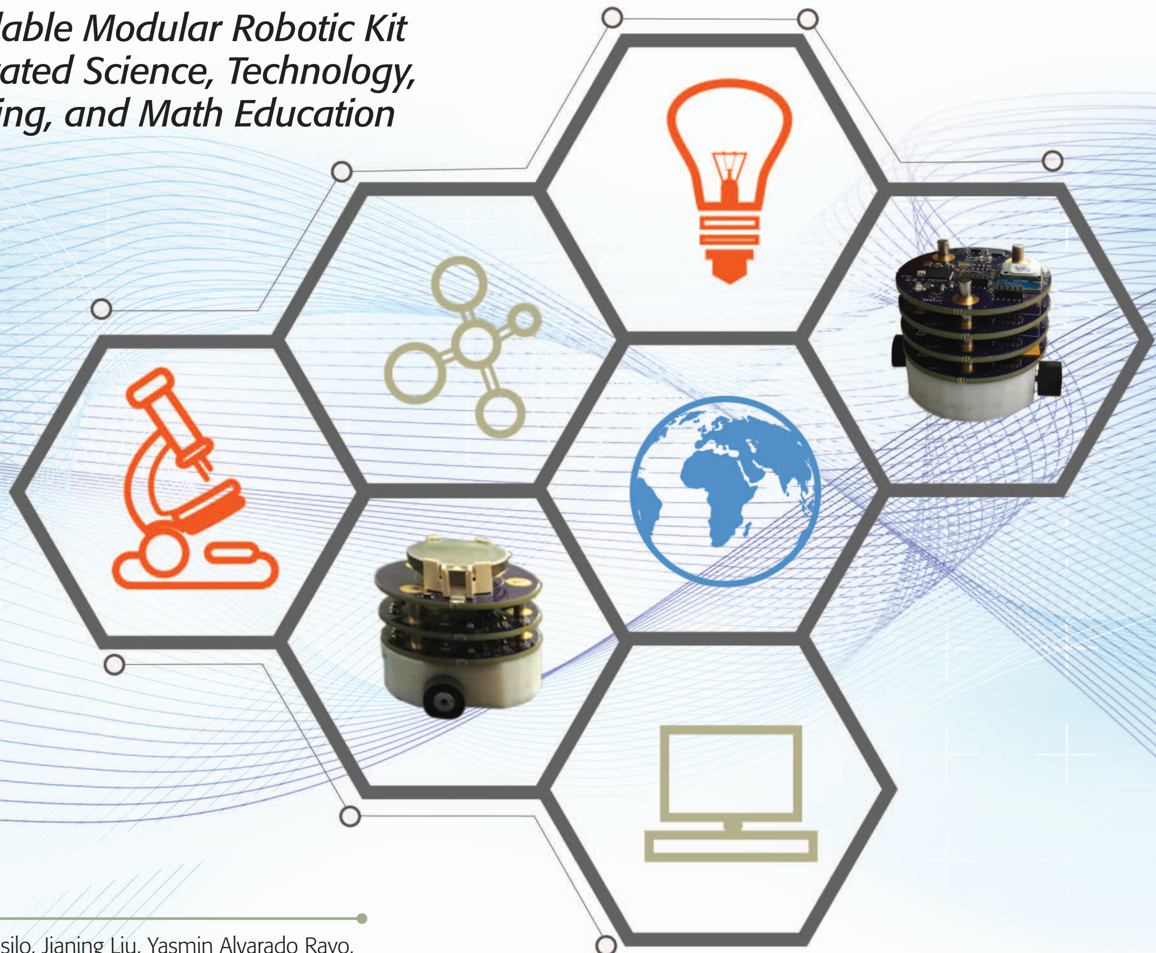
# STORMLab for STEM Education

## *An Affordable Modular Robotic Kit for Integrated Science, Technology, Engineering, and Math Education*





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The demand for graduates in science, technology, engineering, and math (STEM) has steadily increased in recent decades. In the United States alone, jobs for biomedical engineers are expected to increase by 62% by 2020, and jobs in software development and medical science are expected to increase by 32% and 36%, 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 LEGO Mindstorm [4], VEX Robotics [5], and Fischertechnik [6], are composed of 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.

