficient development, but is not critical for education, and will not be discussed here in detail.

The total cost of the assembled parts (plastic chassis, circuit boards, motors, battery, and speaker) is $247. This price enables large robot populations that can support a one-robot-per-student curriculum model, and easy-to-deploy outreach presentations. The design is open-source, and will be released in the fall of 2012. Deploying open-source hardware is more difficult than deploying software, as custom parts need to be made in large enough quantities to be cost-effective [10]. The authors are exploring a distributed distribution model (*crowd sourcing*), that



(a) R-one robot (b) Group photo of the current "swarm" (c) CAD exploded view

Fig. 1: **a:** The current Rice r-one robot is an advanced, low-cost robot that supports research, teaching, and outreach. **b:** This type of system can bridge the gap from simulation to large-scale multi-robot deployments in the classroom. **c:** The CAD exploded view highlighting the ease with which a student can disassemble the r-one sd required by the different lessons.

can leverage the "maker" community to build and test the hardware for interested users who do not have the required technical skills. If successful, this could make the robot available to users at very close to the cost of the parts. This pricing makes it feasible for the instructor to allocate one robot per student. This supports self-directed learning, and encourages exploration of the topic and experiments with the hardware. Instructors can then assign collaborative assignments, and assignments that take more time to complete than is available in a classroom lab. Ownership of the robot helps foster the student's ownership of his/her education, shifting their motivation to succeed from extrinsic to intrinsic. The authors describe their robot-based curriculum in Section IV.

While low cost is a necessary condition, it is not sufficient — the design must be advanced enough to support a variety of *interesting* curricula. The authors' believe that this requires a large, diverse sensor suite. Increasing the number of different things the robot can sense enables a large variety of projects and assignments, with the potential for richer intellectual content. The r-one has a differential-drive chassis, with two wheel encoders, three light sensors, eight bump sensors, a three-axis gyro, and a three-axis accelerometer. Multi-robot algorithms require each robot to sense its *local network geometry*: knowledge about its neighbor's pose relative to its own. The r-one infrared inter-robot communications system provides local communications and measures the bearing and orientation of neighboring robots with a resolution of 22.5°. The user interface consists of three buttons, an array of LEDs, an IR locater beacon, and a 2 Mbps radio for centralized command and control. The rechargeable battery provides four hours of run time and charges from the USB port. The robot is controlled by a 32-bit ARM microcontroller running at 50 MHz, with 256 KB of Flash memory and 64 KB of SRAM. It has a camera, and interfaces via developed a module to interface a GumStix Linux compute moduler [11], which can provide more computational power for applications that require it. When an infrastructure for multi-robot usability that is under development is complete, the r-one will supports wireless reprogramming, centralized data collection, and autonomous docking and charging.

An important consideration in an educational tool is that the robot should have a simple, easy-to-explain design. The exploded CAD assembly diagram of the robot is shown in Fig. 1(c). The robot has a 10 cm diameter, weighs 230 grams, and is composed of a plastic chassis and two circuit boards. These PCB boards have many labeled points that allow the students to use multi-meters and oscilloscopes to probe signals, such as PWM, encoder and communication signals. The top circuit board contains a majority of the electronics: IR sensors, a USB port, and the user interface. The motors and encoders mount directly to the bottom circuit board. These low-cost quadrature encoders are a new design, and use an optical interruption sensor to detect gaps in a custom encoder wheel attached to the rear motor shaft. The encoder wheels are made from plastic on a laser cutter, and provide 0.0625 mm/tick linear resolution at the wheel. The maximum speed is 300 mm/sec.

B. Software Design for Education

The r-one robot supports two development environments: embedded C/C++ programming with embedded debugging support, and embedded Python. Embedded debugging support allows the programmer to step through code and inspect variables, download programs to the hardware, and interact with the programs on the hardware. Embedded debugging is enabled through the use of a JTAG programmer[12].

