Improving STEM Education with an Open-Source Robotics Learning Environment

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Abstract

A four-week robotics program designed to increase STEM education is presented here. This was developed in conjunction with our senior project, where we created an open-source robotics kit in partial fulfillment of the degree requirements for the Computer Science program at Tennessee State University. A non-traditional top-down approach is used, where the students are engaged with hands on activity and critical thinking exercises from the first day. The students are exposed to programming, circuits, robotics, and the engineering design process. The pilot program carried out did not completely follow the proposed four-week curriculum, and these issues will be discussed. Many of the students reported learning key problem solving, critical thinking, teamwork, design, and presentation skills that will readily transfer to multiple areas in their studies and everyday life. The key idea with utilizing robotics as means to increase STEM education is this very transfer of skill, and even though the course deviated slightly from the original plan we believe it was still successful to these ends.

1 Introduction

We are in a new age of technology, where every high school student today has grown up with technology since birth [12]. The lack of education of the processes that drive this technology has become readily apparent, and the push to fix this problem is still falling short. In 2005, as a part of a National Science Foundation research grant, the Computer Science Teachers Association made this same conclusion [5], but little action was taken. For the sake of our community-at-large, finding a way to ensure a healthy technological future depends largely on when and how younger students are equipped to leverage the increasing complexity and vastness of this technology. One way to address this problem is to offer a formalized robotics course before the college level.

Students who avail themselves of this curriculum will open the door to greater opportunities, while setting themselves ahead of others. Such a curriculum engages a wide array of student intelligences, where Dr. Morgan points out, this lack of engagement is a problem many educators face in the classroom today [12]. On top of that, such curriculum taps into the creativity within each student, allowing for self-expression and the possibility for guided exploration of their individual interests. Some students may find the robot movements to be highly engaging, others may prefer to dive into image processing, and another group of students may wish to explore sensing the environment; the list is endless.

Another study, specifically calling for more computer science education published in 2016, noted that the very fundamentals inherent in computer science education have many secondary and tertiary pedagogic aspects such as logical analysis, critical thinking, and problem solving, just to name a few [2]. Many disciplines are now intertwined with computer science, and addressing STEM education as a whole without addressing computer science would be a disservice to our objectives. Robotics is a prime multidisciplinary field that can be the focus needed to teach the concepts of computer science, math, and engineering together. A 2007 study concluded that a robotics education course increased overall scores in other areas such as literacy and math due to the incidental aspects of a multidisciplinary apprach to teaching [1]. The use of robotics and computer science as a means to increase STEM education is one of the most relevant approaches that can be used today.

2 Review of Literature

An extensive review into several related areas was carried to ensure the most relevant concepts and learning theories were utilized. The first area studied are Tangible Learning Environments (TLEs), which are environments where learning takes place with the student interacting with something in the physical world. The second area researched is previous robotics programs, and specifically short duration programs that encompass many concepts, as opposed to a traditional robotics class. Third, we examined and evaluated existing robotics kits that are commonly used in traditional robotics courses.

2.1 Tangible Learning Environments

Tangible learning environments, synonymous with technology enhanced learning environments (TELEs), are learning environments that promote multimodal knowledge acquisition through the use of physical interaction and feedback with the instructional medium. This type of environment facilitates exploratory learning, where the student is able to take an inquiry based approach to new information and more readily relate this to personal experience [13]. TLEs inherently foster creativity, communication, and collaboration, all factors that are linked to better critical thinking and problem solving [8]. These environments provide a more authentic problem space for the student, increasing their enthusiasm and motivation [21]. Student motivation plays an important role in the learning process as it allows them to be more receptive to the content, more engaged with the activities, and more willing to overcome challenges [20][18]. Overcoming these challenges, which they will inevitably face, allows them experience success on a richer level than simply passing a test.

A recent study which aimed to teach students concepts of plotting points in a coordinate space with the use of a robot echoed many of these benefits [8]. They had a large coordinate space on the ground and a robot that moved around on this plane. The student controlled the robot with simple commands such as *move 3 spaces forward*. They also had several virtual environments running as only one student or group could interact with the robot at a time. During the follow up, one of the teachers commented:

> "*That's what I think is really key, is that if they arent even realizing that theyre learning, that they think that they just went on this field trip and had fun, but now they know how to plot points on the positive and negative side. They just think they went and played with a robot, which I think is cool.*"

It is clear that a student is able to obtain a much richer learning experience from an interactive environment, and this is the cornerstone of the Open-Source Robotics Learning Environment.

