Development and Results from User Testing of a Novel Robotics Kit Supporting Systems Engineering for Elementary-Aged Students

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***Abstract*— This paper describes the development of Flutter, a new sensor-driven, robotics technology kit for in-school use with elementary-age students. Our development began by conducting focus groups with teachers (N=6) in which we guided a participatory design process. Through affinity diagramming, we identified science and math as areas of focus for the program; we also brainstormed project-topics with the teachers. The Flutter Kit is controlled by an app that allows for touch based interactions and enables the kits to be programmable by tablets. The app interface, developed with teachers through the use of paper and digital prototypes, builds on the concept of data flow from an input to an output and emphasizes the use of sensor data for creating interactive devices. The central element of the Flutter hardware is a custom microcontroller board that connects to the tablet app via bluetooth; permits students to log sensor data; and controls a buzzer, three sensor ports, three tricolor LEDs, and three servo ports. From observations of four pilot classes (N=84) and student interviews, we generated ideas for future improvements to the system, such as: hardware changes for ease of use and changes to the curriculum to support students' data analysis skills.**

Keywords—educational robotics; elementary school; focus groups; systems engineering

I. Introduction

It is critical to engage children as creators and innovators with technology, such that they develop the skills and mindsets to be technologically fluent makers and members of our increasingly information driven society. Unfortunately, in education settings, children are frequently relegated to the role of technology consumers. By providing experiences investigating data and creating technology solutions to students, we believe that we can support them in the skills, knowledge, and attitudes required to use technology creatively. By working with students at a young age, when they have had less time to be impacted by societal influences, we believe we can engage all students in a meaningful way with technology, including members of traditionally underrepresented groups. Flutter, our sensor-driven, robotics kit, is designed for in-school elementary use and to support these experiences.

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In this paper, we describe the goals of the Flutter project as determined by early focus groups with teachers. We then describe the current state of the program's hardware kit, software application, and curriculum tools. This paper ends with a description, analysis, and discussion of our participatory design process including teacher focus groups and three classroom pilot studies.

II. Related Works

Some educational robotics platforms such as LEGO WeDo involve students in the process of robot design and engineering through robotics kits. LEGO WeDo targets elementary students, ages 7 and older. The LEGO WeDo 2.0 system, which is programmable with a tablet interface using bluetooth low energy, has a built in LED output and two ports that can be connected to motors, motion sensors, or tilt sensors [1].

Many educational robotics platforms such as Ozobot [2], Dash-Dot [3], Bee-Bot [4], and Finch [5] feature pre-constructed mobile robots. These focus on computer science and computer programming activities and eliminate time spent designing, prototyping, and constructing physical robots.

One example of a system that supports and develops student design and engineering skills is littleBits, which allows users with little electrical engineering experience to build circuits using small modular, circuit-board-mounted components with magnetic couplers that provide polarized connections [6].

Engineering is Elementary is a system of 20 curriculum units for integrating engineering into a variety of elementary classroom science topics. These units incorporate lesson plans and assessments around an engineering design activity which include a materials kit with some construction materials and supplies needed for implementation [7].

The Vernier Sensing System with LabQuest 2 Data Logger is most often used in high school classes and provides students with sensing, data collection, and graphing experience without the programmable robot or engineering design aspects of others [8].

In our prior project, Arts & Bots, we developed an educational robotics tool for middle school students based on custom hardware and programming tools, craft materials, and teacher training [9], [10]. The Arts & Bots program has been successfully integrated into non-technical middle school classes, including English Language Arts and Health and Physical Education [11]. Evaluation results from our middle school robotics program led us to develop a new sensor-driven, robotics technology kit for elementary-age students [12].

Our prior work developing the Hummingbird Microcontroller used in Arts & Bots has helped inform the creation of the Flutter Microcontroller, specifically initial output selection, port differentiation, and port connector type [13]. Our prior work developing the CREATE Lab Visual Programmer software for Arts & Bots has helped inform our development of the Flutter Links application [14]. Our goals in the development of that software programming environment were the creation of an app that: 1) supported Computational Thinking, 2) supported Classroom Compatibility, 3) had a Low Barrier-to-Entry, and 4) permitted Compelling Behaviors. The goals of the Flutter program and themes of the Flutter Links app described below build on this work.

III. Program Goals

We began our development by conducting focus groups with teachers (N=6). Through affinity diagramming [15], we identified science and math as the areas of focus for the program, specifically: data and graphing skills, measurement skills, reasoning skills, and thought process explanation practice. Our primary goals are as follows:

1. *Student Confidence with Technology* - Flutter aims to support students in developing confidence using technology to explore and solve problems that interest them.
2. *Student Knowledge of Systems and Sensing* - Flutter aims to support students in developing a systems mindset by supporting their understanding of inputs and outputs in systems through our concrete tools and understanding how sensors can be used to measure and document phenomena.
3. *Applied Data Analysis and Graphing* - Flutter aims to support students in understanding how to take sensor data and create meaningful graphs, analysis, and narratives explaining what the data collected means, all for real-world, hyper-locally collected data.
4. *Engaging and Interactive Robots* - Flutter aims to act as a tool and medium that permits students to express, demonstrate, and explain this sensor data and the phenomena that they are studying to others, through the creation of creative, engaging, and interactive robotic sculptures.

