UNIVERSITY OF LEEDS

This is a repository copy of *STORMLab for STEM Education: An Affordable Modular Robotic Kit for Integrated Science, Technology, Engineering, and Math Education*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/102505/

Version: Accepted Version

Article:

Susilo, E, Liu, J, Alvarado Rayo, Y et al. (4 more authors) (2016) STORMLab for STEM Education: An Affordable Modular Robotic Kit for Integrated Science, Technology, Engineering, and Math Education. IEEE Robotics and Automation Magazine, 23 (2). pp. 47-55. ISSN 1070-9932

https://doi.org/10.1109/MRA.2016.2546703

(c) 2016, IEEE. This is an author produced version of a paper published in IEEE Robotics and Automation Magazine. Personal use of this material is permitted. Permission from IEEE must be obtained for all other users, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works for resale or redistribution to servers or lists, or reuse of any copyrighted components of this work in other works. Uploaded in accordance with the publisher's self-archiving policy.

Reuse
Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

eSMAC: an Affordable Modular Robotic Kit for Integrated STEM Education

Ekawahyu Susilo, Jianing Liu, Yasmin Alvarado Rayo, Ashley Melissa Peck, Pietro Valdastri
Dept. Mechanical Engineering, STORM Lab.
Vanderbilt University
Nashville, TN 37212, USA
ekawahyu.susilo@vanderbilt.edu, jianing.liu@vanderbilt.edu, yasmin.alvarado-rayo@vanderbilt.edu,
ashley.m.peck@vanderbilt.edu, p.valdastri@vanderbilt.edu

Justin Montenegro
Hume-Fogg Academic Magnet High School: Science
Metro Nashville Public Schools
Nashville, TN 37203, USA
justin.montenegro@mnps.org

Mark Gonyea
Stewarts Creek High School: Mathematics
Rutherford County Board of Education
Smyrna, TN 37167, USA
gonyeam@rcschools.net

I. Introduction

The demand for graduates in Science, Technology, Engineering and Math (STEM) has steadily increased in the last decades. In the United States alone, jobs for biomedical engineers are expected to increase by 62 percent by 2020, while jobs in software development and medical science are expected to increase by 32 percent and 36 percent, respectively [1]. Combined with an insufficient number of students enrolled in STEM fields, this will result in about 2.4 million STEM job vacancies by 2018 [2].

Therefore, increasing the number of STEM graduates is currently a national priority for many governments worldwide. An effective way to engage young minds in STEM disciplines is to introduce robotic kits into primary and secondary education [3]. The most widely used robotic kits, such as the LEGO Mindstorm [4], the VEX Robotics [5], and the Fischertechnik [6], are composed by libraries of prefabricated parts that are not interoperable among kits from different vendors. As recently surveyed in Kee [7], alternatives to these popular kits are either highly modular, but very expensive (e.g., Kondo [8], Bioloid [9], Cubelets [10], K-Junior V2 and Kephera [11]) and unaffordable for the majority of schools, or single-configuration and low-cost robots (e.g., AERObot [12], iRobot [13], and Boe-Bot [14]) with a restricted number of activities possible. An affordable solution that provides a number of interchangeable modules is littleBits [15]. This platform offers a variety of sensing and actuation modules that use magnets to connect, but lacks programmability, and thus it limits students' ability to learn about coding.

In this paper, we introduce for the first time the educational STORMLab Modular Architecture for Capsules (eSMAC) robotic kit. The eSMAC is a low-cost and interoperable robotic kit with a variety of functional modules that can be easily connected together thanks to a snap-on 3-wire magnetic connection. The eSMAC robots have a 40 mm diameter cylindrical footprint, with functional modules that can be stacked one on top of each other. The available modules include actuation, sensing, wireless communication, programmable units, and audio/visual indicators. The robots can be programmed through a web-based user interface installed either as a plugin or an app on the Google Chrome browser. At the time of writing, eSMAC robots have been applied to different educational activities, ranging from a robot soccer game to maze exploration. These activities can be integrated in core subjects of STEM curricula, such as Physics, Computer Science, Engineering, and Math. The eSMAC robotic kit is the educational version of the SMAC design environment [16, 17], which is aiming to lower the barriers for design space exploration in the field of medical capsule robots by providing an open source library of hardware and software functional modules.

II. The Role of Robotic Kits in the Next Generation Science Standards

This section focuses on the recent reform of STEM education that is happening in the United States (US) with the introduction of the Next Generation Science Standards (NGSS) [18], and on the role that robotic kits may play in this new framework. While this shift in paradigm for education is specific for the US, the same underlying concepts apply to STEM education around the world. In the real-world application, science relies on technology, mathematics and engineering. Engineering itself depends on findings from science and applications of mathematics. Textbooks and lectures are important for teaching, but adding hands-on connected learning may improve understanding of the basic concepts and, ultimately, engage more students.

The quality of STEM education in the US has been an ongoing point of concern for policymakers and educators since the 1957 launch of the Soviet satellite Sputnik. Ever since, there has been a consistent push to ensure that students graduate prepared to join and lead jobs involved in scientific and technological research and innovation. Since the 1990s, coordinated efforts by the National Science Foundation, other research oriented groups, and teacher educators led to the piecemeal adoption of science standards that emphasize the doing of science over the rote memorization of facts. Teachers were encouraged to make lessons inquiry-based and hands-on rather than relying on textbooks and direct instruction.