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**The robots can be programmed through a web-based user interface installed either as a plug-in or an app on the Google Chrome browser.**

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 it lacks programmability, thus limiting students' ability to learn about coding.

In this article, we introduce the educational STORMLab Modular Architecture for Capsules (eSMAC) robotic kit, a low-cost and interoperable robotic kit with a variety of functional modules that can be easily connected together with a snap-on three-wire magnetic connection. eSMAC robots have a 40-mm diameter cylindrical footprint, with functional modules that can be stacked on top of one another. 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 plug-in or an app on the Google Chrome browser. At the time of publication, 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] that aims to reduce 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.

## Role of Robotic Kits in Next-Generation Science Standards

Here, we focus on the recent reform of STEM education in the United States that is occurring with the introduction of next-generation science standards (NGSS) [18] and on the role that robotic kits may play in this new framework. This shift in paradigm for education is specific to the United States, but 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 United States has been an ongoing point of concern for policymakers and educators since the 1957 launch of the Soviet satellite *Sputnik*. Ever since then, there has been a consistent push to ensure that students graduate prepared to join and lead jobs in scientific and technological research and innovation. Beginning in the 1990s, coordinated efforts by the National Science Foundation (NSF), other research-oriented groups, and teacher educators led to the piecemeal adoption of science standards that emphasize doing science using rote memorization of facts. Teachers were encouraged to make lessons inquiry based and hands-on rather than rely 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 US$350. For a school to stock a single science classroom with ample motion detectors for a class of 25 students to have enough to use in groups, the school would need to spend around US$2,000. This is a prohibitive amount for U.S. urban or rural public schools, as well as for the average suburban private school, especially given the fact that nowadays school teachers are spending an average of US$500 of their own money on classroom supplies [20].

Most STEM teaching and learning in K–12 grades in the United States has focused on science and mathematics but very little on technology and engineering. Even in schools that teach all four subjects, all are taught as separate subjects instead of as an integrated curriculum. This situation will eventually change with new reforms in teaching and learning methods, placing more connection among STEM disciplines. In April 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 that students know how to accomplish science, the NGSS outline performance expectations that state how students can demonstrate their mastery of a standard. These performance expectations are based on the science and engineering practices associated with the disciplinary core ideas tied to each standard. Furthermore, 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 and connect 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 require 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 US$100 to US$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 those modules that 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 ease with which students can make connections among STEM disciplines.

Depending on the intensity of after-school programs and subject diversity, schools may wish 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 a VEX Robotics [5] one-wire interface. Even the physically compatible one-wire interface between two vendor-specific modules, such as Bioloid [9] and VEX Robotics [5], does not implement the same communication protocol. Bioloid implements a serial multidrop protocol that works as simultaneous input and output, whereas VEX Robotics can only be configured as an input or output at any one moment in time. Although the ideal solution would be for all robotic kit manufacturers to agree on a single communication standard that is easy to understand, multilingual, 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 must and has already fulfilled: module-level reconfigurability, reliable communication, multilingual and easy-to-use software interfaces, an affordable cost, and a variety of applications suitable for NGSS-based STEM education.

## The eSMAC Modular Robotic Kit

### *eSMAC Snap-On Modules*

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

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

- input: analog or digital inputs with sensing capabilities (e.g., temperature, humidity, pressure, push button)
- 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 (dc) brushed electric motor, dc 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).

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

**Most STEM teaching and learning in K–12 grades in the United States has focused on science and mathematics but very little on technology and engineering.**

Every time an eSMAC module is powered on, either by snapping on a battery module or snapping it onto a group of modules, it begins to listen for synchronization signals. These signals contain the channel that the modules are currently using, an advanced encryption standard (AES) encryption key for secure communication and joining the network, and synchronization period. A synchronization signal is sent periodically via a data