2.2 Previous Robotics Programs

Several programs have been carried out with great success as well. Goldman, Eguchi, and Sklar [9] conducted two programs in the summer of 2003 with a group of inner-city kids in New York. Their program utilized the Lego Mindstorms platform and the RoboLab programming environment. First, they taught students about the design process, then high level programming, and finally application. Overall, they reported a high degree of satisfaction, with having something tangible to show their family and friends as the main source of motivation. Also, they reported the teacher-to-student ratio as another highly important factor, having approximately a 1 to 6 ratio.

Another study conducted by Barker and Ansorge [1] in 2007 sought to examine the use of a robotics based curriculum to improve achievement scores of pre-teenage students. Although the target age group is significantly less than ours, many of the key concepts and ideas remain relevant. In their study the 4-H robotics curriculum is used, which as above utilizes Lego Mindstorms and RoboLab. The 4-H program is designed around Kolbs experiential learning model, which has many similarities with the approach we use. Here, the students engage in the activity and must exercise problem solving skills early on. They also carried out a test after the program to assess the effectiveness of the program with positive results.

A third program carried out in Pennsylvania by Cappelleri et. al. [4], was an intensive three-week course that the authors state combines theory with hands-on practical experience in cutting edge technologies. They developed a top-down curriculum, engaging the students with hands-on activities at the beginning of the course which provided a focus to introduce the fundamentals thereafter. Their course was more focused towards the mechanical engineering aspect of STEM education and robotics, but also taught simple embedded programming and the design process. The students were in class from 9am to 5pm every day for three weeks as well. They report a high degree of satisfaction with the students and retention of the material, and make note of the importance of the amount of time the students spent on learning the material and completing the final project.

2.3 Existing Robotics Kits

An extensive review of current robotics learning platforms such as Lego Mindstorms® or VEX® was conducted as part of the initial research. Lego Mindstorms was initially released in 1998, and has since grown to include several releases, with the latest being the Lego Mindstorms® EV3 kit [11]. The Lego Mindstorm series of robotics kits provide a high-level interface with robotics, which is good for an introductory course or for younger students, but there is a ceiling to what can be done. For example, LEGO Mindstorms® projects are effective in the specific domain of robotics, but outside of that there is little transfer. There is no interface to learn in detail about electronics and circuits outside of what sensors they provide. With on-your-own type projects, a student would exclusively have to use Lego Mindstorm brand sensors and pieces as well, and therefore be unable to purchase cheap off-the-shelf sensors when needed. Along with that, a common starter kit costs around $349.99.

The VEX® Robotics Design System was released in early 2000's, and is the most pervasive robotics platform among high schools which offer a robotics program or sponsor a robotics competition team [17]. There are many different types of kits available, making it accessible to a wide age range. Typically, the focus of the program is for a team to designing a robot capable of completing one or more tasks, utilizing engineering design principles, and culminating in a competition among other schools. From a learning point of view this is great. These kits, however, are far too expensive for an individual to purchase, or for institutions with little to no funding support. The basic starter kit is around $439.99, and replacing the specialized computer would cost $239.99.

The cost of these kits is a major drawback, along with the fact that these kits are not open-source. This means if you want to do anything extra, you need their proprietary equipment, which will be expensive. Also with these kits, the student is limited to what the microcontroller is capable of, and they are only capable of very specific things. The Raspberry Pi, on the other hand, is a complete computer. It has a desktop interface, games, an internet browser, multiple programming interfaces like Scratch, Mathematica, and Python, and much more.

Student who utilize a Raspberry Pi in a robotics course can quickly transfer what they learn to self-regulated projects and exploration outside of the classroom. They could create a web server and start a website, make an automated dog feeder, develop an intruder detection system (detailed below); the possibilities are limitless. This device, which is substantially more powerful and capable than the microcontrollers used above, costs only $39.99. If you break this computer, you wont break the bank replacing it, and all of your saved data is on an SD card where it can easily be retrieved. Our aim is not to criticize the other kits mentioned above, as there is no doubt they are beneficial and improve learning outcomes [14][10]. Our goal is to establish a cheaper alternative that is open source, more capable, and can be readily integrated into student projects outside of the classroom.