The tools for implementing this type of instruction have lagged behind the calls for better instruction. Depending on the age and financial resources of students and the school, science materials range from simple boxed kits that allow students to verify known phenomena to sensitive measuring devices that work as part of a larger teacher- or student-constructed investigation. Unfortunately, the tools that allow student-driven inquiry tend to come at a much higher price than the heavily directed lab-in-a-box, leading to a disparaging chasm of equality between schools that have adequate funds and those that do not. Vernier markets digital classroom measuring devices [19] that work well and are durable. For a physics lesson involving kinematics, Vernier's Go Motion measures and displays position, velocity, and acceleration to a high degree of accuracy and precision. The cost of one motion detector and its requisite software, however, exceeds \$350. In order for a school to stock a single science classroom with enough motion detectors for a class of 25 students to have enough to use in groups, the school would need to spend around \$2,000. This is a prohibitive amount for US urban or rural public schools, as well as for the average suburban private school, especially given that nowadays school teachers are spending an average of \$500 of their own money on classroom supplies [20].

Most STEM teaching and learning at K-12 grades in the US has focused on science and mathematics, but very little in technology and engineering. Even in schools that teach all four subjects of STEM, all are taught as separate subjects instead of as an integrated curriculum. This situation will eventually change with the new reforms in teaching and learning methods, placing more connection among STEM disciplines. In April of 2013, the National Research Council, the National Science Teachers Association, the American Association for the Advancement of Science, and Achieve released the NGSS for adoption by state boards of education. In an explicit shift to ensure students know how to do science, the NGSS outlines performance expectations that state what students can do to demonstrate their mastery of a standard. These performance expectations are based in the science and engineering practices associated with the disciplinary core ideas tied to each standard. Further, the performance expectations are linked to other standards found in common state standards for mathematics and language arts. The intent of the NGSS is that students must be able to participate in the process of exploration and investigation that underlies science, while connecting the concepts they internalize to material learned in other disciplines. Students need a platform to link learning across a variety of curricula that allows them to participate in the discovery process.

Just as with prior attempts at making science education more hands-on and exploratory, the NGSS requires the proper tools to allow students to engage with their environment in a process of discovery and refinement. To ensure that these tools can reach even the most underfunded systems, schools, and classrooms, the tools must be inexpensive (i.e., from \$100 to \$200 for a class of 25 students) and serve multiple purposes. A robotic kit provides the means by which students can control and engage their environment on their terms. A modular robotic kit provides a base that can be connected to a variety of sensors, actuators, and probes to make that engagement of the environment robust. Students can determine which modules are most appropriate for their investigation, perform the exploration, refine their results, and repeat the investigation. Thanks to modularity, the same kit can be used by a variety of curricula for different hands-on activities, thus facilitating the students to make connections among STEM disciplines.

Depending on the intensity of after school programs and subject diversity, schools might want to obtain modular robotic kits from more than one vendor. Unfortunately, there is no written standard for educational robotic kits, thus each vendor designs and creates its own standard. For example, LEGO Mindstorm [4] two-wire communication is a proprietary solution similar to I2C which is not physically compatible to VEX Robotics [5] one-wire interface. Even the physically compatible one-wire interface between two vendor-specific modules, like Bioloid [9] and VEX Robotics [5], does not implement the same communication protocol. Bioloid implements a serial multi-drop protocol that works as simultaneous input and output, while VEX Robotics can only be configured as an input or output at any one moment in time. While the ideal solution would be for all robotic kit manufacturers to agree on a single communication standard that is easy to understand, multi-lingual, and platform independent, a more practical approach is to create bridge modules. This would achieve interoperability among kits from separate vendors, thus strengthening the interconnections among different educational activities and optimizing at the same time the investment in teaching equipment for the school. Thus, we propose a list of requirements that eSMAC needs to and has already fulfilled: module-level reconfigurability, reliable communication, multi-lingual and easy-to-use software interfaces, an affordable cost, and a variety of applications suitable for NGSS-based STEM education.

III. The eSMAC Modular Robotic Kit

A. eSMAC Snap-on Modules

The eSMAC robotic kit has been designed aiming to achieve ease of use, modularity, interoperability, and low cost. Each module implements a different function and can be connected to the others thanks to three magnetic contacts that are used for synchronization, communication, and power delivery. A programmable microcontroller is integrated in each module to implement the communication protocol and the user commands specifically related to the module function.