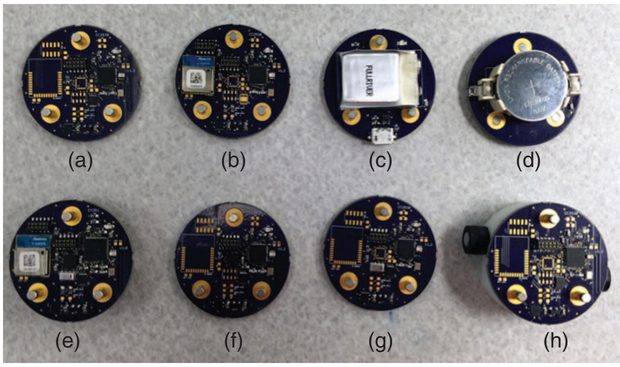


**Figure 1.** A selection of eSMAC functional modules. (a) The output module can be used to drive motors, relays, or buzzers to generate sound; (b) communication module implements BLE; (c) powering module with a lithium ion polymer battery and an onboard charger; (d) powering module with a rechargeable 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 IMU; (g) input module with a barometer; and (h) mobility module with two independent brushed motors connected to rubber wheels.

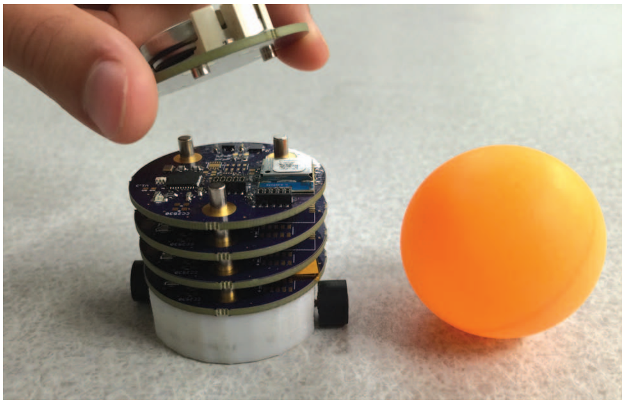

**Figure 2.** A two-wheel mobile robot composed of powering, communication, mobility, and two input (barometer and IMU) modules next to a table-tennis ball (diameter 40 mm) for a size comparison.

communication point by a master module. If 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, 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.

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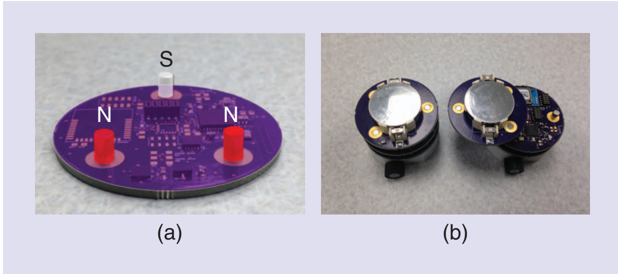


**Figure 3.** (a) A photo of magnetic contact polarities and (b) two possible ways to stack modules.

### *Module Connectivity and Safety*

Each module is designed and built on a fully assembled printed circuit board (PCB) with three magnetic contacts embedded in the PCB. For module interconnection safety, those three magnetic contacts are placed at positions of 90° (S–N polarity for data communication point), 225°, and 315° (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 checked by a bridge rectifier built into 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 the local network and becomes a stand-alone device.

### *Software Architecture*

#### Readability, Interoperability, and Multiplatform Programmability

eSMAC software architecture is based on JavaScript Object Notation [(JSON) https://developers.google.com/blockly). This notation was selected because it is human readable, multilingual, and computer-platform independent. eSMAC robots are controlled by commands in the form of JSON strings sent from a controlling device such as a personal computer (PC), smartphone, or tablet. 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 presents a simple way to group data together in a straightforward manner, making it easy for programmers to read and understand. To illustrate this, a simple example of JSON to light up LED1 is represented by {"led1":1}.

JSON strings can be exchanged among devices via serial port, Bluetooth, or 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 the string and informs the module of the next step. This approach enhances the interoperability of eSMAC, because it enables a clean-cut two-way communication between the controlling device and each module, regardless of the type of communication channel chosen. Another advantage worth mentioning is that JSON is completely language independent. A variety of programming languages, such as C, can be used to parse and generate JSON strings. Similarly, JSON is supported by most major operating systems (OSs) and platforms, including Windows, iOS, Linux, and Chrome OS; this saves the drudgery of converting languages for different systems and platforms.

