Robotics Education To and Through College

Brian R. Page[1], Saeedeh Ziaeefard[2], Lauren Knop[3], Mo Rastgaar[1], and Nina Mahmoudian[1](✉)

[1] Purdue University, West Lafayete, IN 47907, USA
{page82,rastgaar,ninam}@purdue.edu
[2] Ohio State University, Columbus, OH 43210, USA
Ziaeefard.1@osu.edu
[3] Michigan Technological University, Houghton, MI 49931, USA
lknop@mtu.edu

Abstract. Robotics education has made great strides to enable the next generation of engineers and workers with early education and outreach. This early education effort is able to engage students and promote interest, however an integrated pathway to and through college is needed. This pathway needs to build upon early experiences with opportunities to advance across age groups. This paper presents the authors experience developing robotics curriculum across age groups. Middle and high school education has been implemented in a summer camp environment utilizing two co-robotic platforms, a water sensing robot called GUPPIE and an assistive robot named Neu-pulator, engaging 201 total students between Summer 2014–2017. The university course is a senior level technical elective introducing autonomous systems through a mobile robotic platform, a smart car, with 72 total students in Spring 2017 and 2018. In this work, the survey results gathered from Summer 2017 pre-college and Spring 2018 college level activities are presented. Overall observations and lessons learned across age groups are also discussed to better create a pathway from young learners to practicing engineers. The key to success of robotics programs at any age are hands-on, exciting activities with sufficient expert support so that students are able to learn in a frustration free environment.

Keywords: Project-based learning and robotics · Robotics curricula · Robotics education · Marine robots · Assistive robots · Mobile robots

1 Introduction

The field of robotics is rapidly expanding into most aspects of everyday life. To encourage technological competency of the future workforce, we need to be able

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to introduce fundamental concepts of robotics at an early age. Significant effort has been put forth in engaging young students particularly in the middle and high school age groups [1]. These efforts have shown a large degree of success, however, the progression from early robotics education to university level education is not clear. This paper presents the authors experience teaching robotics programs to students from middle school through graduate school. For middle and high school students, the authors have organized a one week Summer Youth Program (SYP) over recent years introducing collaborative robotics. 201 students have attended this camp which introduces the GUPPIE and Neu-pulator. These two co-robots are based on the theme of robots helping people. At the university level, 72 students have completed a 3-credit senior level Mechanical Engineering undergraduate course on autonomous systems. In this course, students build and program a small autonomous vehicle to navigate through a model town. Both groups follow a similar hands-on, project-based approach. This paper extends our previous work [2–9] by presenting the most recent survey results from the 2017 summer youth programs and 2018 autonomous systems courses along with the generalized lessons learned across all age groups.

All our educational efforts have followed a project-based approach, promoting interdisciplinary learning opportunities in order to generate a more meaningful learning experience. The choice of platform is one of the determining factors in crafting these interdisciplinary learning opportunities. Table 1 shows a brief comparison between platform options. For the middle and high school group, the interdisciplinary learning theme is manifested in our co-robotics approach (Neu-pulator and GUPPIE) that pairs robotic applications with helping human life to teach STEM concepts. At the university level, the smart car is able to help students connect robotics to the broader applications of engineering. Our approach divides robotics into five fundamental disciplines: (1) engineering modeling and design, (2) electronics and circuitry, (3) programming, (4) assembly and pro-

Table 1. Comparable robotic platforms

Platform	Domain	Target audience	Cost (USD)
GUPPIE [2–7]	Marine (AUV)	Middle school	27
Neu-pulator [3,8]	Manipulator	Middle school	121
Elegoo Car + Pixy [9]	Ground	University	140
KUKA youBot [10]	Ground/Manip.	University	30000
AERobot [11]	Ground	Middle school	10
Duckiebot [12]	Ground	University	150
SeaPerch [13]	Marine (ROV)	K-12	179
OpenROV [14]	Marine (ROV)	University	899
DENA [15]	Marine (ROV)	University	Unknown
Adventure-I [16]	Marine (AUV)	University	Unknown
Service-Arm Type CS-113 [17]	Manipulator	University	Unknown
LEGO NXT Arm [18]	Manipulator	Middle/high	350

(a) (b) (c)

Fig. 1. (a) The GUPPIE during pool testing. (b) The Neu-pulator during experiment and demonstration. (c) The smart car while going through model town.

duction, and (5) testing and troubleshooting. Students are able to practice the engineering design process through each hands-on activity.