In terms of functionality, the eSMAC modules can be classified as follow:

- *Input*: Analog or digital inputs with sensing capabilities (e.g., temperature, humidity, pressure, pushbutton)
- *Output*: Analog or digital outputs with indicators (e.g., light, sound indicators)
- *Mobility*: Analog or digital outputs with rotational or translational motion actuators (e.g., direct current brushed electric motor, direct current brushless electric motor, servomotor, muscle wire)
- *Communication*: Analog or digital interfaces to communicate among blocks (Bluetooth, Wi-Fi)
- *Powering*: Analog interface with a source of power (rechargeable battery, coin battery)

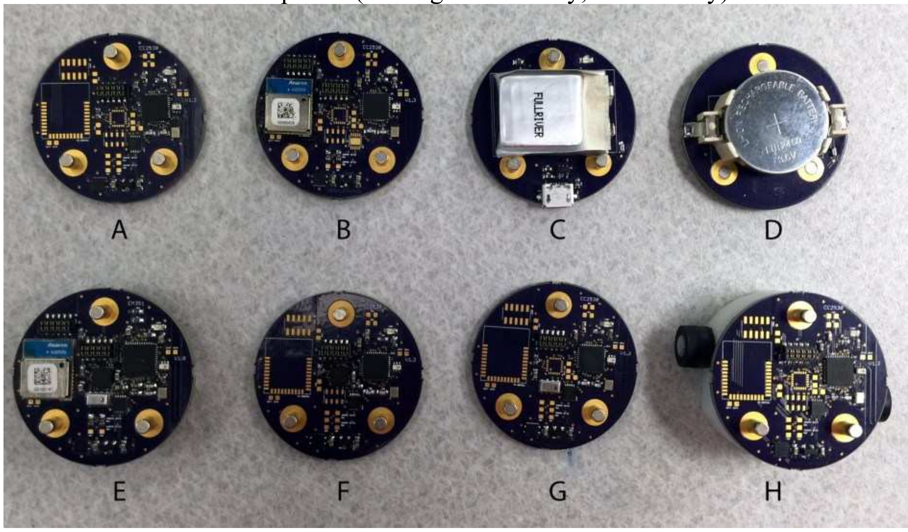


Figure 1. Selection of eSMAC functional modules: (A) Output module that can be used to drive motors, relays, or buzzers to generate sound; (B) Communication module implementing Bluetooth Low Energy (BLE); (C) Powering module with a lithium ion polymer battery and an on-board charger; (D) Powering module with a rechargeable coin cell slot; (E) Module embedding multiple functionalities (BLE, IMU, barometer, and motor driver, all powered by a rechargeable battery on the backside); (F) Input module with an inertial measurement unit (IMU); (G) Input module with a barometer; (H) Mobility module with a couple of independent brushed motors connected to rubber wheels.

A selection of eSMAC modules is represented in Figure 1. The diameter of each module is 40 mm, while the thickness ranges from 6.4 mm for the module in Figure 1.A to 19.2 mm for the one in Figure 1.H. It is worth mentioning that, for certain activities, size may become a dominant requirement over modularity. For this reason, the module represented in Figure 1.E integrates input, output, communication, and powering in a single module. A 2-wheel mobile robot composed by a powering, a communication, a mobility, and two input (barometer and IMU) modules is represented in Figure 2 next to a table tennis ball (diameter 40 mm).

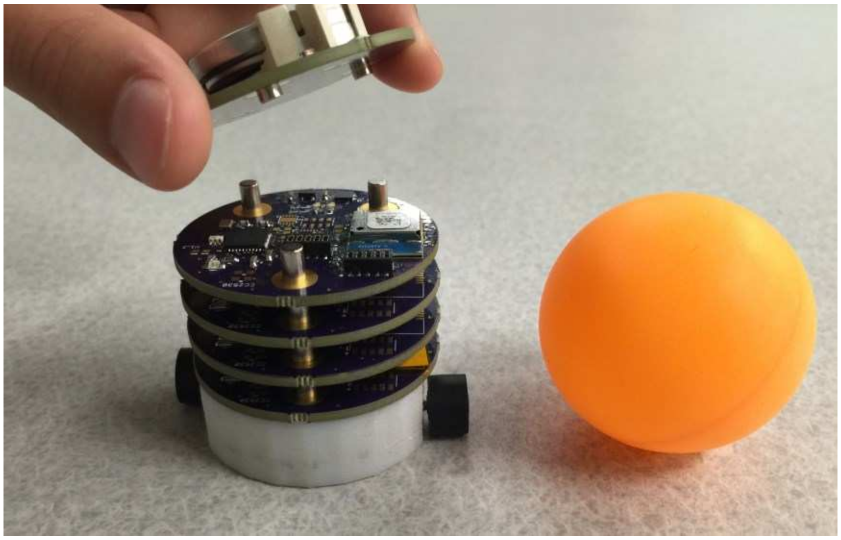


Figure 2. A 2-wheel mobile robot composed by powering, communication, mobility, and two input (barometer and IMU) modules

next to a table tennis ball (diameter 40 mm) for a reference of size.

Every time an eSMAC module is powered on, either by snapping on a battery module or snapping it onto a group of modules, it starts listening for synchronization signals. These signals contain the channel the modules are currently using, Advanced Encryption Standard (AES) encryption key for secure communication and joining the network, and synchronization period. A synchronization signal is sent periodically via the data communication point by a master module. In case a signal is not detected after a certain period of time, the module is allowed to promote itself as master, assign its own channel, and start sending its own synchronization signal. If a synchronization signal is detected, then the newly connected module will try to join the network. An example of the assembly process required to build the robot represented in Figure 2 is provided in the supplementary downloadable multimedia material.