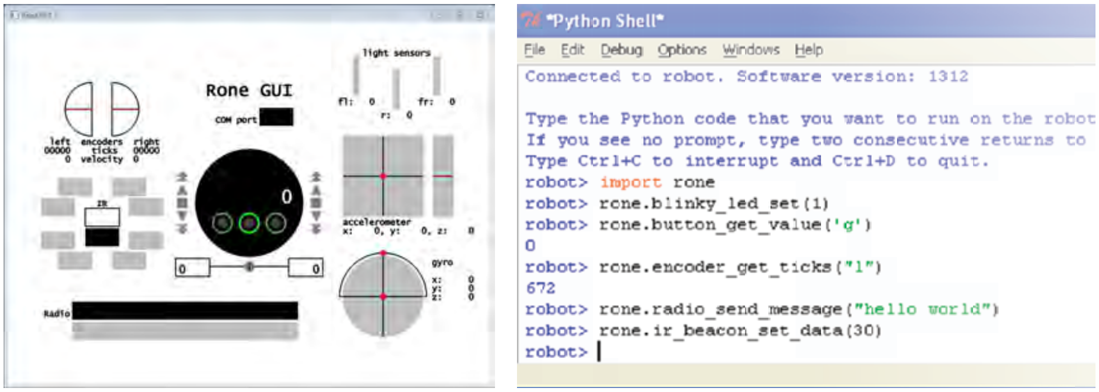
Advanced undergraduate and graduate classes benefit from using the C/C++ programming language tools since it allows their curricula to cover operating system concepts such as multi-threading and real-time operation. The ARM processor is powerful enough to run many useful teaching algorithms, such as Kalman filters or particle filters. Fig. 5 shows the results from Rice's graduate robotics class. Less-experienced programmers benefit from a simpler development environment. Graphical programming languages, like LEGO Mindstorms [13], can limit more advanced students, and do not allow a good introduction to programming concepts like abstraction and modularity. Computer science departments have tackled similar problems for introductory courses and many have moved to languages such as Python that are both easy-to-use as well as powerful [14], [15], [16]. Python combines a simple syntax with a garbage-collected environment that prevents a programmer from having to deal with pointers and memory management.

The r-one embedded Python programming language makes it easier for new programmers to produce working software, while still allowing experienced students to develop at an advanced level [17], [18]. The r-one's embedded Python virtual machine is based on the open-source Python-on-a-Chip project (http://code.google.com/p/python-on-a-chip/). Others have ported Python-on-a-Chip to a Lego NXT robot, but have not yet shown that Python can be used effectively to control a robot [19]. The r-one's port includes a full set of libraries that give Python programs access to all of the robot hardware [20].

Student can write non-trivial programs in Python, such as velocity control loops, simple light sensor behaviors, and network protocols. Additionally, the interactive prompt turns development into an exploration-based activity. Users familiarize themselves with the environment by programming interactively, one line at a time, as shown in Fig. 2(b). If a statement does not accomplish the desired behavior, or causes an error, the user can immediately type a different statement and observe the result. Users can explore the behavior of both built-in functions and those they have defined themselves. This low turnaround time encourages experimentation in programming.

IV. A PROBLEM-BASED CURRICULUM

Problem-based learning has been integrated into professional education within the medical field since the 1960s, where is now considered to be a mature approach. Courses that use the r-one robot bring the strengths of problem-based learning into an engineering curriculum, namely an emphasis on active, transferable learning and the potential to motivate students. [21], [22], [23] The three different classes designed around the sound problem-based learning pedagogy enabled by the r-one robot are ENGI 128: Introduction to Engineering Systems, a first-semester



(a) GUI for interacting with the Robot. (b) Interpreter prompt on the robot.

Fig. 2: **a:** The GUI allows a new user to quickly visualize sensor readings, test different motor settings. The GUI also allows for sending and receiving radio and IR messages to other robots. **b:** The interactive prompt serves as a debugging interface. Any errors in robot operation or programming are returned to the user here in real time.

introduction to engineering, COMP 551: a graduate Advance Robotics Lab, and COMP 651: Special Topics in Robotics, which spent the Spring semester of 2012 focused on building a public outreach demonstration.

A. *ENGI 128: Introduction to Engineering Systems*

Rice's first-semester freshman engineering systems course, ENGI 128 [24], has two main goals. The first of these is to help reverse the declining numbers of students declaring technical majors in science, technology, engineering, and mathematics (STEM) [25]. This is particularly acute among women and minority students, where social pressures in middle and high school can discourage them from pursuing their STEM interests [26].