The Neu-pulator (Neurally Controlled Manipulator) and GUPPIE (Glider for Underwater Problem-solving and Promotion of Interest in Engineering) are used to introduce middle and high school students to assembling, programming, and testing of robots. This paper builds upon previous iterations of the GUPPIE and Neu-pulator project over recent years [2–6,8] with the most recent results and minor design updates. Over the course of a week-long camp, students learn robotics concepts in a hands-on, project-based manner. This is guided by our custom workbook that is distributed to students during the week. The students are introduced to engineering design process, mechanical engineering, electrical engineering, biomedical engineering, and environmental engineering. Utilizing Neu-pulator and GUPPIE, the overall theme of the curriculum is helping people. Every task is framed in such a way that the students are able to understand how robotics and STEM can be incorporated to improve peoples lives. Students work in pairs or in small groups to encourage team building skills and reduce the stress associated with solo development.

The smart car used at the university level also helps students learn robotics concepts in a hands-on, project-based manner. The car enables students to apply skills learned in other courses such as linear control and circuits to the real-world. The entire course is built around how autonomous mobile platforms function with students learning all the key concepts of autonomous cars. Due to the structure of the course, students work on one key concept per week, culminating in autonomous operation in a model town. While each student has to develop their own system, the course is set up so that the weekly lab sessions are highly collaborative to accelerate learning.

The remainder of this paper presents the platform designs in Sect. 2, the curriculums in Sect. 3, recent survey results for SYP and university level in Sect. 4, and a generalized observations & lessons learned in Sect. 5.

2 Robotic Platform

The Neu-pulator, GUPPIE, and smart car are all easy to assemble robots with common core functionality and components. The Neu-pulator is an assistive robot resembling a prosthetic, the GUPPIE is an exploratory, water sensing robot, and the smart car is a toy car. The robots use low-cost, off the shelf products to enable students to continue creating new systems after they graduate from the program. All the platforms have significant overlap in hardware choice, which unifies the curriculum between the three platforms and across age groups.

The **GUPPIE**, Fig. 1a, is an extremely low-cost underwater glider. It's design has been simplified down to the critical components for basic operation to allow students to focus on the main requirements and functionality of underwater gliders. The GUPPIE is built inside of a sealed tube and contains a buoyancy drive, control system, and energy storage. Mounted on the outside of the hull is a wing and trim weights to enable flight. The total cost for the GUPPIE is 27 USD. The current revision is an iterative improvement over previous GUPPIEs to focus on reducing the cost and increasing the accessibility of the platform [2–6].

The **Neu-pulator** robot [3,8], Fig. 1b, is designed to resemble the characteristics of a human arm and introduces students to basic concepts in robotic manipulation; including types of joints, degrees of freedom, end-effectors, and how these all tie into the forward kinematics of a robot. The Neu-pulator is composed of two revolute joints that are actuated by two low-cost servo motors. These joints resemble the motion produced by the elbow and wrist joints of a human arm. In between each joint are wooden linkages, approximately 15 cm in length, which act as the upper and forearm of the robot. Using these 2 degrees of freedom (DOF), the robot's end effector can reach to many different positions within its joint space. The Neu-pulator's total cost is 121 USD. Due to this, the platforms are shared between small groups of students rather than in pairs.

The **smart car**, Fig. 1c, combines two off the shelf hobby level robotics solutions. The Elegoo Smart Car kit provides the mobile platform including everything required for basic navigation at a low cost. With the addition of a Pixy camera, the car is able to navigate based on visual information. The smart car is a simple four wheel, skid-steerable mobile platform controlled by Arduino. The full kit used in the course is 140 USD enabling each student to have their own car. By ensuring a 1:1 robot:student ratio, every student is required to show competency in all aspects of robotics, as expected in a university level course.