B. Modules Connectivity and Safety

Each module was designed and built upon a fully assembled Printed Circuit Board (PCB) with three magnetic contacts embedded in it. Concerning module interconnection safety, those three magnetic contacts are placed at positions of 90 degrees (S-N polarity for data communication point), 225 degrees, and 315 degrees (dual N-S polarities for powering points) around the circular PCB, as shown in Figure 3.A. With this magnet polarity placement, snapping modules together can only be done in one way, leaving no room for errors. The dual N-S polarities for power include a resettable fuse and reverse polarity protection. Users do not need to worry about placing the battery in the wrong way, because issues arising from reverse polarity are taken care by a bridge rectifier built in every module. Battery module placement can be flipped and the rest of modules can still maintain steady power delivery as illustrated in Figure 3.B; however, with the data communication point left unconnected, the robot is disconnected from local network and becomes a standalone device.

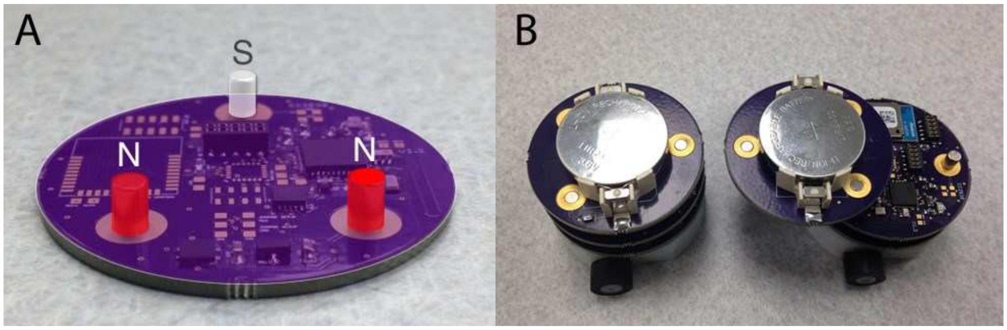


Figure 3. (A) Illustration of magnetic contact polarities; (B) Two possible ways to stack modules.

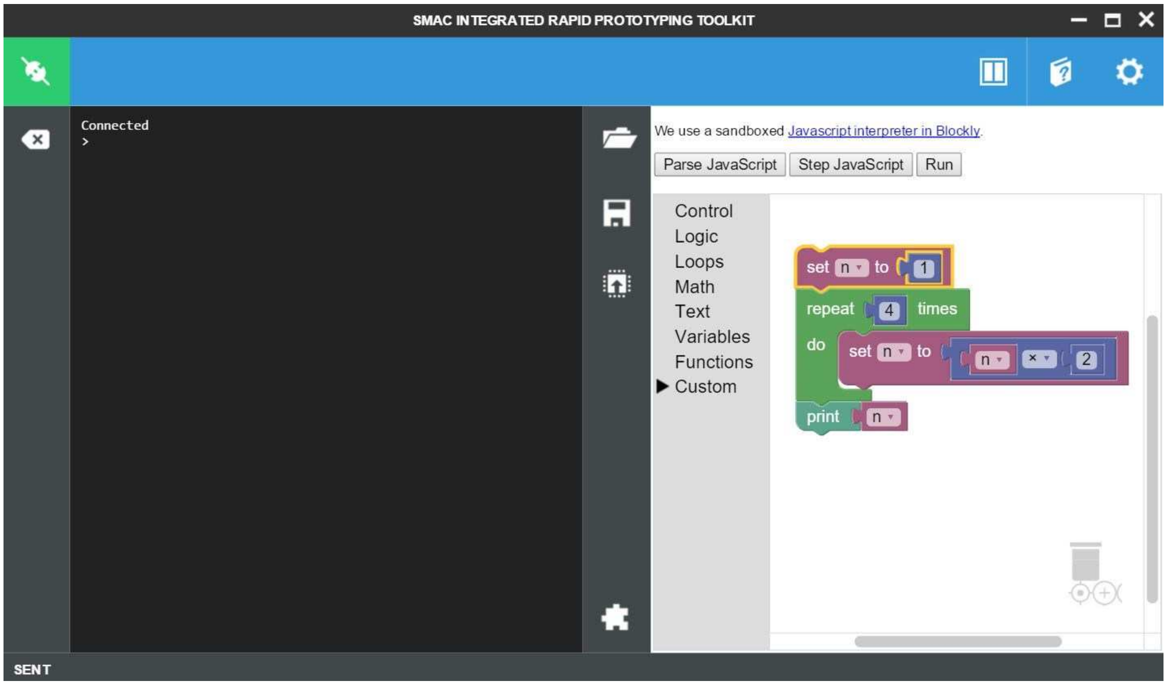
C. Software Architecture

1) Readability, Interoperability, and Multiplatform Programmability

The eSMAC software architecture is based on JavaScript Object Notation (JSON, https://developers.google.com/blockly/). This notation has been selected because it is human readable, multi-lingual, and computer platform independent. The eSMAC robots are controlled by commands in the form of JSON strings sent from controlling devices such as PC, smartphones, and tablets. This string notation can be roughly divided into two parts: a key and its properties. A key can be any configurable part of the robot, such as a light emitting diode (LED) indicator or a servomotor. The key can be configured with one or multiple properties. For example, an LED’s on/off property can be denoted in 1 (on) or 0 (off). JSON is a simple way to group data together in a straightforward manner, thus making it easy for programmers to read and understand. To illustrate this, a simple example of JSON to light up LED1 looks like this:

```
{“led1”:1}
```

