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Adapting Engineering Education to Resource-Constrained Middle Schools: Teaching Methodologies and Computing Technologies

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***Abstract*—Middle school students are at a critical age where exposure to science, technology, engineering, and mathematics (STEM) fields can greatly impact their career goals. Unlike other STEM fields, many schools do not have the expertise or resources needed to acquire and utilize existing engineering education platforms. Thus, we have begun to investigate how to adapt proven interactive project-based learning techniques for resource-constrained middle school environments as well as evaluate interactive platforms or platform characteristics that can be adapted to ensure greater accessibility of these materials.**

Keywords-Engineering Education, Project Based Learning, Interactive Technologies, Accessible Computing Platforms, Computer-Human Interaction and Design

I. INTRODUCTION

Science, technology, engineering and mathematics (STEM) education is essential in today's world where technology and science based industries are considered one of the major driving forces in the nation's economy [6], contributing to several of the fastest growing job markets [28]. Due to the lack of formal engineering education in secondary schools, many precollege students in the United States have expressed no interest in an engineering career and are unaware of the opportunities offered by an engineering profession [1][8]. Paramount in this effort will be helping all students develop dispositions for engaging in the basic processes of scientific inquiry, as well as overcoming inequities of gender, ethnicity, and economic background.

While providing engineering experiences opportunities to students of all levels can be beneficial, research studies reveal that students in middle school are at a critical age where exposure to engineering, or even exposure to a variety of career paths, can greatly impact their future education goals [5][33]. In the US, the typical age of middle school students range from 11 to 14 years old. Middle school presents a critical time at which to expose students to engineering experiences, enabling students to get involved with engineering extracurricular activities as well as align curriculum goals to prepare for college requirements [33], thereby increasing student's acceptance and success rate in engineering college programs [11]. Students with a strong background in STEM education are more likely to pass advanced placement programs tests, and successfully graduate from higher education institutions [4]. Furthermore, studies have found that female middle school students express more interest in nontraditional fields such as law and engineering [32], whereas this interest fades in high school. One of the reasons for this loss in interest may stem from the fact that women begin to show less confidence in their mathematical and science abilities [9][17] and therefore do not believe majoring in engineering is a possibility [12].

The benefits of project-based learning (PBL) are well known in the mathematics and science education research community. PBL allows students to learn by doing and applying ideas as they engage in real-world tasks that are important to them [2][14]. In PBL environments, students often use learning technologies as they investigate the world around them. Compared to traditional classrooms where students listen to a lecture or read a book, students in PBL environments show increased interest and motivation [3], and even achieve higher scores [10][27]. Yet, research has also shown that creating and sustaining technology-infused PBL environments is difficult, due in large part to high cost and limited teacher expertise.

The challenge remains in how to make engineering education accessible to middle school environments that are oftentimes resource-constrained. There is a need for the development of middle school engineering pedagogical curriculum and educational platforms that accommodates the limited budget and expertise of economically disadvantaged schools. Access to dedicated computers labs is not ubiquitous enough to consider as standard equipment, while many off-the-shelf platforms are cost prohibitive. Furthermore, development and maintenance of engineering programs are often left to math and sciences teachers who are already time-constrained and do not have backgrounds in engineering or engineering education. To overcome many of

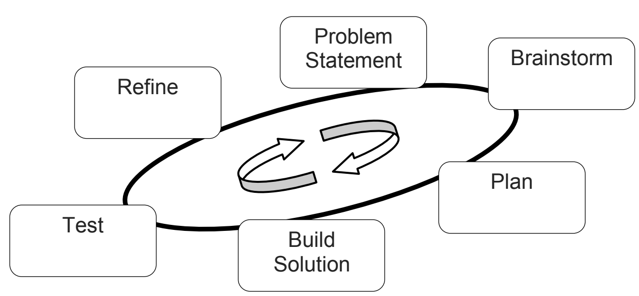

Figure 1. Engineering Design Cycle

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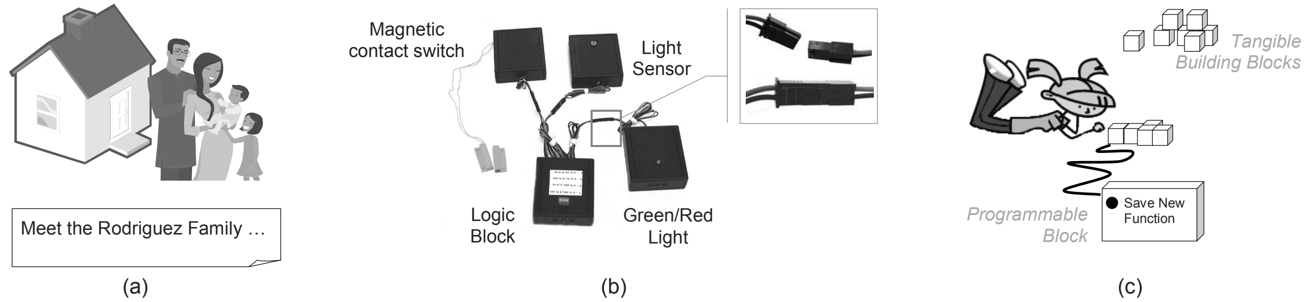

Figure 2. Smart House project module starts with (a) a generalized problem statement, (b) fixed function eBlock platform to build a variety of interactive projects, and (c) a tangible programming interface extension to define new block functionality.

the challenges faced by resource-constrained middle schools we have begun to investigate the pedagogical and technological requirements needed for the development of accessible engineered based learning modules.