The second goal is to give first-year college students direct experience with three technical majors, Electrical Engineering, Mechanical Engineering, and Computer Science, and demonstrate how they fit together into engineering systems. The aim is to increase *engineering literacy* by presenting a broad, interesting introduction to these disciplines, so students who *are* interested, even if they did not know (or admit) this before college, can make a better-informed choice of major. In contrast, other introductory courses are discipline-specific and do not give students a chance to explore majors easily.

The curriculum covers electrical/mechanical/computational systems, Table II, with a focus on modularity, mathematical analysis, and feedback control, which are unifying themes in all

discpline	low-level (foundational)	high-level(inspirational)
Mechanical Engineering	gears, torque & speed, transsmissions	feedback control
Electrical Engineering	bits/bytes/volts/amps, sensors	wireless communications
Computer Science	Python programming	robotics, distributed algorithms
Systems Engineering	abstraction, modularity	power systems, global localization

TABLE II: This table illustrates the mapping of low-level "foundational" topics to the challenging "inspirational" projects among the different STEM focuses for ENGI 128. This mapping allows the students to realize how the simple concepts taught early on can produce complex behaviors.

engineering areas. For each major, the instruction starts with a low-level "foundational" topic, and builds up to a challenging "inspirational" project that uses advanced concepts from sophomore or junior courses. Connecting theory to practice is critical to motivating students, so the course studies common, but complicated, engineering systems; hybrid cars, train locomotives, cell phones, and GPS receivers. The innovation of the course experience, and its centerpiece, is the r-one robot described in Section III. In lieu of a textbook, each student is given a robot to keep for the semester. The robot is an exemplar of a complex engineering system; the students learn about its electrical and mechanical design, and program it throughout the semester. It being an advanced personal robot allows engaging, hands-on homework to be assigned.

The semester is punctuated with in-class *design challenges* which reinforce the homework and lecture content with fun, hands-on creative activities. The curriculum, features seven design challenges that inculvate key ideas such as force and torque, velocity control, wireless communication, and distributed algorithms. The key to completing all of these design challenges is collaboration. The students therefore tackle them in groups, and are given freedom to approach the problem however they see fit. Because this is a first-semester class, students have a wide range of experience with different parts of the curriculum. Collaborating across the group they are able to share their preexisting knowledge and discuss the material covered in class. This seems to work well; most groups successfully complete the design challenge, and the students report that their peer instruction was helpful, in particular when learning to program the robots. To motivate the students to overcome any initial resistance to group collaboration, challenge winners were awarded fabulous prizes, such as movie tickets and chocolate bars.

(a) An r-one maneuvering during a design challenge.

(b) A group assessing their progress in the current design challenge.

(c) An r-one preparing to score a point for its team.

Fig. 3: **a:** The physical composition of the r-one allows the students to identify the different components visually, both while initially learning about the robot and during each of the design challenges. **b:** With the problem-based approach students were placed into small groups such as that seen in this photo. **c:** Engineering the design challenges to have physical goals that give the students real-time feedback on their progress helped to motivate the students and foster an environment of friendly competition.

After the first two iterations of ENGI 128, surveys of engineering literacy were administered using a Likert scale, to determine the student opinion towards the r-one, the class, and the design challenges [27], Fig. 4. These surveys indicate that the first two offerings of this class were successful in increasing *engineering literacy*. The students reported us that the class helped them understand the different majors, and how they interact and overlap:

> "Excellent overview of engineering systems. I loved this class because McLurkin talked about tons of different systems (trains, helicopters, LCDs) in great detail in a helpful way for understanding them, and at the same time worked us through the ins and outs of working with high-level controllers for speed, navigation and communication on some pretty sophisticated little robots."

The students enjoyed the robot that they carried around for the duration of the semester. Many gave them names, and were sad to return them. When the homework was challenging, they told the authors that it was their desire to see the robot complete the task that drove them to work harder. This evidence suggests that the idea of the advanced personal robot was a success. An anonymous student comment received in the Fall 2010 ENGI 128 Course Evaluations reads:

> "The course is well-structured to allow you to experiment and learn on your own (take-home robots!) and to collaborate with other students all along the way (design challenges are great and several homeworks are written to be done in groups). All in all, definitely a course to take if you can, Freshmen! It accomplishes its goal of helping