JSON strings can be exchanged between devices via serial port, Bluetooth, and Wi-Fi. Each eSMAC module has a JSON interpreter, an embedded tool to parse received JSON strings. When a JSON string is received via serial port, Bluetooth, or Wi-Fi, the interpreter processes it and informs the module what to do next. This approach enhances the interoperability of eSMAC as it enables a clean-cut two-way communication between the controlling device and each module, regardless of what kind of communication channel is chosen. Another advantage worth mentioning is that JSON is completely language-independent. A variety of programming languages can be used to parse and generate JSON strings, like C. Similarly, JSON is supported by most major operating systems and platforms, including Windows, iOS, Linux and Chrome OS; this saves the drudgery of converting languages between different systems and platforms.



```
Connected
>
```

We use a sandboxed Javascript interpreter in Blockly.

Figure 4. A screenshot from the SMAC-IRP programming environment: the terminal on the left panel and Google Blockly on the right panel.

A Google Chrome app "SMAC-IRP" (Integrated Rapid Prototyping Toolkit) has been created based on the open-source Espruino environment (https://github.com/espruino/Espruino) to manipulate JSON strings. The SMAC-IRP includes a terminal window, a code editor, and Google Blockly (https://developers.google.com/blockly) with a JavaScript interpreter. The terminal window allows user to type a command in JSON and send it to the module connected to the controlling device; the process can be reversed for the module to send feedback to the controlling device. The code editor has a similar functionality except it allows users to modify the code before sending it to the module. To make the programming process more engaging for students, Google Blockly has been incorporated into SMAC-IRP. Blockly is a visual programming tool--it breaks down all programming elements into different blocks. A unit of block may represent a function or a loop; when students step through a program built by blocks, a corresponding block will be highlighted to indicate which step is currently in process. In this way, students can easily see how a program flows and understand the logic behind it. Meanwhile, what Blockly does in the background is that its JavaScript interpreter converts the blocks into actual code, which will then be processed and executed by the computer. The visual and interactive features of Blockly make it an ideal tool to teach students about basic programming. The SMAC-IRP is available for download at https://github.com/SMACproject/SMAC-IRP and is compatible with different operating systems, as long as a Chrome or a Chromium browser can be installed. A screenshot of the SMAC-IRP programming environment with Google Blockly parsing code and stepping through the program is represented in Figure 4.

2) *Synchronization*

The JSON parser used for interpreting commands and responses can also be used to parse synchronization signals. A synchronization signal is sent periodically over local/wired connection by the master module to let all of the connected modules know about the local/wired network they are joining to. This synchronization signal contains information about wireless channel/frequency, wireless AES encryption key for secure communication over wireless connection, and synchronization period. Any module connected to a master module has to listen to the synchronization signal and set all wireless radio transceiver parameters accordingly.

3) *Bluetooth Communication*

Once the JSON communication and data synchronization are set up, a Bluetooth mobile application can be used to control the functionalities of eSMAC robots. Bluetooth has many advantages for the eSMAC platform. It is low-energy and offers a reliable and private connection over large distances. Since most smartphones and tablets today are equipped with Bluetooth compatibility, this provides great flexibility for devices that can be used to control the modules.

Anaren Atmosphere Developer (https://atmosphere.anaren.com/) was used to create and design a mobile application that connects with the Bluetooth Low Energy (BLE) module on the robot. This online development environment provides a user-friendly platform to quickly create smartphone applications where the app and firmware for the chip are developed simultaneously. The developer provides a combination of a graphical user interface along with C and JavaScript coding that is easy to use, while still maintaining a wide range of functionalities. Another benefit of the Atmosphere Developer is the compatibility with many different platforms. Since the development environment is online, this allows access to the same documents from any PC with a web browser running any operating system. The Atmosphere app can be downloaded on both Apple and Android smartphones and tablets, and the Developer offers support for creating graphical layouts to fit the screen sizes for any device. These benefits make it easy to create new apps to expand the capabilities of the robots even further.

When a robot is powered up and all modules are synchronized, the Bluetooth application built with Anaren Atmosphere can send signals containing commands and data to the robot BLE module. The BLE module will send signals to the other modules through the communication point, telling them to synchronize to the same channel. Afterwards, all modules will be on the same channel and able to communicate through wireless. Then, each module who receives a command will parse it with an embedded JSON parser. In this manner, all modules will receive and process the same information sent by the Bluetooth application.

In a nutshell, all modules synchronize to the same wireless channel first. Then the master module (in this case, the BLE module) receives data in the form of JSON strings through serial port, Bluetooth or 802.15.4 wireless. Other modules then communicate and exchange data from one to another, also in the form of JSON strings, through wireless communication. The JSON strings can be used as commands, for getting feedback of sensor status, and for sensor data collection over wired or wireless connection.