The Flutter program revolves around achieving these goals through the implementation of our hardware, software and professional development tools towards a project-based learning experience for the students. This provides students with opportunities for experimentation, self-directed exploration, and failure but also scaffolds to ensure that students are learning necessary content. In the following section, we detail the design of the Flutter program as a result of our teacher focus groups, describing the intended features and function of the hardware, software, and curricular tools that we have developed.

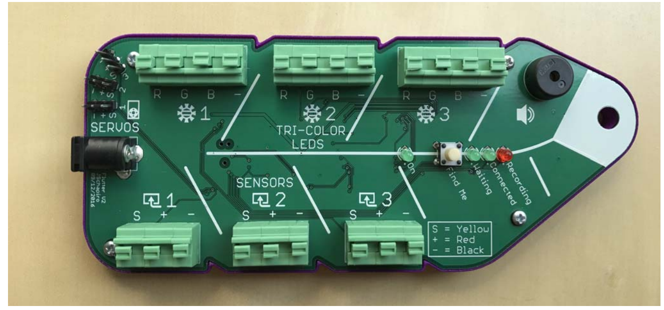

Fig. 1. Flutter microcontroller board.

IV. Program Description

These four goals of the Flutter program are each addressed in part and enabled by the current program hardware, software, and curriculum. The main components of the Flutter program are a hardware kit with a custom microcontroller, a custom android app programming tool, and a set of curriculum and teacher training tools and models.

A. *Hardware Features*

The central element of the Flutter hardware is a custom microcontroller board that controls a buzzer, three sensor ports, three tricolor LEDs, and three servo ports; connects to the tablet app via bluetooth; and permits students to log sensor data. The board design supports students' needs for creating engaging robots with interactions based on one-to-one relationships between the sensors and outputs, while supporting the development of systems thinking skills. Additionally, students collect data from the various environmental sensors, supporting their study of world phenomena through the use of scientific measurements and practice of data analysis and graphing.

Based on information gathered during our focus groups as well as our past projects, we incorporated a key in the board's silkscreening for easy reference, indicating what color wires corresponded to each port on the Flutter board, that is, yellow for signal and black for negative power (Fig. 1).

The board design is largely the result of our experience designing the Hummingbird for middle school students in combination with focus group discussions. The Flutter board itself is physically larger than the Hummingbird board, enabling the text and icons indicating the location of hardware ports to be larger and the push button connectors for the tri-color LEDs and sensors to be larger and further spaced apart. We also limited the inputs and outputs available on the board to 3 analog sensors, 3 servos, and 3 tri-color LEDs. This lowers the potential for overstimulation when introducing the board in a classroom when compared to the larger variety and number of inputs and outputs available with the Hummingbird. The inputs and outputs are visually separated on the board, each

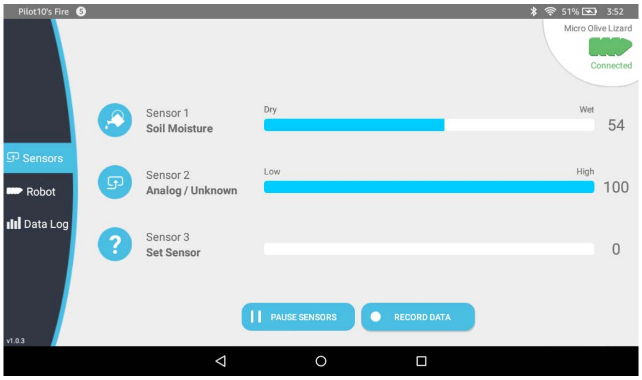

Fig. 2. View of sensor outputs, as used in Pilot 3.

primarily located on one side. There is also a 3-D printed case used to create a more stable base for the students when they are pressing down on the connection ports to insert the wires.

B. Software Features

The Flutter Kit is controlled by a tablet-based app. From conversations with teachers, we learned that students in our target age group (6-12-year-olds) are more comfortable using touchscreens. In order to lower the threshold of accessibility for Flutter use and interaction, we chose to base our app on a tablet and connect to the Flutter board via bluetooth. This enabled students to program the board with touch screen interaction. For example, Fig. 4 shows the four settings students must consider when configuring an LED. In addition, tablet-based programming eliminates the need for laptops or desktops which reduces the overall program cost.

The app identifies each Flutter by a name that is generated from the MAC address of the Flutter's bluetooth chip. Each name is composed of two adjectives and an animal type (e.g. Inspiring Sapphire Horse). The chosen first, middle, and last name originate from a list of 64, 64, and 256 names, respectively. This naming scheme guarantees a unique name for every possible MAC address from the specific bluetooth chip manufacturer.