The Google Chrome app Integrated Rapid Prototyping Toolkit (SMAC-IRP) has been created based on the open-source Espruino environment (https://github.com/espruino/Espruino) to manipulate JSON strings. 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 a user to type a command in JSON and sends 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 that 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 that 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 the step currently in process. In this way, students can easily see the way in which a program flows and understand the logic behind it. Meanwhile, in the background Blockly's JavaScript interpreter converts the blocks into actual code that can then be processed and executed by the computer. The visual and interactive features of Blockly make it an ideal tool to teach students 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 Chromium browser can be installed. A screenshot of the SMAC-IRP programming environment with Google Blockly parsing code and steps through the program is presented in Figure 4.

## 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 a local/wired connection by the master module to inform all of the connected modules which local/wired network that they will join. This synchronization signal contains information about wireless channel/frequency, the wireless AES encryption key for secure communication over the 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.

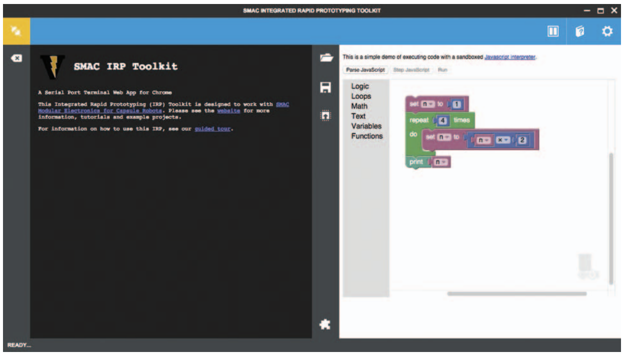


**Figure 4.** A screenshot from the SMAC-IRP programming environment, with the terminal in the left panel and Google Blockly in the right panel.

## Bluetooth Communication

Once 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, including low energy and a reliable and private connection over large distances. Because 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 in which the app and firmware for the chip are developed simultaneously. The developer provides the combination of a graphical user interface along with C and JavaScript coding that is easy to use and maintains a wide range of functionalities. Another benefit of the Atmosphere Developer is compatibility with many different platforms. Because 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 screen sizes of 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

**Table 1. Cost breakdown for the eSMAC toolkit.**

| | Robot base | IMU | Barometer | BLE module | Battery | Charger | Buzzer | LED | Total |
|---|---|---|---|---|---|---|---|---|---|
| Estimated Cost (US$) | 30 | 10 | 15 | 30 | 5 | 5 | 15 | 10 | 120 |

the other modules through the communication point, instructing them to synchronize to the same channel. After this, all modules will be on the same channel and able to communicate through wireless. Then, each module that receives a command will parse it with an embedded JSON parser. In this manner, all modules 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 a serial port, Bluetooth, or 802.15.4 wireless. Other modules then communicate and exchange data, also in the form of JSON strings, through wireless communication. JSON strings can be used as commands, for receiving feedback of sensor status, and for sensor data collection over a wired or wireless connection.

### *Cost Breakdown*

A low-cost and flexible toolkit can help to provide an affordable STEM education for middle and high school students. One advantage of the eSMAC toolkit over similar robotic kits is its fairly low cost. For estimation purposes, we give a rough cost breakdown in Table 1 of different modules and hardware parts of the eSMAC kit, based on a manufacture environment outside of a university research lab. The total estimated cost of an eSMAC toolkit is less than US$150, an affordable amount for average public schools given current budgets [20]. In addition, the toolkit does not need to be purchased as a whole: Teachers can buy only those parts or modules that they need and avoid unnecessary expenses for irrelevant parts.