3 Robot Design

One of the key aspects of the robot is an aesthetically pleasing physical design. We took this very seriously. After all, a student is not likely to use a robot if its bulky, cumbersome, or has an unattractive appearance. This would detract from the instruction and lead to reduced attention in the classroom. Figure 1 depicts a rendering of the first prototype, which several students felt it to be aesthetically pleasing with good symmetry and proportions. The circle face at the front will be on a pan and tilt unit, which serves as the neck of the robot allowing it to look up, down, and around.

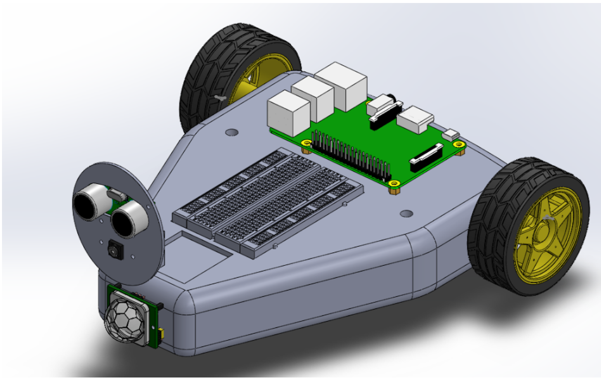

Figure 1: Robot CAD View

The software developed is the main aspect of the robot itself, which turns the Raspberry Pi into a highly functional robot. Our software package can be used on any existing Raspberry Pi based robot as well, not just the robot that we designed, increasing its availability. The central focus of the software is to allow the student to complete the tasks associated with the various learning outcomes. The robot is capable of autonomous navigation, remote communication, computer vision, email handling, sensing, exhibiting several behaviors, and much more. The student will learn how to complete all of these task throughout the course.

All physical connections are interfaced with code in only one file, so that the user can easily modify their connection settings without editing multiple files, as well as to provide one place in which all hardware connections are established. One aspect of our robot that will be extremely fun and interactive are the robots behaviors. These are just very simple actions that the robot will do at predefined times or in response to a predefined event. Think of the famous robot R2D2; immediately upon the prompt you may have imagined one of the beeping or light patterns, this is what is meant by behavior.

4 Curriculum Design

The curriculum that we are designing is the core of the entire kit, and is still in development. We have industry and academic experts with over 40 years of curriculum development experience aiding in writing and review to ensure maximum clarity and cohesiveness in the instruction. Ralph Tylers curriculum development model has been a successful model that has withstood the test of time, and is a highly-recommended way to approach curriculum development [16]. Tylers Rationale, as it is called, starts with four instrumental questions that, upon addressing during the curriculum development phase, ensure a solid framework for instruction. These questions outline the general backwards planning approach, which has proved time and again to be very successful. The first question asks, What are the educational objectives we seek to attain? The second question is, What educational experiences will lead to the attainment of these objectives? Followed by, How can these educational experiences be effectively organized? Finally, How can we determine if our objectives were met? This framework is key to any type of curriculum development, as giving awareness and attention to these questions help lay down the foundation for the material to be covered.

We came up with 12 S.M.A.R.T. (specific, measurable, attainable, realistic, and timely) objectives divided among three intellectual areas, Computer Science, Programming, and Robotics. Within each category, the objectives are sequentially obtained, the previous being a foundational block of the next. Within each objective is a module-based lesson plan that is manageable and the achievement can be measured. In this manner, achieving the objective is incidental; the student does not place focus on pass or fail, but rather completing the tasks and reflecting on the outcome. Some of the tasks are very basic, such as identifying parts of a robot, or completing a block diagram of a standard computer architecture. Others are more complex, such as writing an algorithm to identifying colored objects in the cameras view frame, or avoiding obstacles while navigating an unknown environment. These learning experiences are formed from an inquiry based approach, which has been shown to have a positive impact on academic achievement [7].