D. Cost Breakdown

One advantage of eSMAC toolkit over similar robotic kits is its fairly low cost. For estimation purpose, we have given a rough cost breakdown of different modules and hardware parts of the eSMAC kit, based on a manufacture environment outside of a university research lab:

	Robot base	IMU	Barometer	BLE module	Battery	Charger	Buzzer	LED	Total
Est. Cost ($)	30	10	15	30	5	5	15	10	120

Table 1. Cost breakdown for the eSMAC toolkit.

The total estimated cost of an eSMAC toolkit is less than $150, an affordable amount for average public schools given their current budgets [20]. Furthermore, the toolkit does not need to be purchased as a whole. Teachers can choose to only purchase the parts or modules that they need, avoiding unnecessary expenses on irrelevant parts. By offering a low-cost and flexible toolkit, we hope to provide an affordable STEM education for middle and high school students.

IV. Application Examples

With the support of versatile software architecture and flexible hardware configurations, eSMAC robots have so far been implemented in a variety of hands-on applications fitting different STEM curricula.

A. Robot Soccer Game

A possible application of the eSMAC robotic kit is robot soccer. Multiple users can each control their own robot with a smartphone app to play soccer with a table tennis ball in a miniature game field, as illustrated in Figure 5 for a 2-on-2 game. As represented in Figure 5, each robots is composed of three modules implementing mobility, communication, and powering functionalities. A smartphone app has been developed with Anaren Atmosphere for the eSMAC BLE module to send JSON commands to the robots over Bluetooth. The smartphone can also receive feedback from the robot when the JSON commands are processed. The Bluetooth connection is ideal for a soccer game because it provides an exclusive point-to-point connection from the smartphone to the robot allowing several users to control their own robot and play on teams. An example of a robot soccer game implemented with eSMAC robots is provided in the supplementary downloadable multimedia material.

Playing the robot soccer game is an effective introduction to the eSMAC robots, as no prior knowledge of robotics is required. While some may question the educational merit of playing robotic soccer in a classroom, the amount of learning that can take place is definitely significant. Take for instance in a computer science classroom, object-oriented programming could easily be taught by creating a robot "class" that is responsible for controlling each robot. Then a computer science teacher could easily hand over that class to students and inform them that a "forward" in the game is indeed a soccer player, but would behave differently from a "goalkeeper", who is also of the same "class" soccer player. Therefore, students might be able to derive a subclass that inherits from the original class of "soccer player". Students could then instantiate their own players based on the classes and subclasses created. This one example would provide an opportunity for a computer science teacher to model in a tangible manner an abstract concept such as class creation in object-oriented programming.

The cost of materials to make the mini soccer game field is around USD $10 (two foam board 20x30 inches, box cutter, glue, and a table tennis ball), while the cost of a single modular soccer player is about $70 (robot base, BLE module, rechargeable battery module and battery charger).

Figure 5. Four eSMAC robots playing 2-on-2 robot soccer with a table tennis ball.

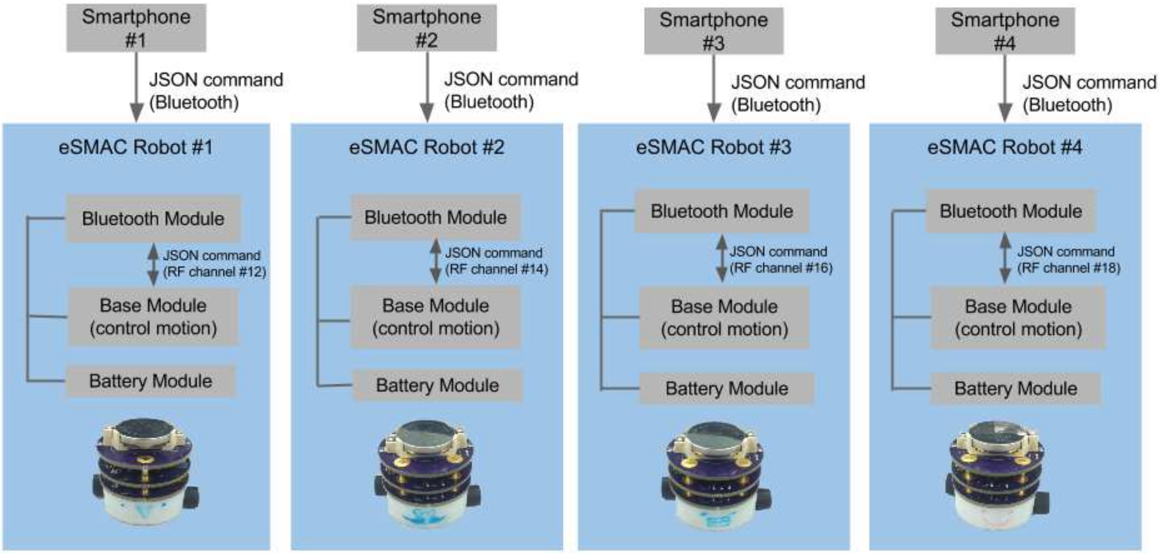


Figure 6. Diagram of modules being used to implement 2-on-2 robot soccer.