## 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.

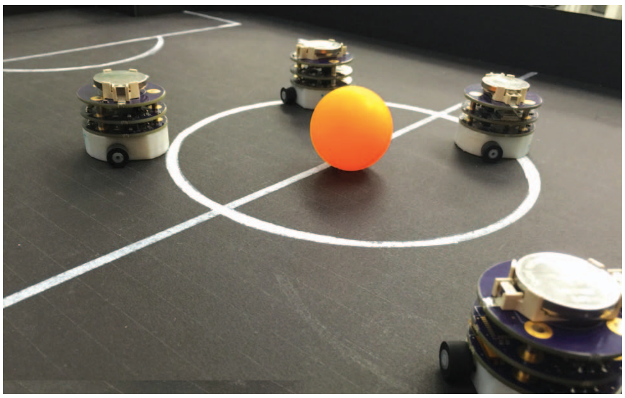

**Figure 5.** Four eSMAC robots playing two-on-two robot soccer with a table-tennis ball.

### *Robot Soccer Game*

One possible application of the eSMAC robotic kit is robot soccer. Multiple users each control their own robot with a smartphone app to play soccer with a table-tennis ball in a miniature game field, as seen in Figure 5 for a two-on-two game. Each robot is composed of three modules implementing mobility, communication, and powering functionalities. A smartphone app developed with Anaren Atmosphere for the eSMAC BLE module sends JSON commands to the robots using 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. See Figure 6 for block diagrams used for two-on-two soccer. An example of a robot soccer game implemented with eSMAC robots is provided in the supplementary downloadable multimedia material.

Playing robot soccer is an effective introduction to eSMAC robots, because no prior knowledge of robotics is required. Although some may question the educational merit of playing robotic soccer in a classroom, the amount of learning that can take place is significant. 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. A computer science teacher could then easily hand over that class to students and inform them that a forward in the game is indeed a soccer player, but it would behave differently from a goalkeeper, who is also of the same class soccer player. Students may be able to derive a subclass that inherits from the original class of soccer player and then instantiate their own players based on the created classes and subclasses. This example illustrates an opportunity for a teacher to model, in a tangible manner, an abstract concept such as class creation of object-oriented programming. The cost of materials to create the mini-soccer game field is approximately US$10 (two 20×30-in foam boards, box cutter, glue, and table-tennis ball), and a single modular soccer player costs about US$70 (robot base, BLE module, rechargeable battery module, and battery charger).

### *The Maze Explorer*

Another application of the eSMAC robotic kit is in a maze unit plan that aligns with middle-grade-level