To address how these experiences can be organized effectively, we relied on the principles covered in a highly successful curriculum development book by Wiggins & McTighe [19]. They begin in a similar manner as Tyler, where the desired results, measures, and experiences must be identified. Then, They provide several questions to answer that aid in organizing effective instruction. Some of the question include, What do the students need to understand about this topic to perform well on an assessment? Another one is, What are the big ideas we want the students to explore via inquiry? These questions, among others, help shape the modules and ensure the knowledge will be effectively assimilated and facilitate the tranfer to other domains in the future. A well organized instruction is a key component to effective learning outcomes. Sections, tasks, and modules are specifically linked to one of the three intellectual areas, so that the student knows exactly what they are in relation to the big picture.

5 Course Implementation

Below is our initial four-week lesson plan. As we found out upon implementation, this is a very ambitious plan that requires student engagement for 5+ hours a day, which we did not have. We followed the plan as best as possible, with a fair degree of improvisation, which will be discussed in the next section. One of the first things that may stick out is the amout of time devoted to reviewing the material that was covered. This may seem unnecessary, however current research in cognitive psychology and education reveals otherwise. Reviewing the material is important because it offers a chance for the student to assimilate important information, or quickly recall relevant information and strenghten the connections with the material [15][6]. By reviewing recently covered material before a block of instruction, the student is effectively primed for what they are about to learn, which helps the student to better conditionalize the subject matter. This conditioning process increases the efficiency of their knowledge organization heirarchy, making them better learners [3]. These are major concepts to consider when designing the curriculum, as our aim is to incorporate and exploit the most relevant factors related to learning, we felt these to be highly relevant.

	Week 1				
	Monday	Tuesday	Wednesday	Thursday	Friday
	Course Introduction, overview, and pre survey	Review of yesterday's Lesson	Review of yesterday's Lesson	Review of yesterday's Lesson	Review of yesterday's Lesson
	Introduction to Linux [LO-02], T-3, T-4	Introduction to the hardware interface [LO-01]	Introduction to circuits and ohms Law [LO-06], [LO-07], T-14, T-15	Python Programming [LO-04], T-8, T-9, T-10	Robot assembly [LO-09], T-17
		Electronic safety [LO-06]			
	Introduction to the Raspberry pi [LO-01], T-1, T-2	Introduction to basic electronics [LO-06], T-13	More electronics, circuits, and ohms law (with videos and other instructional media)	Programming a simple circuit [LO-04]	Interface with the robot, sensors, and picamera [LO-10]
	Review of today's lesson	Review of today's lesson	Review of today's lesson	Review of today's lesson	Review of today's lesson

Figure 2: Week 1 Course Outline

	Week 2				
	Monday	Tuesday	Wednesday	Thursday	Friday
	Review week 1, survey and feedback on week 1	Review of yesterday's Lesson	Review of yesterday's Lesson	Review of yesterday's Lesson	Review of yesterday's Lesson
	Introduction to computer science [LO-03], T-5	Engineering design process with the intruder alarm project / class discussion / questions catching up	Programming with the operating system and camera [LO-05], T-11, T-12	Introduction to robotics [LO-08], T-16	Writing a remote control script to control the robot from the keyboard [Ed's learning framework]
				Robotics Fundamentals [LO-08], applications of robotics, and videos	
	Design an algorithm [LO-03], T-7 (intruder alarm project)		Complete the intruder alarm project [LO-03], [LO-05], T-7, T-11, T-12	CSRBot API	Self guided exploration of the robot
	Review of today's lesson	Review of today's lesson	Review of today's lesson	Review of today's lesson	Review of today's lesson

Figure 3: Week 2 Course Outline

	Week 3			
Monday	Tuesday	Wednesday	Thursday	Friday
Review week 2, survey and feedback on week 2	Review of yesterday's Lesson	Review of yesterday's Lesson	Review of yesterday's Lesson	Review of yesterday's Lesson
Soldering lab	Robot Navigation [LO-09], [LO-10], [LO-11], T-19, T-20	Binary and Hex numbers, conversion, ascii chart [LO-03], T-6	Discrete Digital Signals Lab	Student driven instruction -what do the students want to learn? -what was not covered well enough? -Q&A Day
	Robot Navigation [LO-11], T-25	Digital logic [LO-03]		
Review of today's lesson	Review of today's lesson	Review of today's lesson	Review of today's lesson	Review of today's lesson