During the focus group, we tested paper prototype app interfaces with the teachers to refine the process and interactions. The app interface builds on the concept of data flow from an input to an output and emphasizes the use of sensor data for creating interactive devices. The app design

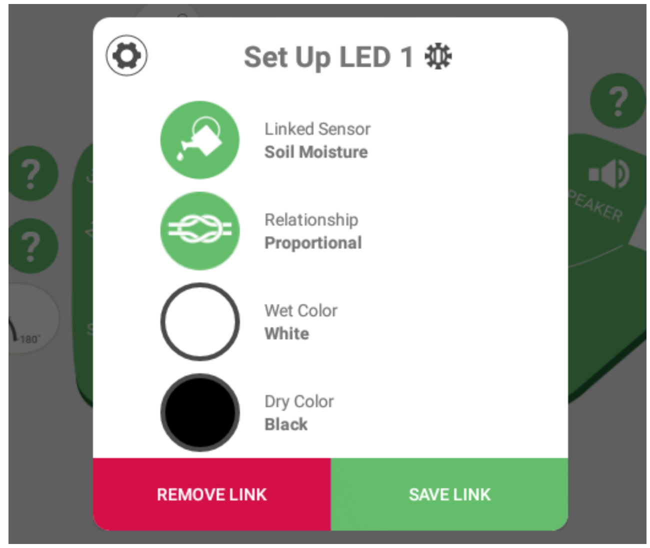

Fig. 4. The control for configuring a relationship between a sensor and output. Tapping any of the four elements allows the user to configure settings for that element of the relationship.

employs real-world grounding, using visual similarities between the physical hardware and the app design to communicate app functionality (Fig. 3). Sensor values update on the app display in real-time to make interaction with sensors easy to understand (Fig. 2). Anything programmed on the app is stored on the board, meaning that the board can continue running the program without a tablet, any tablet with the app can connect to the board, and the board retains the program even if it gets unplugged.

The final feature of the system is the ability to record sensor data over a configurable time period and then view recorded data logs (Fig. 5).

C. Curriculum Features

The curricula developed currently integrate well into science and math classes, with hands on data collection, science experiments, and robot design. Teachers have flexibility in designing their curriculum to meet their lesson goals. The projects developed are geared toward open-ended problem solving and utilize scaffolding as an approach to technology integration.

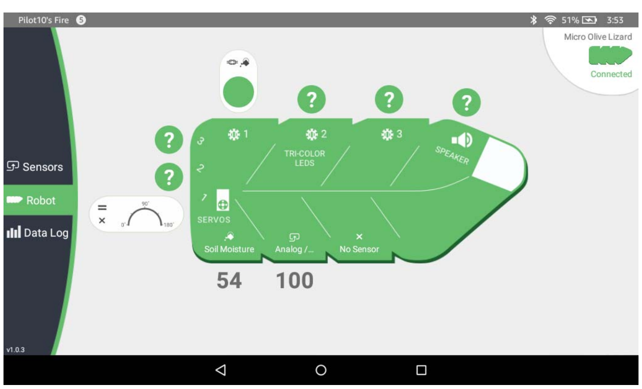

Fig. 3. Screenshot of the Flutter app as used in Pilot 3. This screen allows students to configure relationships between inputs and outputs. Clicking on one of the question marks opens a control panel (Fig. 4).

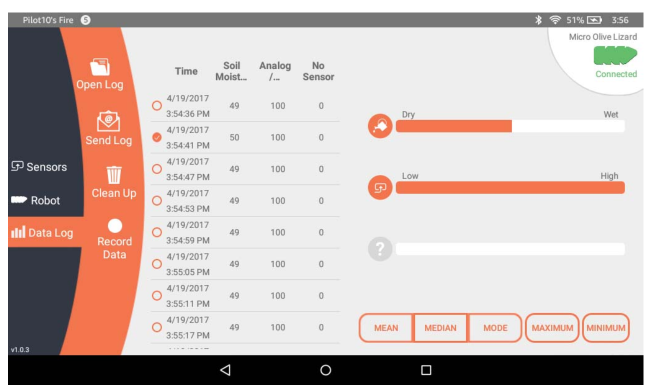

Fig. 5. Screenshot of the Flutter app as used in Pilot 3. Students can record data and display logs of recorded data.

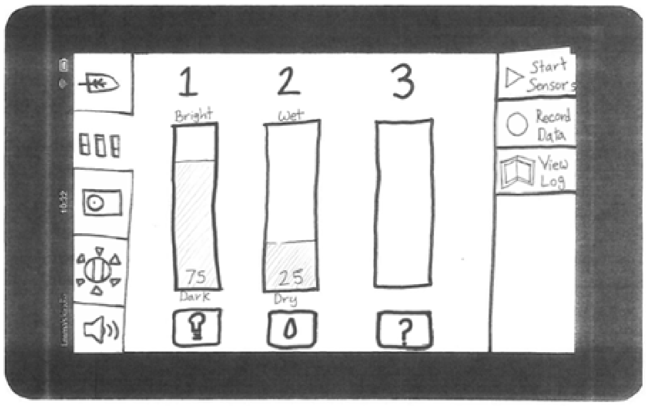

Fig. 6. Example screen from paper prototype used in focus group design session.