3 Curriculum

The developed curriculum across age groups follows the engineering design process. The core idea is that all robotic systems operate in a 'see-think-act' cycle [19]. The robotic system starts by sensing the environment before thinking about where it is and what it needs to do. Once a decision is made, the robotic system performs an action. Each age groups curriculum builds on this idea with age and skill appropriate content.

In the SYP program, each of the concepts is covered throughout the week [3]. The program is a five day residential summer camp held at Michigan Tech including 28 h of instruction following our custom workbook. The program is kept at a 4 to 1 student:teacher ratio. Instructors for the program are both graduate and undergraduate students. To inspire young learners, the overall theme of the curriculum is based on helping human life. Every task is framed in such a way that the students are able to understand how robotics and STEM can be incorporated to improve peoples lives.

The SYP curriculum focuses on hands-on learning. Students are introduced to the engineering design process from concept generation through prototype testing in an accelerated environment. This is guided by a custom workbook that features picture-based instructions. As an example, during one of the early programming projects the workbook lists all materials needed, has a cartoon circuit diagram, and then guides the students through setting up the code with description of each step. Projects progress through the engineering design process, mechanical/electrical engineering, controls, and programming.

At the university level, the curriculum focuses more on introducing higher level robotics specific concepts with a focus on controls and programming. Similar to the middle school curriculum, the goal of the university level course isn't to create technical experts. It is to create engineers who are able to intelligently understand and discuss autonomy. Additionally, the Autonomous Systems course forms a strong, hands-on foundation for further work on becoming a technical expert.

The university curriculum is broken into a traditional lecture section based on [19] and a custom developed hands-on laboratory section. In the weekly, 2-hour labs over the 14-week semester students proceed through 9 labs from basic programming fundamentals to vision based navigation. Every lab has a 1–2 page guide which lays out lab requirements. The early labs have more thorough explanations of steps to take, possible pitfalls, and other hints. As the course progresses, the guides become sparser with the final project guide having just the project requirements. The semester culminates with a 4-week long intensive final project where students must program their vehicles to autonomously navigate through a model town. The lab sections are kept at approximately 10:1 student:teacher ratio to provide students sufficient assistance while developing their skills.

The remainder of this section covers key concepts introduced in the youth program using GUPPIE and Neu-pulator as well as highlights of the university level course. Only changes and critical curriculum components are mentioned with more in depth coverage of the curriculum in our other work.

3.1 Engineering Design Process

The youth program introduces students to the engineering design process. This is accomplished initially through a hands-on activity constructing micro-gliders [7]. Micro-gliders are simple wood stick and paper clip assemblies that are deployed into a fish tank. Micro-gliders operate similar to the GUPPIE on a downward trajectory. The goal of the micro-glider is to travel as far as possible on the downward trajectory in the tank. This activity teaches students about force interactions of buoyancy, gravity, drag, and lift. In order to succeed at the micro-glider challenge, students quickly learn that they need to iterate through the design process. For example, changing the relative location of paper clips and sticks. Additionally, it serves as the first team building event of the week to help get the students comfortable with speaking up. This is particularly necessary to increase engagement from under-represented groups. The activity helps students figure out how to balance the glider, and in effect, how to control the GUPPIE. This experience aids students understanding of how to control pitch by shifting the center of gravity relative to the center of buoyancy.

3.2 Mechanical/Electrical Engineering

Through using a Computer Aided Design (CAD) software, key concepts of mechanical design as well as the assembly process of both the GUPPIE and Neu-pulator are introduced. In the CAD segment, students design and model the Neu-pulator components that they will later use. This includes modelling of the links and joints to examine the range of motion of the design. During this section, we also introduce the concept of additive manufacturing as it pertains to the manufacturing process for GUPPIE components.

Prototyping and 3D printing helps to make the connection from the CAD sessions early in the week to the real parts during fabrication. The GUPPIE relies on the use of 3D printed components, unfinished printed circuit boards (PCBs), and a pre-fabricated hull. The hull includes a polycarbonate tube and 3D printed end cap that are epoxied together. To assemble the GUPPIE electrically, the students are taught how to solder components onto a PCB such as LEDs, resistors, and wires. Due to the low cost of the GUPPIE, every pair of students is able to have a custom GUPPIE. Similarly, the assembly process for Neu-pulator involves building of the mechanical and electrical systems. Both the Neu-pulator and the GUPPIE use similar components which simplifies assembly by the students due to increased familiarity.