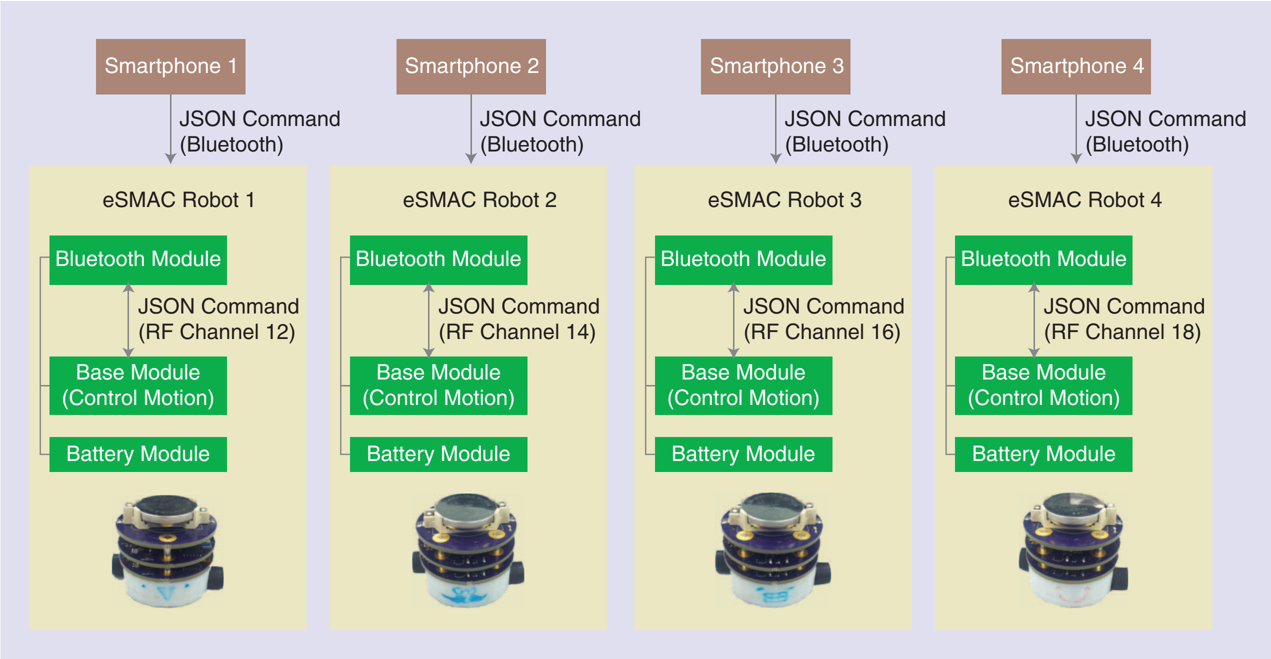


**Figure 6.** A diagram of modules used to implement two-on-two robot soccer.

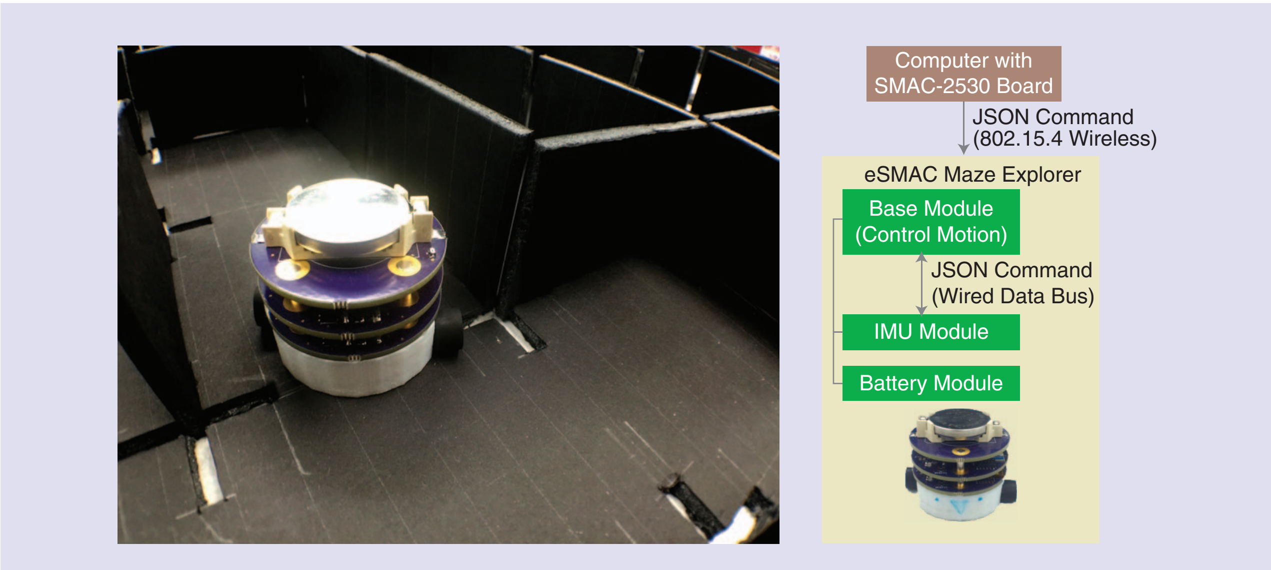


**Figure 7.** A maze explorer and diagram of modules used for its implementation.

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 begin navigating the robot through a maze of their own design. They must then navigate the robot through the maze again, using a preprogrammed 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 then 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 maze explorer and its block diagram are shown in Figure 7. The cost of materials to create the reconfigurable maze is about US$10 (two $20 \times 30$-in foam boards and box cutter), and one modular maze explorer costs approximately US$50 (robot base, IMU module, rechargeable battery module, and battery charger).