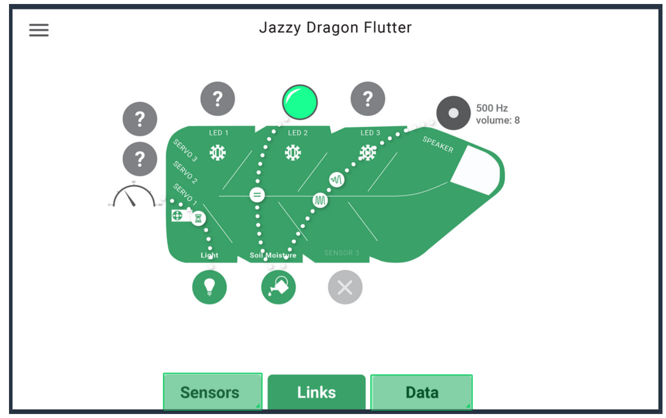

Fig. 7. Screen from one of the two digital prototypes used during focus groups.

V. Methods

We scheduled four focus groups to occur in the summer and fall of 2016. All participants were elementary school (K-6) teachers. For the focus groups, teachers were selected based on availability and grade level. Three to four weeks were scheduled between each focus group to allow for board and app design iteration. We collected notes and drawings done by the focus group participants as well as observation notes written by researchers.

We scheduled four pilots to occur between January 2017 and June 2017. Teachers were chosen through an interview process, asking about teacher experience and student demographics, as well as flexibility in scheduling. For the pilot, teachers or teacher teams were chosen to ensure that all aspects of the app and board could be tested across different types of classrooms and age groups. Additionally, we selected teachers who were not specifically technology or computer class teachers, to ensure the design of the hardware and software was accessible to a wider range of teachers. We scheduled time in between each pilot to allow for redesign of both the app and the firmware for the board. Based on our prior work with Arts & Bots, we estimated that each pilot should roughly take 10 class periods (2 weeks of single periods or 1 week of double periods). When scheduling pilots, we scheduled each for 2 weeks but allowed the teacher to determine the final duration of the project. One or more researchers attended class sessions, taking observation notes and photographs of the students and teachers working. We also conducted interviews with students and teachers at the conclusion of each pilot. Teacher interviews asked about the effectiveness of professional development, integration of Flutter with the class content, suggestions for improvement to the Flutter hardware and app, and teacher perceptions of the project. Student interviews focused on student reactions to the project, ease of use of the Flutter hardware and app, and suggestions for improvements for the hardware and app.

VI. Teacher Focus Groups

Six elementary school teachers participated in at least one of four scheduled focus groups. Each session functioned as a particular aspect of our participatory design process. The first focus group primarily served as time to brainstorm potential curriculum ideas (N = 3). The second (N = 4) and third (N = 1) focus groups tested our app design through the use of both paper and digital prototypes, respectively (Fig. 6 and Fig. 7). We presented our final app designs during our fourth focus group (N = 4).

VII. Classroom Pilots

A. Pilot Overview

Pilot 1 took place in a small, urban charter school located in Pittsburgh, PA. The participants (N=10) were all in second grade. Five participants were male and five were female. The project took seven school days to complete, not including initial research conducted by the students. In total, we observed classroom instruction and student interaction for 13 hours and 40 minutes. Additional, unobserved class time was dedicated to this project during its two week duration. The students were broken up into groups of two or three. Each group was assigned a habitat to research: woodlands, grasslands, desert, or rainforest. Students researched their habitats and drew pictures of three animals that could live and survive in that environment. Each student then combined their three animals into a super animal that could act as a protector of the habitat. The groups then combined their drawings, collaborating on a final animal that they would build together. After their designs were finalized, the teacher introduced the hardware components associated with Flutter, specifically, the board, tri-color LEDs, servos, and sensors. The students then revisited their drawings and, using symbols for the components, indicated the location of the hardware components for the build. In order to help students understand the relationships between inputs and outputs, the teacher organized an if-then game. If the teacher touched her shoulders, the students touched their feet. If she touched her head, they touched their knees. Before each group was allowed to begin building, teams needed to explain the relationship between their sensors and outputs. Once their teacher gave them her seal of approval, the teams chose the building materials and began construction of their robot. They collected sensor data overnight between day six and day seven of the pilot and practiced graphing with sample data.

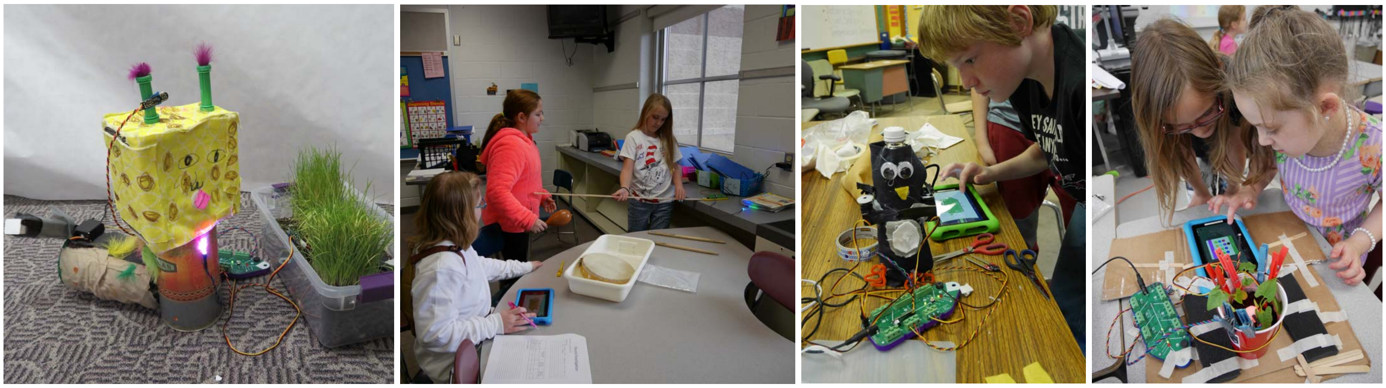

Fig. 8. From left to right, robot and terrarium from Pilot 1, students recording sound volume at different distances during Pilot 2, student programming penguin robot in Pilot 3, students programming an LED during Pilot 4.