3.3 Controls

Controls topics are not directly introduced to the students, however key concepts of controls are introduced in every portion of the program. Through hands-on activities, students are able to gain experience with different concepts in controls. For example, the micro-glider introduces balancing forces, the Arduino starter kit introduces automatic control, and the Neu-pulator prototype arm introduces closed-loop control. This approach means that students are not overwhelmed with abstract concepts and are instead able to learn controls gradually through practical implementation. More explicit controls topics are covered during the programming and testing of the robotic platforms. The goal of the controls education section is for students to gain an applied understanding of how control systems work. For the middle school age group this means knowing how microcontrollers interact with the world and learning the concepts of feedback and closed-loop control. At the university level, more controls topics are introduced culminating in creating a state based linear control system using visual feedback to drive through a model town.

Control of the GUPPIE is accomplished using a bang-bang feedforward control system with feedback from a single limit switch, Fig. 2a. The buoyancy engine in the GUPPIE is built around a continuous servo with a power screw to convert the rotational energy from the servo into linear motion of a plunger. The plunger is weighted to increase the mass shift associated with buoyancy changes and cause pitching motion. To dive, the plunger is pulled forward in the vehicle which also pulls water into the vehicle. The plunger is pulled in until a limit switch is depressed. This switch triggers the controller to advance to the next state where it waits a pre-determined amount of time for the vehicle to dive. Once the vehicle has completed the dive it expels water, pitches up, and glides upward for a timed maneuver until the process is repeated. This control system operates in an open loop, timing based fashion.

Control of the Neu-pulator is completed using a proportional feedback control system, Fig. 2b. This control system uses a proportional value of the students EMG values as the reference input into the servos. The servos themselves have feedback control systems that maintain the desired angles. This basic closed-loop control encourages students to experiment with the code, changing the response of the motors to the input. This often leads students to start thinking about more complex control scenarios for the robotic arm such as using inverse kinematics to solve the joint angles for a target end effector location.

Control of the smart car is more advanced than the middle and high school platforms. Due to the extended schedule and additional background knowledge available for the university course, the control system grows to involve multiple feedback loops and multiple discrete control states, Fig. 2c. The primary feedback sensor is the Pixy camera which outputs an array of information related to what it sees. The controller processes this information to localize and decide where it is in the model town. The vehicle state machine then determines which control method is implemented and sent to the h-bridge for motor control.

3.4 Programming

Introducing students to programming is the major component of curriculum consisting of 12 h out of the total 28 h program. Beginning on the first day, we introduce Arduino through several small projects from the Arduino starter kit. In particular, the students learn the structure of Arduino, how to write and upload codes, and how to search for help. The starter kit also introduces students to electrical engineering concepts such as circuits by having students build a circuit on a breadboard consisting of resistors, LEDs, and buttons. Concepts required for control of the GUPPIE and Neu-pulator are then introduced during the remaining days including conditional decision making, timing, *for* and *while* loops, reading sensors, and controlling servos. Once these concepts are