Figure 4: Week 3 Course Outline

	Week 4			
Monday	Tuesday	Wednesday	Thursday	Friday
Review week 3, survey and feedback on week 3	Review of yesterday's Lesson	Review of yesterday's Lesson	Review of yesterday's Lesson	Review of yesterday's Lesson
How to troubleshoot	Image Processing [LO-12], T-26, T-27	Socket Communication [LO-13], T-29, T-31	Email activated intruder alarm (final project utilizing over half the learning objectives in one complete system)	Finish final project, course wrap up, Q&A, course survey, acknowledgments
Troubleshooting practice sheet	Review of today's lesson	Review of today's lesson	Review of today's lesson	

Figure 5: Week 4 Course Outline

This course was beta tested during the 2017 Tennessee State Universitys Engineering Concepts Institute Summer Bridge Program, which takes a group of recent high school graduates (10 students in this case) and prepares them for college life and success during a 30-day resident program. The students were available for 2 to 2.5 hours a day, 5 days a week, with the exception of 3 days where they were not present for the course.

We began the instruction with a pre-test on the concepts and topics that were to be covered, to assess what each student already knew. All students essentially had no prior knowledge, except for one student who had familiarity with Python programming. The post course results are detailed in the next section. The students unboxed their Raspberry Pi kits on the first day, and basic Linux operations were covered. For the rest of the week Python programming was taught. Fundamentals such as types, variables, math operations, functions, loops, and user input was covered. It was planned to complete the robot assembly by the end of the week, but due to supply logistics this did not happen. However, there was no shortage of material to cover, and this allowed for more instruction on programming, which aided the students in the long run.

During the second week, robotics, electronics, circuits, Ohms Law, and electrical safety was covered. About half of the week was devoted to covering robotics fundamentals, with the core concept being PEAS (Performance measure, Environment, Actuators, Sensors).

Then, the students built a simple LED circuit with a button, and programmed the circuit with two different button operations. One function required the button be continuously pressed for the LED to illuminate, the other function utilized single button presses to turn the LED on and off. The students found this very engaging, and an increased motivation to learn more was noted.

Figure 6: Students Working on Circuits

The third week was devoted to developing an Intruder Detection System, which utilized a camera, buzzer, passive infrared (PIR) motion sensor, and an email handler script that we (the instructors) wrote but did not cover in detail. When motion is detected, this system takes a picture and sends it to the students email. The students learned about simple algorithm development, process flow and control, and troubleshooting both hardware and software issues.

During the last week, we reviewed all the major concepts covered, and improvised with an open ended creative design project. The students, in groups of two, brainstormed a real-world problem that could be addressed with an autonomous robotic solution. We introduced the engineering design process, which the students followed very well. The nature of the robotic designs presented were quite diverse, spanning from an aquatic underwater lifeguard for an oceanic environment, to an autonomous roof and gutter maintenance robot. This project allowed the students to apply what they learned during the previous week about robots.

Figure 7: Students Programming

The students also completed a short presentation using the following outline as their template: Title, Overview, Problem Statement, Background, Goals & Objectives, Design Criteria, Implementation, Results, Conclusion. They found this template structure to be very intuitive, aiding in the creation process. For the results, they were asked to be reasonable and creative in coming up with likely positive results for their system since they did not actually build, test, and implement the designs in real life. The main point of this project was to introduce the engineering design process, learn strong public speaking and presentation habits, and apply what they learned in the previous weeks. The course culminated with taking a slightly different version of the pre-test, giving their presentations, and acting out a scenario to demonstrate the intruder detection system to their parents.

6 Results

The results of the beta test are highly promising, even though the students did not fully build their robots and utilize the software to the fullest. 7 out of 10 students scored above 90% on the final test, and 2 of the 10 students scored above 80%. The student who scored below 80% entered the program 2 days late, and missed 2 days during the week. See the end of the paper for the test and answers to the 11 quantifiable questions asked. The last question was open ended and asked, "What did you learn from this course?" Below are several responses.