Pilot 2 was conducted in a large, rural public school located approximately 45 minutes outside of Pittsburgh, PA. The participants (N=42) were in fourth grade. 23 of the participants were male and 19 were female. The project continued for 10 school days. In total, we observed 11 hours and 15 minutes of class time; this does not include additional, unobserved class time devoted to the project. The teachers running the pilot work as a team, planning their lessons together, but each run their own class. Students were broken up into groups of three, with seven groups per class. Initially, each teacher introduced the Flutter board and its accompanying hardware parts to their class. Students were given a packet, containing a picture of the board and spaces to write vocabulary words. Three different experiments were conducted looking at sound, light, and distance. Before each experiment, each class spent a day learning relevant terms. When exploring sound, the students used the Flutter "Sensors" page to view the sound sensor reading as three different instruments were measured at one, two, or three yards away from the sensor (Fig. 8). In order to study the properties of light, such as opacity, groups used the "Sensors" page to measure the light reading of a flashlight through plastic wrap, parchment paper, and aluminum foil. To study distance, each group built a robot and used a servo and a distance sensor to manipulate the robot's arm movement as a hot wheels car rolled closer to the robot. After each experiment, students reviewed their data and were asked to draw conclusions, even exploring potential human errors that could influence the results.

Pilot 3 conducted in a small, rural public school located approximately 75 minutes outside of Pittsburgh, PA. The participants (N=9) were in an emotional support classroom for students in first through fifth grade. The participants were between eight and eleven years old. Seven participants were male and two were female. The project lasted for eight class school days. We observed for a total of nine hours and five minutes; no other class time was dedicated to this project. The project curriculum centered on birds, exploring habitats, migration, and other aspects of the avian life cycle. Initially, students reviewed vocabulary words with their teacher, explaining terminology related to the habitats of birds. To review concepts, the class played a "Fact or Fiction" game. The teacher read statements about birds and students went to one end of the classroom depending on if they felt it was fact or fiction. Each student was instructed to have a reason for why they chose that particular side. Next, the teacher guided the students through a game of charades, in which the students modelled particular avian activities. In preparation for construction of their robots, students created a bird's nest from craft materials. The activity served as practice in working with the craft materials, making choices in an open-ended construction activity, and practicing appropriate classroom behavior. The teacher introduced the class to the hardware and software, and each student chose a job. Students worked in teams of three to build their robot birds. The teacher ensured that each group could explain the relationship between the sensor inputs and the robot outputs and how the relationship could be applied to bird behavior.

Pilot 4 was conducted in a small, rural school approximately 90 minutes outside of Pittsburgh. All participants (N=23) were in a second grade class and were between seven and eight years old. Eleven were male and 12 were female. The project lasted for a total of 7 days. We observed for a total of 7 hours. There was also additional, unobserved class time dedicated to the project. The project curriculum focused on plants. Students planted soybeans. Each day by hand, they recorded the physical qualities of the pant, such as its height or number of leaves. If no changes were seen, the student wrote, "No changes". Additionally, each day, students used the Flutter app to record sensor data for 5-10 minutes. Once the recording was finished, each student was instructed to graph the data points, adding onto the sensor data recorded from the previous day. Students also experimented within the app, changing the type of relationships between the sensor input and the outputs.

B. Pilot Comparison

In each case, piloting teacher(s) participated in two days of Professional Development (PD) prior to the start of their pilot. During the PD teachers received instruction in use of the hardware and app, and built and programmed a practice robot. They brainstormed curricular topics and areas for integrating Flutter into their classrooms. After selecting a curricular focus, they developed the curriculum and materials needed to teach their pilot class.

The 4 pilots varied in their use of Flutter in the classroom. Pilot 1 implemented an integrated design project, guiding students through a design and build process for their group's robot. Pilot 2 used Flutter primarily as a scientific instrument, focusing on individual experiments. Pilot 3 implemented a creative project with a larger emphasis on scaffolding. Pilot 4 emphasized inputs, outputs, and data collection.

Pilots 1, 3 and 4 are most similar in structure and goal. However, Pilot 1 had the most extended design and build period. In Pilot 1, the students spent the majority of their time designing one robot per group with the Flutter hardware pieces integrated into the function of the robot. Pilot 3 broke up the designing and building portions of the project into smaller activities that often enabled the students to rehearse aspects of the project build with the Flutter hardware pieces. Pilot 3 also did not have time dedicated to robot design specifically, rather the students practiced hands-on building activities. Students in Pilot 4 designed structures focused on using the inputs and outputs, but continued to change and reconfigure their designs each day as they collected data.