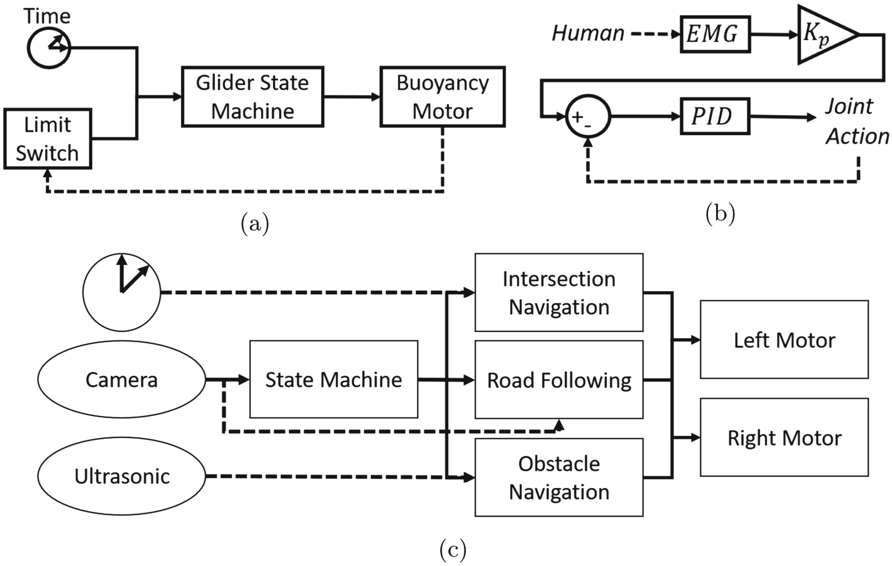

Fig. 2. (a) The control system in the GUPPIE uses a timing based, feedforward controller aided by a limit switch to control the buoyancy system. (b) The Neu-pulator control system is a proportional controller based on EMG signal that is fed into the servos onboard PID controller. (c) The smart car control system is more complex than the other platforms. It includes multiple sensors and a state machine deciding between different control modes depending on the environmental conditions.

presented, students assemble and program a prototype Neu-pulator that they control using potentiometers. To completely program the GUPPIE and Neu-pulator, students need to demonstrate a firm understanding of how the vehicle works, how to instantiate and manage variables, conditional decision making, and timing. The developed codes are tested multiple times on prototype platforms prior to deployment on the actual robots. This enables students to learn through experience with a low-stress test environment.

At the university level, the course initially focuses on development of baseline programming ability. The majority of students in the class have either no experience or limited experience with programming. The university students start with the same tutorial sessions as the middle school students, then rapidly progress to more advanced topics.

4 Survey Results

Using the described curricula and robotic platforms, the authors have engaged a total of 201 middle and high school students over four years through the SYP program including 106 girls. Additionally, 72 university students have completed the autonomous systems course. This paper presents the results from the most recent round of curriculum revision with 51 SYP students during Summer 2017 and 36 university students in Spring 2018. These results are from discrete groups of students so the long term impact of consistent robotics education cannot be concluded. This section presents specific survey results for each group, while overall observations and lessons learned across age groups is presented in Sect. 5.

4.1 Summer Youth Programs 2017 Results

In the Summer Youth Programs a pre-survey, daily surveys, and post-survey were used to evaluate the performance of the curriculum and robotic platforms.

When asked about how their perceived ability to do robotics changed? Students overwhelmingly stated that their ability increased. In fact, 36/51 of the students stated that their coding skills improved. This matches the goals and teaching distribution of the course as the majority of time was spent on teaching students how to program.

When asked what the students favorite segments were, the majority of students (36/51) stated that they enjoyed building or programming. While the mechanical assembly of the actual robotic platforms was not the focus of the course, it was what students had the most experience with prior to the camp and where they were most comfortable. The activities helped the majority of students (85%) to learn about Arduino programming and building circuits. The students stated that they liked that they learned how things work, how programs interface with parts, and how to do programming from scratch and troubleshooting.

Other questions on the survey included career choices, personal history, challenges encountered, and favorite robot. Of particular note in the survey results are some of the individual student responses when asked what are robots useful for. Students gave answers ranging from prosthetics to “military action”. The majority of students gave a response focusing on helping human life such as “I think that robots can be useful for assisting elderly and help perform minor medical diagnoses.”

When asked about teachers performance, overall, the students liked that the teaching team was knowledgeable and capable of explaining problems when they asked for help, yet the students were also allowed to work independently and solve problems on their own. Further, the students liked that the teaching team was friendly and approachable and each instructor had different strengths and ways of explaining solutions, “I liked how since they were many of them, if you didn’t understand one way it was explained you could get a second opinion and they could word it in an understandable way.” Although most students appreciated the teaching efforts, some students became frustrated especially when they had to wait for assistance. “I really would only change the number of staff because sometimes you had to raise your hand for a while.” These results indicate that the selection of instructors is very important for youth robotics. In particular, having multiple instructors with different ways of explaining abstract concepts helps students from different backgrounds to understand.

When asked about how they would improve the course? Students responded that they would increase the quantity of coding and assembly by possibly building more robots and a longer camp. Several student mentioned that they wanted to customize the platform more, "time and parts to let us tinker." A consistent theme in the survey was that students would prefer to have a workbook with no errors and to have more robust components.