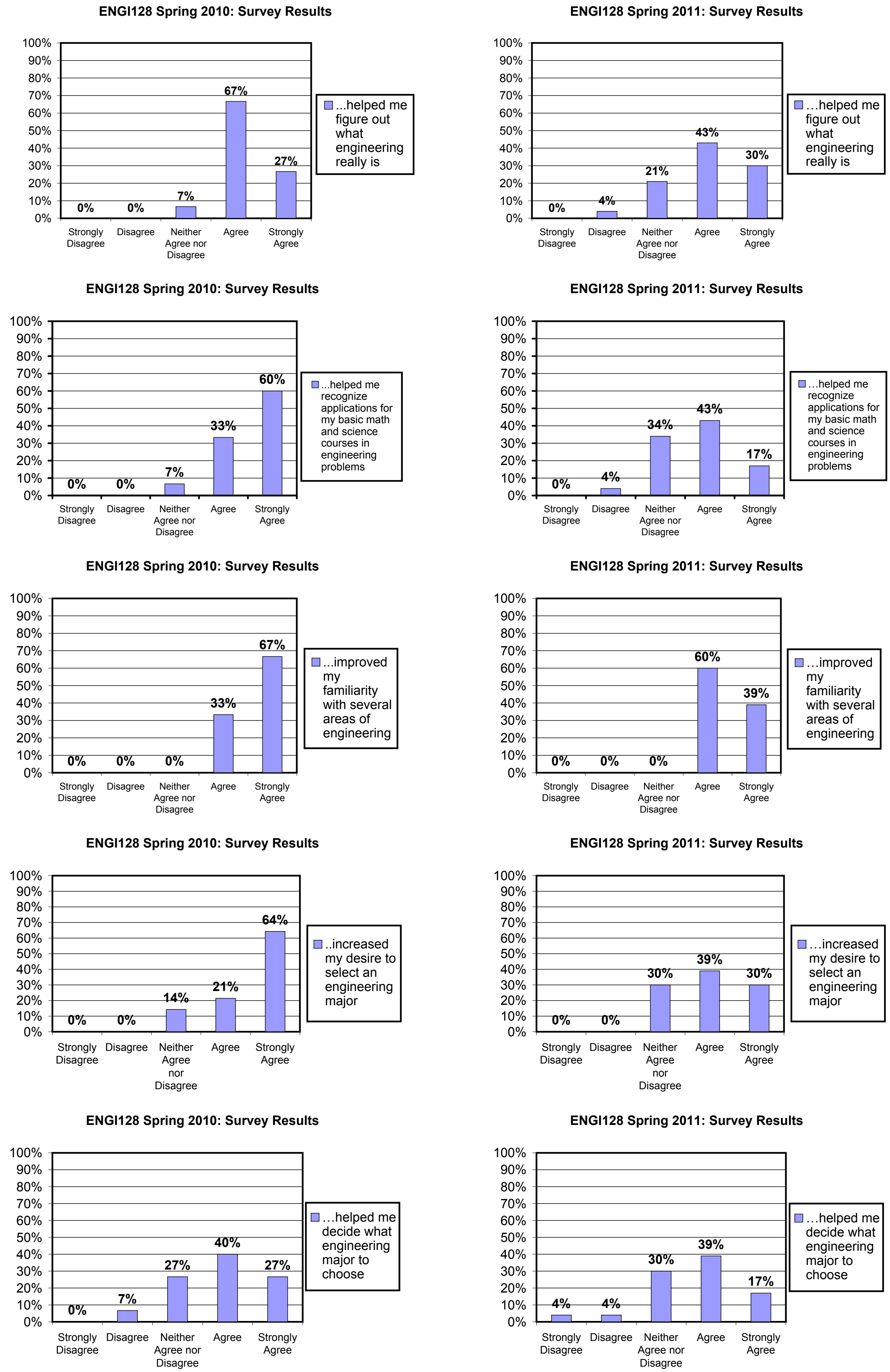


Fig. 4: These survey results highlight the impact that ENGI 128 had on the students' opinions of STEM majors. The course was a success in that it helped students solidify what their ideas of engineering entailed, how STEM subjects are integrated in all aspects of their lives, and help to increase their desire to major in a STEM field.

people decide which engineering major to aim for."

For future work, the authors are planning to conduct a longitudinal study of students in these initial classes to see if their interest in engineering continues though graduation, and how it compares to the student population in general.