VIII. System Design Influences and Discussion

From observations of the pilot classes and student and teacher interviews, we generated ideas for future improvements to the system. We used Affinity Diagramming [15] to group improvement directions into the following five main themes:

Theme 1: Classroom Compatibility
Theme 2: Student Engagement
Theme 3: Teamwork
Theme 4: Systems and Sensing
Theme 5: Low Barrier to Entry

Theme 1: Classroom Compatibility

In order to achieve our goals of Student Confidence with Technology, Student Knowledge of Systems and Sensing, and Applied Data Analysis and Graphing, we designed Flutter to integrate into classrooms. While informal learning environments provide one means of reaching students, we specifically target classroom use as our primary design case as a means of engaging and exposing all students and not just those with a pre-existing interest in technology. Classroom compatibility design features came from our previous work, input from focus group teachers, and classroom observations.

An important component of classroom compatibility is *meeting educational standards*. We explored curricular topics with teachers during the focus groups, resulting in three example curriculum ideas which guided app development: understanding plant life, studying weather, and designing community-supporting technologies. Each curriculum idea aligns with grade-relevant learning standards, promotes open-ended solutions, and enables data gathering and exploration. From our preliminary investigations into elementary math curriculum we saw that *data graphing* was a common curricular theme, and this was confirmed by our focus group teachers. One teacher stated "Third grade focuses on multiplication and division; fourth grade does long multiplication and division; fifth studies fractions and decimals; all students do data analysis and graphs." Thus data collection, data logging, and data display were all discussed by the focus group as we designed features of the app (Fig. 5). The teachers directly guided the decisions not to show sample data graphs in the app but to allow basic statistics to be toggled on and off (Fig. 3).

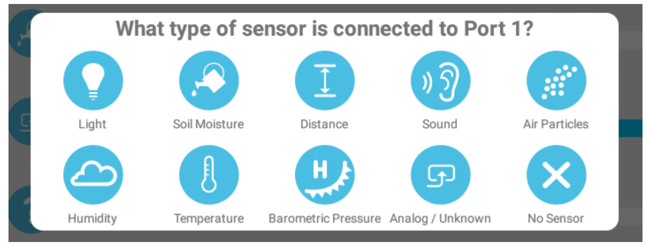

Fig. 9. The sensor selection popup displays icons and a simple name for each sensor.

Tieing data collection to the curricular topics and standards, the focus groups also discussed potential science-related sensors that could be included in the kit (Fig. 9). App word choices were based on feedback from focus group teachers to be simple, but still to provide correct vocabulary for discussion, strengthening ties to science and English standards.

In follow up interviews pilot teachers from all three pilots stated that the Flutter did help them meet curricular standards.

Age appropriate safety is an important consideration for materials designed for the elementary school classroom. With older students we have used exacto knives and hot glue during robot construction activities. For elementary classrooms teachers supplied scissors or had students mark where they wanted a teacher to cut with an exacto knife. We tested a variety of adhesives which could be used during robot construction. We recommend double sided foam tape and super cool temperature hot glue (130 degree Fahrenheit) in addition to the standard craft adhesives of tape and glue. If teachers used regular temperature hot glue guns, they operated the glue guns themselves and placed glue where students directed.

Theme 2: Student Enagement

Student engagement was expressed and observed through four major categories: interactivity, playfulness, compelling behavior, and authenticity of accomplishment. The app itself promotes a type of *interactivity* through data visualizations. On the "Sensors" page, each student can set the sensor and watch live readings move from left to right on a visual display (Fig. 2). The design of the board promotes *playfulness* through the animal naming scheme, the buzzer sound, and the board shape. Each board has a three part name: two adjectives and one noun. The first adjective describes quality, size, or age (adventurous, mini, ancient). The second adjective is a color, location, or material (red, ocean, copper). The noun is a mythical or natural animal (centaur, horse). Students were frequently amused by the names and repeatedly asked teachers to discuss the names, such as Cheesy Orange Lizard. The Flutter board is shaped like a feather, with small designs on its sides, suggesting the wispy border that naturally occurs in feathers (Fig. 1). While watching demos, students were immensely focused, calm, and determined. They found that the robot exhibited extremely *compelling behavior*, even shouting, “You’ve got to come see this” to researchers observing the class. When they do work with the board and parts, they express an *authentic sense of accomplishment*, saying statements such as, “I did it!” and “No one helped me do the robotics [and I did it]”.

When teachers introduced Flutter, specifically the relationships between inputs and outputs, they integrated games into their curricula. For example, the if-then game described in Pilot 1. Flutter can promote playful classroom interaction. Additionally, when discussing relationships with the teacher from pilot 1, she noted that having only a proportional relationship did not support the students’ desired reaction. Instead, they wanted reactions to happen immediately. As a teacher, she felt that having a relationship type that had the ability to change more frequently as well as one that changed slowly would be ideal. In the version of the app used in Pilot 4, we added frequency and amplitude relationships. These relationships allow for output movement even when the input value does not change. For example, the servo can move quickly when the temperature is hot and move slowly when the temperature is cold. Observation of student behavior during Pilot 4 showed students to be engaged with these relationships, exclaiming “Oh my gosh! I get what it does!” and jumping up and down as they explored the relationships.