4.2 Spring 2018 Autonomous Systems Results

At the university level a more extensive pre-survey and post-survey were used to evaluate performance of the curriculum. With the extensive survey, we were able to identify several key questions that are able to indicate program effectiveness.

At the beginning of the course we asked students if they had any programming experience. All students said that they had some experience with programming in MATLAB as it is a required component in other courses, however, 16/36 students said that they had some experience with the language used in the course, Arduino. This result combined with our experience teaching Autonomous Systems in the Spring 2017 led us to expand the programming tutorial sections at the beginning of the semester to establish a sufficient baseline knowledge.

When asked what students wanted to do after graduation students gave a wide range of responses from "I want to work in the aerospace industry! I'd love to work at NASA and help further our knowledge of the solar system." to "After receiving my undergrad degree, I will continue my schooling and pursue a graduate degree in mechanical engineering. After that I want to work in the powersports industry as an NVH (Noise, Vibration, and Harshness) engineer." In total, 12/36 wanted to immediately apply the knowledge gained in autonomous systems to a manufacturing related career. This is partly due to the university's long term relationship with the automotive industry.

When comparing the pre- and post-surveys, the confidence in computer programming was identified as the most important question. At the pre-survey, students indicated that they were moderately confident with a mean score of 3.92 on a scale from 1 to 7 versus 4.76 on the post-survey. Additional post-survey results indicate that students thought the work in autonomous systems was more interesting than their other courses (6.37) and they learned more than in other courses (5.57). When combined, these results demonstrate that students appreciated the hands-on nature of the course and the way the material was presented.

Two post-survey results stand out in addition to the mentioned Likert scale questions. When asked if the course has helped them to receive an offer of employment, 20/36 students indicated that it had. This result indicates that the market is in need of new engineers with hands-on robotics experience. Additionally, when asked if they were interested in an advanced level autonomous systems course, 30/36 students answered yes and 36/36 said they would recommend the course to a friend.

5 Observations and Lessons Learned

While the survey results are focused on the 2017 summer youth program and the 2018 autonomous systems course, the iterative nature of the improvements to the curriculum means that we can generate overall observations and lessons learned based on the 201 total (106 female) middle and high school students introduced to GUPPIE and Neu-pulator as well as the 72 university students introduced to the smart car.

Common across all age groups and iterations of the program is the need for high quality support to aid learning. For the youth groups we maintain a 5:1 student:teacher ratio or better, while at the university level 12:1 was sufficient. With this amount of support, students were able to succeed. Teaching assistants in the youth programs need to have a functional understanding of the specific robotic platform but do not need to be experts in robotics and programming. At the university level though, the teaching assistants need to have a deep understanding of mobile robotics and be good at troubleshooting. This is because of the customization allowed during a full semester, every student will develop a very different project as the course progress resulting in unique challenges.

Additionally, students of all age groups appreciate the hands-on nature of the projects. Younger students appreciate having something interesting to show off and experiment with, particularly as it relates to helping human life. University level students are able to see hands-on applications of what they have learned in other courses. Several of our university level students have leveraged the project-based experience in Autonomous Systems to gain employment opportunities.

As the ubiquity of robotics increases over coming years, students of today will require interdisciplinary knowledge to live in the coming smart society where autonomous systems are integrated into everyday life. This interdisciplinary knowledge requires time and practice to develop, and by starting early, students are given the best chance of succeeding in the future. However, just providing early engagement opportunities is not enough. Continued engagement through university level is necessary and can be built around a common learning experience. This common experience follows the same ‘see-think-act’ regardless of the specific project and technical competency. Using these lessons learned, a fully integrated continuous learning program from middle school through graduate school can be created.

Overall, an integrated pathway from middle school through university must maintain a motivating learning context in order to engage the students. For example, we have tried to focus on helping human life in pre-college and autonomous cars at the university level. Additionally, we have found that younger students are surprisingly adept at technical challenges, however, managing frustration is key to learning. We have had good success with integrating play and learn together. As the students get older, they become less agile with new concepts but are better able to manage stress resulting in more consistent learning.

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