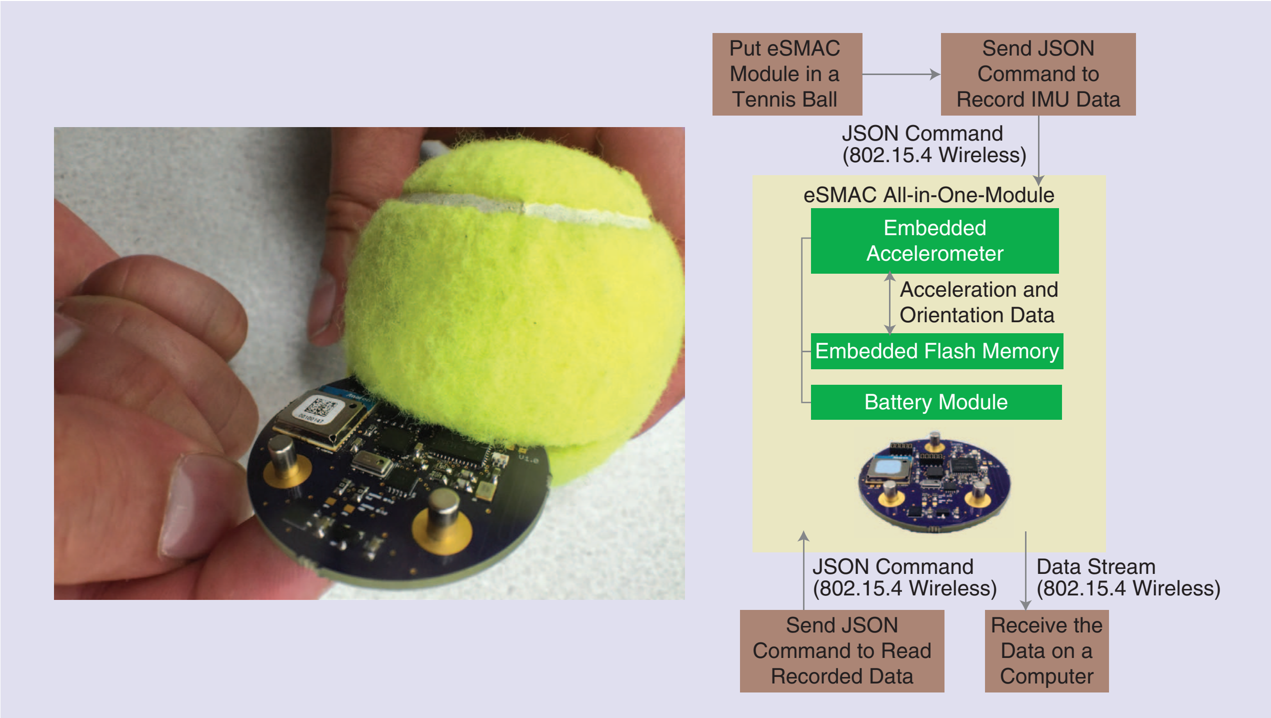


**Figure 8.** A multifunctional module embedded in a tennis ball and its block diagram.

### *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 a 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 US$40.

With the ability to embed this multifunctional module in a tennis ball, mathematics and science teachers can collect actual data from an object in flight and use that data as a model for investigating trajectories of objects. In terms of learning outcomes, this application offers students hands-on experience with physics concepts such as acceleration, velocity, and atmospheric pressure. Investigations using this affordable tool can reveal to students many 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.

> **Thanks to 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.**

## Conclusions and Future Work

The eSMAC robotic kit is designed in collaboration with high school teachers for improving STEM education along the lines suggested by NGSS, recently introduced in the United States, that call for a more effective integration when teaching science and engineering. Thanks to 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. Because the software is open source, students can download and change the source code to add functionalities of their choosing.

Future work will progress in parallel directions to expand the module library, enhance system reliability, and deploy 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. The 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 extensive classroom use. The same concern also applies to unprotected PCBs. To enhance the overall physical reliability of the toolkit, we plan to design and include durable transparent cases for each module. We will deploy eSMAC robotic kits into a number of local high schools to collect a quantitative analysis of 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 textbooks and lab kits. Both groups will complete a survey and relevant standardized tests at the beginning and end of the semester. Results will be compared to quantify the impact of the eSMAC robotic kit.

## Acknowledgments
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