Student engagement is perhaps the most important outcome of any classroom initiative. When students are engaged, it promotes greater classroom and student success and development. Students are more likely to demonstrate persistence and achievement in their work [16]. Without student engagement, none of the other goals of our project can really be achieved. Specifically, student engagement promotes Student Confidence with Technology and enables students to be more motivated achieving and creating engaging and interactive robots.

Theme 3: Teamwork

Students in all pilots needed to collaborate in groups of two or three. At times, this resulted in conflict, especially during the design and build phases. The teachers in general emphasized fairness and discussed the expectations of each student. The teacher from Pilot 1 separated building materials into separate bins, providing a limit for how many of each type of material each group was allowed to use. One teacher in Pilot 2 gave each team member a particular portion of the robot build or experiment the student was in charge of. In Pilot 3, all students had a job for every day the Flutter materials were in use.

Teamwork is a life skill that must begin being cultivated at a young age. Especially in today’s society, most careers require teamwork that engages in meaningful delegation. By assigning roles and discussing fairness, teachers are offering students the opportunity not only to acknowledge personal responsibility in collaborative work, but also to recognize the value in their own personal contribution to the success of a project [17]. As students begin to recognize the value in their skills and contributions to group work within the Flutter project, they simultaneously begin to recognize and exhibit *student confidence with technology*.

Theme 4: Systems and Sensing

The theme of Systems and Sensing is directly tied to the Flutter goal of *Student Knowledge of Systems and Sensing*. We observed that students sometimes entered the project with *high expectations* of what a robot should be able to do and what they would be able to create. For example, one group wanted to add many more sensors than the maximum of three supported by the Flutter board. When the teacher reminded them they could only have three, a student responded that other robots could do more. Additional misconceptions surrounded the instruction and introduction of sensors. Students at first misunderstood and thought that sensors acted as outputs, rather than inputs. The teachers at that time had to stop and ask if they thought a sound sensor made a sound. Most students were uncertain so the teacher paused the class to review the difference between sensors and the robots' outputs.

In the follow up interview, one teacher noted the difficulty her 2nd grade students had with positioning the sensors on their robots. They wanted to put sensors in the eyes and ears of the robot, not understanding the sensor would need to be in the terrarium in order to sense the light or soil moisture within that habitat.

As students worked on the project they developed *knowledge about how robots and systems function*. The app allows students to create proportional, derivative, and change relationships between inputs and outputs (traditionally referred to as proportional, integral, and derivative controller). These are the three main components of a textbook control system called a PID control (proportional - integral - derivative control) which is taught in most engineering courses of study.

During the first three pilots, students used proportional control. In Pilot 1 the teacher and students had conversations about how the inputs impacted outputs. Students struggled at first to grasp the relationships, but their understanding improved over time. In Pilot 3 the teacher asked each team to describe the relationship between the input and the output and how that would relate to a bird. The teacher was excited that students were able to make connections between the inputs and outputs and reported feeling particularly gratified that one of her lower performing students was making connections and understanding the system so well. In the fourth pilot, students started with proportional control and then experimented with derivative and change relationships as well to discover how the different relationships would impact their robots’ behavior. Through trial and observation, they learned how the different controls resulted in different behaviors.

Theme 5: Low Barrier to Entry

Low barrier to entry means that novice users can easily learn to use the system. Low barrier to entry is important for promoting our program goals of *Student Confidence with Technology* and *Student Knowledge of Systems and Sensing*.

We achieve low barrier to entry through multiple means as described below.

Real world grounding is a method employed to reduce abstraction by tieing app functionality to the physical world and hardware. The primary example of real world grounding in the app design is using an image of the Flutter board as the organizational layout for creating links between inputs and outputs (Fig. 3). A second example was the representation of LED color selection as a set of 14 color swatches rather than as fully configurable red, green, and blue values.

Error prevention is key to low barrier to entry both in hardware and in the app. For example, the Flutter hardware will not be harmed by wires being plugged in incorrectly. The one possible incorrect plug configuration that could harm the board is if a servo is plugged in across servo ports. To prevent this, the pins have been aligned on the board such that it is physically impossible to bridge across ports. In the app, the current program state is saved automatically to the Flutter board so that if the Bluetooth connection is terminated or power to the board is lost, no work is lost and students can always pick up where they left off. We observed that sometimes students did not stop to read prompts or try to understand what was being conveyed by a screen on the app. Instead they excitedly clicked on anything that could be clicked to see what would happen. It was important that the app be robust to such interactions and that random clicking was unlikely to cause harmful, confusing, or difficult to recover from states within the app.

Clear communication and labeling designed with the age of the target population in mind enables the Flutter hardware and software to guide student interaction. A key printed directly on the board tells students which color wire to plug into each port (Fig. 1). A main color identifies each of the three primary screens of the app, allowing teachers an easy reference point. Icons with simple text identify sensor types (Fig. 9). The pop-up for configuring relationships between outputs and sensors opens with 3 out of 4 required settings in a functional default state, so that once the student chooses the sensor they have a functional example relationship (Fig. 4).