B. COMP551: Advanced Robotics Lab

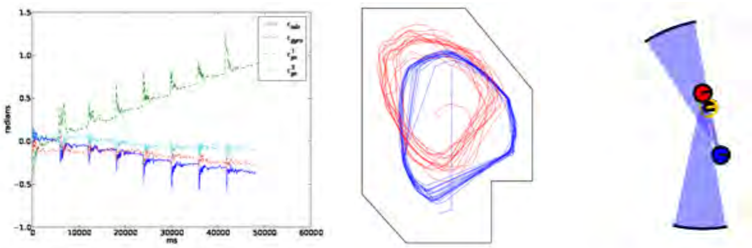
COMP 551 has in common with ENGI 128 the innovation of assigning one r-one robot per student. Here, however, instead of working towards the goal of introducing first-year students to engineering systems, the goal is to present advanced robotic topics, including sensing, localization, mapping, motion planning, and state estimation.

COMP 551 is designed around a large final project. The initial offering of the class afforded students the freedom to develop their projects in either the embedded Python environment or in C/C++, with an embedded multi-threaded real-time operating system, FreeRTOS [28]. Either development environment, coupled with the robust sensor suite of the r-one, allowed the students to explore the advanced curriculum, which highlights three projects: gyrodometry, Monte-Carlo localization, and particle filters [29].[1]

Gyrodometry is a simple, computationally-inexpensive method for fusing odometry and gyroscope data on a mobile robot. Gyrodometry is effective in reducing orientation errors caused by non-systematic, or catastrophic, odometry failures, such as those due to bumps or wheel slippage when the robot is turning, which cannot be addressed by the Kalman filtering schemes used in related work. Gyrodometry also does not suffer from the drift associated with gyroscope orientation methods. Fig. 5(a) indicates that the resulting fusion of odometry and gyroscope information reduced the error. This approach was written entirely in Python and became part of the r-one Python library provided to ENGI 128 students.

One of the final projects implemented Monte-Carlo localization using limited sensing for the r-one robot. Though the final results had a significant amount of error, they do show trends of the r-one being able to localize. Fig. 5(b) illustrates the MATLAB output from this MCL

[1]Grateful acknowledgement to Brent Stevens and Cynthia Sung for providing their project descriptions and graphs for this publication



(a) Gryo-Encoder Error (b) Monte-Carlo Localization (c) Particle Filter Estimation

Fig. 5: **a:** The r-one combines gyro and encoder odometry to improve its localization. The lower lines indicate that the combined localization has the least error. **b:** Output from MCL localization using the built-in IR sensors. The upper trace is the estimated position and the lower trace is actual measured ground-truth position. The constant rotation error was due to a poorly-calibrated localization camera. **c:** The r-one has enough computation and memory to run a particle filter in real time. The lower robot is estimating the position of the upper robot. The robot outline between the two robots indicates the estimate. This can run with around a 10 ms update rate with 1000 particles.

localization using the built-in IR sensors. The upper trace is the estimated position while the lower trace is the measured ground-truth position. The ground-truth of the r-one was provided through a fiducial tracking system, the AprilTag system [30]. The constant rotation error was due to a poorly-calibrated localization camera.

Another final project in COMP 551 was to produce a workable particle filter able to estimate the pose of a neighboring r-one. This began as a simulator built with the hardware limitations of the r-one in mind. As the particle filter framework was built up, it demonstrated that the r-one platform was capable of producing a reasonable estimate of a neighbor's pose, despite its limited computational power, memory and sensors. In Fig. 5(c) the lower robot is estimating the position of the upper robot. The robot outline is the estimate. This can run with around a 10 ms update rate with 1000 particles.

C. COMP651: Special Topics in Robotics

The final course to use the robots was COMP 651: Special Topics in Robotics. While primarily a seminar class, in the Spring semester 2012 it featured a semester-long design project. The goal was to build a museum exhibit for the Museum of Science in Chicago's upcoming robot exhibit [31]. As this was a design project class, the students bore most of the responsibility of organizing their schedule, budget, design specifications, testing, and evaluation. Again, the ability to give each student a robot was leveraged, and the curriculum from ENGI 128 and