B. *The Maze Explorer*

Another application of the eSMAC robotic kit is in a maze unit plan that aligns with middle grade-level physical science standards or secondary grade-level engineering design standards. Students begin by learning about and completing mazes while reflecting on the processes they follow to run through the maze. As an introduction to robotic programming and control, the students then begin navigating the robot through a maze of their own design. They must then navigate the robot through the maze again using a pre-programmed series of steps that they calculate using basic constant velocity equations and measurements of the maze. Repeated iterations of this task instill an understanding of the challenges and limitations in programming robots. The final lesson of the unit requires the students to construct their own hypothetical robot design for navigating the maze, which they will present and defend to other classmates. In this case, the robot takes advantage of an input module (IMU or range sensing) to detect contacts with the maze walls, a mobility module, and a powering module. A picture of a maze explorer and its block diagram are represented in Figure 7.

The cost of materials to make the reconfigurable maze is around USD $10 (two foam board 20x30 inches and box cutter), while the cost of one modular maze explorer is about $50 (robot base, IMU module, rechargeable battery module, and battery charger).

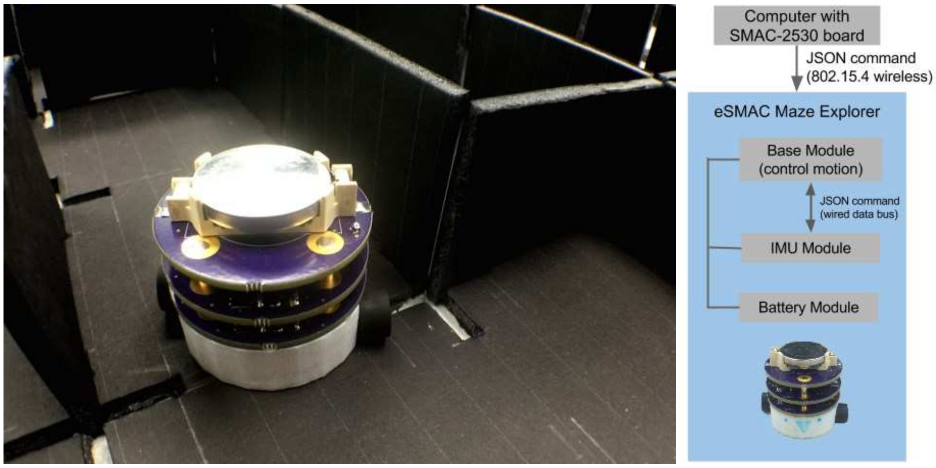


Figure 7. Maze explorer and diagram of modules being used for its implementation.

C. *Multifunctional Module for Experiments in Dynamics*

The multifunctional module represented in Figure 1.E, which includes a barometer, an IMU, BLE connectivity, and a coin cell rechargeable battery, can be inserted into a tennis ball or tied onto a water bottle rocket to measure acceleration, orientation, and altitude. Data can be transferred from the module to the student's PC once the experiment is over. The cost of the multifunctional module, represented in Figure 8 together with its block diagram, is about $40.

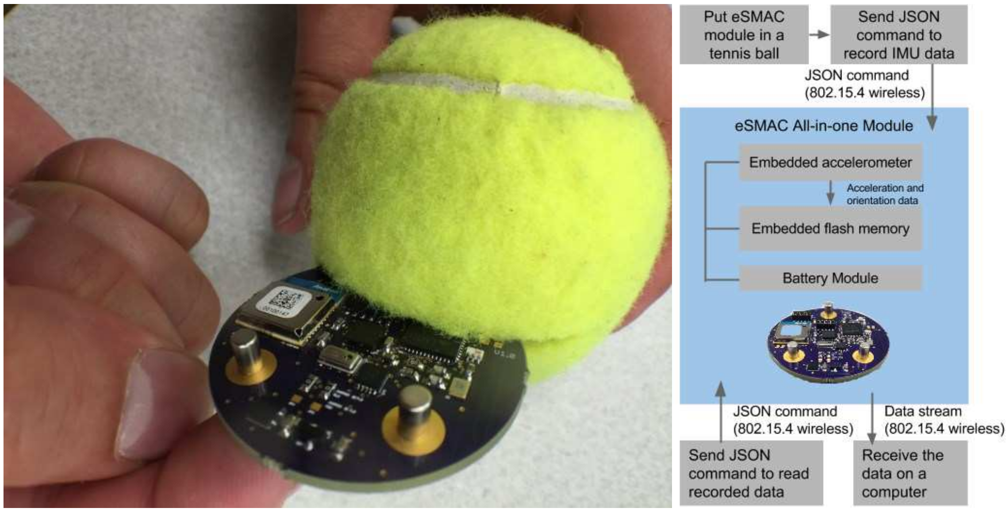


Figure 8. Multifunctional module embedded in a tennis ball and its block diagram.

With the ability to embed this multifunctional module in a tennis ball, mathematics and science teachers can collect actual data of an object in flight and use that data as a model for investigating trajectories of objects. In terms of learning outcomes, this application will help students get hands-on experience with physics concepts such as acceleration, velocity, and atmospheric pressure. With this affordable tool at the hands of teachers and students, investigations can reveal many of the standards that teachers set out to share. When students develop their own conclusions, learning becomes much richer and long lasting. The requirements set by the NGSS can be easily met using this modular equipment in a classroom.