IX. Conclusion and Future Directions

Over the course of the past 18 months of development we have worked on the refinement of a technology-based, science and sensing program for elementary-aged students. We believe that it is critical to engage children as creators and innovators with technology, such that they develop the skills and mindsets to be technologically fluent makers and members of our increasingly information driven society. We sought to engage with students in 2nd through 4th grade. Starting with our initial concept and lessons learned from our middle-school robotics program, Arts & Bots, we developed the four primary goals of the Flutter program. These were: Student confidence with Technology, Student Knowledge of Systems, Applied Data Analysis and Graphing, and Engaging and Interactive Robots.

We worked with elementary teachers through focus groups (N = 6) to develop initial lesson and curricular ideas and a novel systems- and sensing-oriented tablet application. This tablet application has real-time sensor feedback, gives students the ability to configure robot outputs to respond in relation to sensor inputs, and allows sensor data logging.

Following the teacher focus groups, we then provided professional training to five teachers and, with them, conducted with four pilots in 2nd - 4th grade classrooms (N = 84 students). Over the course of these pilots, we have developed and refined the Flutter Kit's hardware, software app, and curriculum. Our observations from the focus groups and pilots can be clustered into five major themes, described above.

In the future, we plan to further refine the app per our pilot outcomes, identify and complete modification to the Flutter hardware and kits, work on the development of new curriculum materials, and create formal teacher professional development models. Once the Flutter program is fully formalized, we intend to evaluate the efficacy of the program in achieving our stated goals of student confidence, knowledge of systems and sensing, applied data analysis and graphing, and engagement.

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REFERENCES

[1] L. Education, "WeDo 2.0 – Support – LEGO Education", Education.lego.com, 2017. [Online]. Available: https://education.lego.com/en-us/support/wedo-2. [Accessed: 28- Apr- 2017].

[2] "Education | Ozobot", Ozobot.com, 2017. [Online]. Available: http://ozobot.com/stem-education. [Accessed: 28- Apr- 2017].

[3] "Wonder Workshop | Home of Dash and Dot, robots that help kids learn to code", Wonder Workshop, 2017. [Online]. Available: https://www.makewonder.com/dash. [Accessed: 28- Apr- 2017].

[4] "Bee-Bot", Bee-bot.us, 2017. [Online]. Available: https://www.bee-bot.us. [Accessed: 28- Apr- 2017].

[5] "Finch Robot | The Finch", Finchrobot.com, 2017. [Online]. Available: http://www.finchrobot.com. [Accessed: 28- Apr- 2017].

[6] A. Bdeir, "Electronics as material: littleBits", in 3rd International Conference on Tangible and Embedded Interaction (TEI), 2009.

[7] "Research Instruments | Engineering is Elementary", Eie.org, 2017. [Online]. Available: http://www.eie.org/engineering-elementary/research/research-instruments. [Accessed: 28- Apr- 2017].

[8] "Elementary Science Packages > Vernier Software & Technology", Vernier.com, 2017. [Online]. Available: http://www.vernier.com/products/packages/elementary-science. [Accessed: 28- Apr- 2017].

[9] E. Hamner and J. Cross, "Arts & Bots: techniques for distributing a STEAM robotics program through K-12 classroom", in Third IEEE Integrated STEM Education Conference (ISEC), Princeton, New Jersey, 2013.

[10] E. Hamner, J. Cross, L. Zito, D. Bernstein and K. Mutch-Jones, "Training Teachers to Integrate Engineering into Non- Technical Middle School Curriculum", in IEEE Frontiers in Education Conference (FIE), Erie, PA, 2016.

[11] E. Hamner, L. Zito, J. Cross, B. Slezak, S. Mellon, H. Harapko and M. Welter, "Utilizing Engineering to Teach Non-Technical Disciplines: Case Studies of Robotics within Middle School English and Health Classes", in IEEE Frontiers in Education Conference (FIE), Erie, PA, 2016.

[12] Jennifer Cross, "Creative Robotics for Talent-based Learning," Ph.D. dissertation, Robotics Institute, Carnegie Mellon Univ, Pittsburgh, PA, 2017. (in press)

[13] T. Lauwers, "Aligning Capabilities of Interactive Educational Tools to Learner Goals", Carnegie Mellon University Robotics Institute, 2010.

[14] J. Cross, C. Bartley, E. Hamner and I. Nourbakhsh, "A Visual Robot-Programming Environment for Multidisciplinary Education", in IEEE International Conference on Robotics and Automation, Karlsruhe, 2013.

[15] K. Holtzblatt, J. Burns Wendell and S. Wood, "Chapter 8 - Building an Affinity Diagram", in Rapid Contextual Design, 1st ed., K. Holtzblatt, J. Burns Wendell and S. Wood, Ed. San Francisco, 2005, pp. 159-179.

[16] T. V, "Student Engagement", AUA Newslink, 2011. [Online]. Available: http://www.aua.ac.uk/publications.aspx?Category=Newslink. [Accessed: 28- Apr- 2017].

[17] "Communication and Collaboration - P21", P21.org, 2017. [Online]. Available: http://www.p21.org/about-us/p21-framework/261. [Accessed: 25- Apr- 2017].