	ENGI 128 - FALL 2010		ENGI 128 - FALL 2011		COMP 551 - SPRING 2011		COMP 651 - SPRING 2012	
	RICE MEAN	CLASS MEAN	RICE MEAN	CLASS MEAN	RICE MEAN	CLASS MEAN	RICE MEAN	CLASS MEAN
COURSE ORGANIZATION[1]	1.88	2.23	1.89	2.84	1.87	2.6	1.87	1.58
CONTRIBUTION OF ASSIGNMENTS TO LEARNING[1]	1.92	1.59	1.92	2.24	1.9	1.7	1.9	1.58
OVERALL COURSE RATING[1]	1.89	1.5	1.91	2.12	1.87	2	1.89	1.55
STUDENTS CAPABILITIES WERE CHALLENGED[2]	1.84	1.5	1.84	1.72	1.84	1.8	1.82	1.67

	1	2	3	4	5
[1]	OUTSTANDING	GOOD	AVERAGE	FAIR	POOR
[2]	STRONGLY AGREE	AGREE	NEUTRAL	DISAGREE	STRONGLY DISAGREE

Fig. 6: A comparison of the mean results from a university-wide survey conducted each semester across all of the classes that use the r-one platform. The class mean is compared with the Rice mean for the given questions; these classes exceeded the Rice mean 10 out of 16 times.

COMP 551 was heavily relied on to provide a foundation of instruction. The course was a success, with almost all students reporting learning a great deal, and enjoying the experience. Section VI contains more detailed information about this project and the outreach impact.

D. Assessment

Fig. 6 shows the results of a survey conducted for each class that had curricula based on the r-one robot: two semesters of ENGI 128, one semester of COMP 551, and one semester of COMP 651, and compares these results with the mean results for Rice as a whole. The shaded cells indicate where the class mean exceeds the Rice mean. The worsening of the survey scores over time can be attributed to the first author's extended travel during the second iteration of ENGI 128.

E. United States Military Academy - IT105

A small contingent of r-one robots was brought to the United States Military Academy to be used for collaboration and research. They were also used as an exemplar of robot design and sensor utilization for multiple classes of IT105, Introduction to Information Technology. This course has a single lesson devoted to sensors. This lesson is based around the explanation of a sensor receiving some form of environment input (light, sound, physical stimuli, etc.), converting it to an analog voltage and then converting that analog signal to a digital signal to be used by whatever system the sensor is attached to. Typically, this lesson is based on an IED sensor system due to its relevance to the cadet's future profession [32], but two sections were taught using the r-one as the sensor-based system and a further two sections taught using improvised explosive devices, IEDs, as the sensor-based system. Even in light of the the pressing need for future Army officers to understand the IED sensor-based system thoroughly, the two r-one based sections performed approximately 17.8% higher on the sensor test question than did the two IED-based sections. This indicates that their was a deeper retention of the sensor knowledge.

V. MULTI-ROBOT CURRICULUM

When every student in the classroom has a mobile robot, multi-student projects become multi-robot projects, which open up new curriculum areas [5]. These projects can be simple, such as follow-the-leader, or complex, such as building a flocking algorithm with consensus. This section highlights two ENGI 128 projects that best exemplify this.

A. IR Olympics Design Challenge

The ENGI 128 IR Olympics design challenge was designed to challenge the students to use the infrared (IR) communications/localization system on the r-one robots to accomplish a variety of different tasks. The project was team-based; each team comprised six students and their robots. The challenges required the students to develop their own version of distributed algorithms from the robotics literature, such as Follow-the-Leader [33], Clustering [34], and Flocking [35]. The students were given a basic software framework for neighbor communications and *local angular network geometry* (the bearing and orientation of a robot's neighbors), and motor controllers. The challenge was to combine these into the distributed algorithms themselves. The r-one's specialized sensors and communications system, specifically the IR system, is what made the IR Olympics possible. Each student had a single robot, but because the robots had to work together in the challenge, the students had to work together in development. This worked well, with most groups successfully completing several of the challenges. This is a new way for students to collaborate, via the collaboration of their robots. Future offerings of this course will streamline this lab, and attempt to combine these challenges into a single one that involves the entire class.