- "...Ive learned names for different components and parts of robots. Ive programmed a small computer to act as an intruder detection system. Ive learned many applications of robots and how they are very useful."
- "I learned how to better problem solve. Going through the design process and struggling with my project really helped me understand how to work well with others."
- "In robotics I learned about PEAS and all that you have to think about before creating a robot... Taking this course helped me see that it was more than just building robots but that it was really about following the right steps and understanding the process you have to go through before you simply build it."
- "...Most importantly to me, I learned how to make a professional robot design PowerPoint. Throughout my college years presenting and making PowerPoints will be easier because of the skills I learned during this course."
- "I learned applications of robotics and how to use the engineering design process."

Among those responses many students mentioned learning about sensors, programming, robotics basics, and how to make simple circuits.

7 Conclusions

From the open-ended answers recieved and large majority of students scoring above 90%, it is quite evident this program was a success. However, the lesson plan needs to be modified to reflect the amount of time the students are present for instruction. We were quite ambitious, but took the roadblocks and assumptions as a learning experience for ourselves. Also, instruction and task modules for concepts such as navigation and communication needs to be assessed. Since we were unable to completely assemble the robot, several learning objectives were not achieve. We found that even if we had the supplies necessary for each student to assemble their robot, we would have been rushed to cover much of that material, and the quality of learning would have been reduced. The fourth week presented an unforeseen opportunity to introduce other related skills that are highly relevant with a robotics course, which allowed the students to implement the theoretical knowledge they learned with an open ended, creative project. This approach further strengthened the retention of the material covered, and will be fully incorporated into our next iteration of the program. Qualitatively, the students felt the open ended robotics environment was attractive and effective. While we are not advocating or claiming this to be a complete replacement for existing robotics kits or programs, we have shown it to be a cost-effective alternative with substantial learning benefits. We will continue to improve, and in the near future implement this program on a larger scale.

8 Acknowledgements

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9 The Post Course Test

ECI 2017 Robotics Course Post-Test

1. Name the following items:

resistor **capacitor** **led** **motor** **breadboard** **raspberry pi**

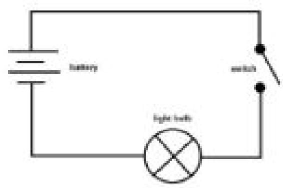
2. What is a robot?
An autonomous electro-mechanical machine capable of sensing its environment and carrying out actions to achieve a specific goal.

3. Explain PEAS.
Performance Measure – The metric(s) in which the effectiveness of the robot is assessed
Environment – The type of environment the robot will be in (static, dynamic, known, unknown, partially known)
Actuators – The types of components that the robot uses to move or interact with its environment (motors, servos, solenoids, clamps, etc)
Sensors – The components the robot uses to collect information from its environment (PIR sensor, photoresistor, sonic range sensor, IR tx/rx, camera, etc.)

4. What is Linux?
An open source operating system

5. What is the engineering design process?
A series of steps used to solve a need or problem. 1-identify the need or problem, 2-conduct background research, 3-brainstorm solutions, 4-select best solution, 5-make a model/prototype, 6-test and evaluate, 7-implementation, 8-redesign

6. What is a circuit? Draw one.
A closed path for electricity to flow from a point with higher potential to a point with lower potential.



7. What is Ohm's Law?
   The current in a circuit is directly proportional to voltage and inversely proportional to resistance. V=IR I=V/R R=V/I I=current V=voltage R=resistance

8. A light has a resistance of 1100 Ohms and a max current rating of .1 amps. How much voltage can be applied before the filament will burn out?
   110v
9. What are some applications of robotics?
   Welding, auto manufacturing, surgery, drones, fruit harvesting, self-driving vehicles, vacuum cleaning, education, research, fun, and more

10. What is an algorithm?
   A finite sequence of steps that are carried out to solve a problem.

11. What is the output of this code when $x = 2, y = 5, z = 3$?

```
def function(x,y,z):
        x = y + x * z
        y = x + 3 * y
        x = x + y + z
        return x
```

40

12. Write a loop that adds the numbers from 1 to 10.

```
sum = 0
for i in range(1, 11):
    sum += i
print(sum)
```

13. What do you hope to learn from this course?
   Open ended question

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