V. Conclusions and Future Work

In this work, we have introduced for the first time the eSMAC robotic kit. This kit has been designed in collaboration with high school teachers for improving STEM education along the lines suggested by the NGSS, a new standard recently introduced in the US calling for a more effective integration in teaching scientific and engineering subjects. Thanks to a modular hardware and interoperable software architecture, the eSMAC kit can be used to engage students in different real-world experiments related to a variety of curricula. This has the potential to facilitate an integrated approach to STEM education. Another advantage of the proposed platform is the extremely low cost of the modules, which makes eSMAC an affordable teaching tool for most schools. Expected learning outcomes range from composing code for programming a robot to a deeper understanding of physical quantities and real-world experiments. Since our software is open-source, students are also welcome to download and change the source code to add functionalities they want.

Future work will progress in parallel directions: expanding the module library, enhancing the system reliability, and deploying eSMAC into the classroom. In particular, we plan to design additional modules to increase the number of experimental activities and lesson plans for STEM curricula. Next modules in our pipeline include Wi-Fi connectivity, aerial mobility with a quadrotor-inspired base, and range sensing via optical and ultrasound techniques. We also plan to implement bridge modules based on JSON to enable interoperability with LEGO Mindstorm and VEX Robotics kits. In addition, during demos of the eSMAC robots to students, we observed that the robot plastic base, which contains the motors, is not robust enough for an extensive classroom use. The same concern also applies to the unprotected PCBs. To enhance the overall physical reliability of the toolkit, we plan to design and include durable transparent cases for each module. In the future, we will deploy eSMAC robotic kits into a number of local high schools, aiming at collecting a quantitative analysis of the educational outcomes. In particular, students will be evaluated to compare cognitive gains on standardized science and math tests, and attitudes toward careers in research science, college admission, and choice of major. Student data will be divided into two groups: students in math and science sections using the eSMAC robots and students in math and science sections using traditional textbook and lab kits. Both groups will complete the survey and relevant standardized test at the beginning and end of the semester. The results will be compared to quantify the impact of the eSMAC robotic kit.

Acknowledgment

This work was supported by the National Science Foundation under Grants CNS-1239355, IIS-1453129, and IIP-1506285. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors wish to thank Dr. Vicki Metzgar and the Middle Tennessee STEM Innovation Hub for the invaluable support along the way.

References

1. A. Bidwell, “Report: STEM job market much larger than previously reported,” U.S. News & World Report, February 2014. Internet: http://www.usnews.com/, [July 21, 2015].
2. Georgetown University’s Center on Education and the Workforce, “2011 STEM report.” Internet https://cew.georgetown.edu/report/stem/, [July 21, 2015].
3. S. Bruder and K. Wedeward, “Robotics in the classroom,” IEEE Robotics & Automation Magazine, vol. 10, pp. 25-29, September 2003.
4. “LEGO Mindstorm.” Internet: http://mindstorm.lego.com/, [July 21, 2015].
5. “VEX Robotics.” Internet: http://www.vexrobotics.com/, [July 21, 2015].
6. “Fishertechnik.” Internet: http://www.fischertechnik.de/en/Home.aspx/, [July 21, 2015].
7. D. Kee, “Educational robotics -- Primary and secondary education,” IEEE Robotics & Automation Magazine, vol. 18, pp. 16-99, December 2011.
8. “Kondo.” Internet: http://kondo-robot.com/, [July 21, 2015].
9. “Bioloid.” Internet: http://www.robotis.com/xe/bioloid_en, [July 21, 2015].
10. “Cubelets.” Internet: http://www.modrobotics.com/cubelets/, [July 21, 2015].
11. “K-Team”. Internet:www.k-team.com, [Nov 16, 2015]
12. M. Rubenstein, B. Cimino, R. Nagpal, J. Werfel, “AERobot: an affordable one-robot-per-student system for early robotics education,” In Proc. of the 2015 IEEE International Conference on Robotics and Automation (ICRA), pp. 6107-6113, May 2015.
13. “iRobot.” Internet: http://www.irobot.com/About-iRobot/STEM.aspx, [July 21, 2015].
14. “Boe-Bot.” Internet: https://www.parallax.com/product/boe-bot-robot, [July 21, 2015].
15. “littleBits.” Internet: littleBits.cc, [Nov 16, 2015].
16. M. Beccani, E. Susilo, C. Di Natali, P. Valdastri, “SMAC — A modular open source architecture for medical capsule robots,” International Journal of Advanced Robotic Systems, vol. 11, pp. 1-16, November 2014.
17. A. Taddese, M. Beccani, E. Susilo, P. Volgyesi, A. Ledeczi, P. Valdastri, “Toward rapid prototyping of miniature capsule robots”, In Proc. of the 2015 IEEE International Conference on Robotics and Automation (ICRA), pp. 4704-4709, May 2015.
18. “The Next Generation Science Standards.” Internet:http://www.nextgenscience.org/, [July 21, 2015].
19. “Vernier Software & Technology.” Internet: http://www.vernier.com/, [July 21, 2015].
20. C. Piehler, “Survey: Teachers Spend $500 a Year of Their Own Money on Classroom Supplies.” Internet: https://thejournal.com/articles/2015/07/23/survey-average-teacher-spends-500-out-of-pocket-on-classroom-supplies.aspx, [Nov 15, 2015].