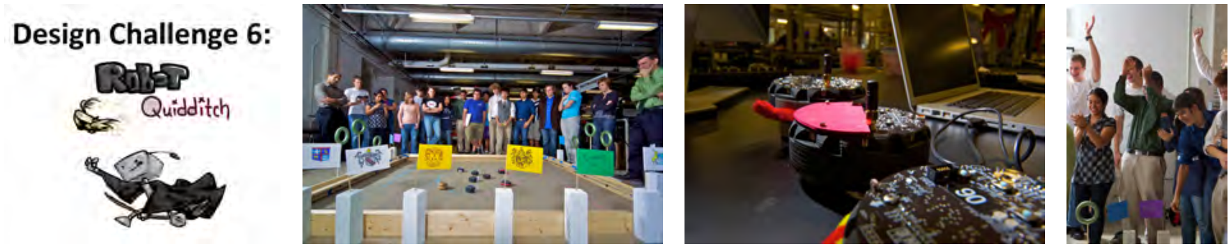
B. Quidditch Design Challenge

The final design challenge in ENGI 128 is a game of robot Quidditch, the fictional game from the J. K. Rowling Harry Potter series of books. Fig. 7 shows an example of the project. The students are grouped into teams of four. They had to develop software to run the robots as a quaffle, bludger, or seeker. The quaffles task is to navigate to the opposing teams goal, without hitting another robot or the sides of the course, and score. The job of the bludgers was to interfere with the opposing team's quaffles to end their scoring attempts. Because all the robots shared the same maximum speed, the students had to develop a good interception technique based on the earlier follow the leader algorithms. Each team also had a single seeker robot, whose only task was to look for the special snitch robot, which ran cunning software written by the course staff. The games ran for five minutes, and the snitch could be caught repeatedly. This project relies heavily on the robotics module from ENGI 128. The students had to develop behavioural state machines [36], neighbor recognition, and obstacle avoidance techniques to build an effective robot quidditch team. It is important to stress that while the course staff was supportive during this project, the students were not given any other help or direction in designing their Quidditch team.

This final project has been very well received, with student teams spending a great deal of time and creativity developing their strategies and algorithms. A requirement was that each team had to produce a "uniform" for their team, and the creativity and excitement that this non-technical requirement engendered helped to motivate and engage students. The final outcome of the competition was not graded, but grades were assigned to the design reports, which illustrated a wide variety of approaches and algorithms. Projects like this benefit from using mass media themes to attract and enthuse students who learn advanced topics in distributed robotics in an interesting and engaging way.

VI. OUTREACH

Tertiary education can have considerable impact outside of the classroom through outreach activities. In this context, the r-one robot is a powerful recruiting tool. Few technically-curious



(a) Final Project Theme. (b) The Robot Quidditch Arena. (c) Robots in “uniforms”. (d) Victory!

Fig. 7: **a:** The final project for the freshman systems engineering class at Rice University was a game of robotic Quidditch, inspired by the fictional sport from *Harry Potter* books. **b:** The robots were fully autonomous, and students had to devise programs that produced winning strategies from local robot interactions. **c:** Robots sported nifty regalia for the final competition. **d:** Cheering students indicates a high level of engagement.

Fig. 8: User Interface for user control of the r-one “swarm”. The user can control a subset of the “swarm” and see how different behaviors work with a multi-robot system. Being able to control the r-one robots had a huge impact on attendees and drew a large crowd to the display.

students can resist a dozen small robots running distributed algorithms. Explaining what a distributed algorithm is, and how robots work, can change the trajectory of a young student’s career. This section describes outreach activities with the r-one robot, and the path towards exploring the multi-robot curriculum more broadly.

A. Museum of Science and Industry

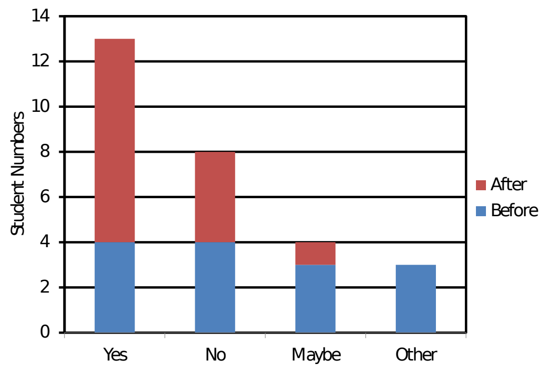
The Museum of Science and Industry asked the authors to build an interactive demonstration for their upcoming exhibit. The ultimate goal is to showcase robotics, including multi-robot systems, and to provide an interesting, educational exhibit. During Robotics Week 2012, the Museum hosted the four academic groups invited to build an exhibit. The Rice team’s aim for

(a) The r-one display at the Museum of Science and Industry.
(b) Getting to know the r-one swarm through the custom user interface.
(c) The r-one always drew a crowd at the exhibit.

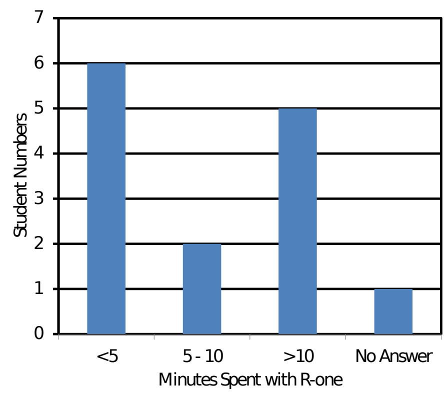
Fig. 9: **a:** One of the outreach activities conducted with the r-one was an invitation to participate in Robotics Week at the Museum of Science and Industry in Chicago, IL. **b:**The authors developed a user interface that would allow the user to control the r-one "swarm" through four different complex behaviors.**c:** The r-one exhibit was a hit, there was always a line waiting to control the "swarm" and a crowd of people with questions about the r-one and the behaviors.

this temporary demonstration had two main purposes: to test the prototype system, and to evaluate how attractive the exhibit was to different groups of people, particularly middle-school-age girls.

The prototype system gives a user control of the robots using the custom user interface shown in Fig. 8, and demonstrated four simple, but interesting, distributed algorithms: Cluster, Flock, Disperse, and Follow-the-Leader [37]. The user interface allows three users to operate the color coded controls, which allowed the user to command a subset of the overall robot swarm. They also allowed a user to switch between the various distributed algorithms. A preliminary survey conducted before MSI with 14 Rice non-engineering undergraduate majors asked if they were more interested in multi-robot systems before or after interacting with the r-one using the user interface. The results indicated that interaction with the user interface could increase interest in multi-robot systems, as seen in Fig. 10(a). Also interesting was that most people would be willing to spend less than five minutes using the system, so the pedagogical content of the demonstration needs to be efficiently conveyed to be effective. Qualitatively, the exhibit was a success. There was usually a line to use the robots, and most people asked questions of the students and museum staff about the inner workings of the software. When used in combination with a static poster, or an interactive touch screen with educational content, this seems to be an effective way to attract people to STEM in general and robotics in particular.



(a) Student responses as to whether they were interested in controlling the r-one "swarm" before and after controlling the r-one.



(b) The time individuals were willing to spend with the r-one.

Fig. 10: **a:** Responses to the question "Are you interested in multi-robot systems?" indicates a significant increase in interest after interacting with the r-one. **b:** Another question posed in the preliminary survey asked how much time they were willing to spend with a multi-robot display. These results give a timeframe for for duration of exhibit demonstrations.

VII. FUTURE WORK AND CONCLUSION

The use of the r-one robot for STEM education is in its early stages. In summer 2012, the authors partnered with BotShop [38], a local outreach program that uses robotics to interest underrepresented minorities in STEM careers. The key robotics elements from the ENGI 128 curriculum will be compressed to build a one-week summer robot camp. The authors are also partnering with the NSF-funded ARTSI alliance [39], which partners HBCU schools with research institutions to encourage more minority students to pursue advanced degrees in computer science and robotics. The partner schools are showing considerable interest in including the r-one, and its associated curriculum, as modules in their courses. Should the grass-roots, crowd-sourcing distribution model prove successful, the robot could take root in the hobbyist "maker" community, which would give it a potentially large impact on the next generation of engineers. This, in turn would make the robot broadly accessible to the educational community. A plentiful supply of low-cost, high-performance robots, would allow a re-imagining of STEM curricula.

This paper, presented the results of using the r-one platform in three semesters of classes. The r-one proved to be an exceptional education tool that became the foundation of Rice's freshman introduction to engineering course that helps recruit more students to STEM majors. It also was used in a graduate-level course on robotics providing a robust platform that could accomplish complex robotic tasks. The design supports novel, engaging multi-robot curricula that could not be taught with existing platforms. Additionally, the platform is an excellent outreach tool, and the authors have given many outreach demonstrations, including an all-day interactive exhibit at the Museum of Science and Industry in Chicago for National Robotics Week. These results show that the r-one robot, and the curricula it supports are an effective way to recruit, retain, and train the next generation of engineers in STEM topics.

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