II. Pedagogical Implications

Inductive teaching methods expose students to concrete experiences related to a concept. Students gather empirical evidence from these concrete experiences to proceed from experience specific observations to generalizations in the form of governing rules, laws, and theories. Inductive methods are a well studied area with numerous examples of use within middle school engineering education [15][18]. Not surprisingly, in the US the National Science Education Standards have endorsed inquiry based instruction over the traditional lecture-based teaching approach in science education [21]. Similarly, in the European Union the introduction of inquiry-based approaches in schools for science education has been proposed [26]. Six categories of inductive methods have been recognized that can be employed in engineering education and include inquiry, problem-based, project-based, case-based, discovery learning, and just-in-time teaching [24].

Project-based methods in particular provide a good fit for engineering education due to the emphasis in the application of knowledge to design and develop artifacts. Moreover, project based teaching methods encompass many of the cognitive skills used by engineer practitioners to generate new ideas, reflect on experiences, and make project decisions in the design and development of new products. Rather than focusing middle school engineering projects solely on the optimization of existing designs, students can additionally benefit from engineering projects that are developed towards the understanding of concepts common among different branches of engineering including, but not limited to, the engineering design cycle and the development of algorithms to solve various problems.

A. *The Smart House Educational Project*

To introduce engineering to a middle school audience, we are beginning to develop a project booklet for teachers containing numerous sub-modules including background information on engineering as a discipline, examples of engineering problems and careers, basic engineering concepts, as well as the engineering design cycle shown in Figure 1 [23]. In addition, the project booklet will strive to clearly define an end product, in which development of the product is the center of the curriculum. We envision the Smart House Educational Project to be a sustainable module that allows middle school teachers to take over engineering instruction without the intervention of an "expert" in engineering. While students share a common goal, individual projects are open-ended and defined by the student groups. Lastly, students are evaluated by examining the characteristics and behavior of their final products.

Modules are tied together by a common storyline of developing smart home products to be used within a family's home, as shown in Figure 2. For example, the project module may start as follows:

> *Meet the Rodriguez family, James, Helen, 7-year old Becky, and 1-year old Robert. They are ready to move to a bigger and better home and have hired your engineering team to design a Smart House system according to their personal needs and lifestyle. A smart home is a home that contains programmable electronic sensors and devices that can be configured for a variety of uses such as security, automatic temperature control, turning on lighting in the driveway at dusk or turning lights off in the bedroom when it is unoccupied. Let's get to know the Rodriguez family and see what types of systems we can build for them!*

As the story progresses, students are guided to the Smart Home requirements. While modules begin by providing direct instructions and small examples to illustrate platform usage, ultimately students will define and implement their own final project by identifying needs and requirements through self-directed and self-managed teams. Students are provided with a high level of autonomy to promote a feeling of project ownership [24] such that students will work in building products that they have identified a need for, and not just because it is requested by a teacher or a lesson plan. Furthermore, modules are designed to be decomposed into smaller subprojects to encourage all team members to

Figure 3. Light Sensor eBlock which includes (1) photosensor, (2) red LED to indicate "no" light is detected, (3) yellow LED to indicate error, (4) green LED to indicate "yes" light is detected, and (5) output connector to interface to other eBlocks.

contribute to the final product, as well as provide a realistic view of working on an engineering design team where a high level of intergroup coordination and communication is essential. Project groups will be responsible for testing and refining solutions. Instead of promoting competition among groups through contests, to motivate the development of an optimal solution, students will present their models along with the reasoning of why and how they build their systems at the end of the teaching module.

III. TECHNOLOGICAL IMPLICATIONS

An interactive computing platform targeted toward non-expert users is needed to enable students to achieve a physical realization of engineering tasks outlined in the project module. Use of the corresponding platform should not require a large amount of training in electronics or programming, as these tasks would detract students from main goal of the project module. Furthermore, while numerous platforms targeting secondary engineering education are available [25], many are cost prohibitive or rely on access to desktop computers.

To begin we have chosen to utilize the eBlock platform, shown in Figure 2(b), to enable students to build a variety of interactive projects. The platform is composed of fixed function blocks that users snap together to implement the desired system functionality. The key to the eBlock approach is to add compute intelligence to components that previously had none - to sensors, switches, light-emitting diodes (LEDs), speakers, etc. The compute intelligence is a standard off-the-shelf PIC microprocessor selected for its low-cost and low-power features. Because the individual interfaces to these hardware components vary, the microcontroller abstracts the interaction between nodes to - "yes", "no", "error" or a numerical value. Essentially a small network is formed by eBlocks that communicate with packets. Users construct eBlocks system in a spatial programming paradigm and can visualize in real time what type of signal a particular eBlock is sending or receiving.

Figure 3 provides an illustration of a light sensor eBlock. When the photosensor mounted on the top of the eBlock

TABLE I. COST OF INDIVIDUAL BLOCKS.

	Block Type	*Parts Cost (1,000 volume)*	*Parts Cost (100,00 volume)*
Sensors	Button	$ 3.08	$1.85
	Motion sensor	$ 6.11	$3.67
	Light sensor	$ 3.50	$2.10
	Magnetic sensor	$ 4.00	$2.40
Output/ Display	Normal LED (light)	$ 3.15	$1.89
	Green/red LED (light)	$ 3.24	$1.94
	Beeper	$ 3.37	$2.02
	Electric relay	$ 3.00	$1.80
Intermediate	2-Input logic	$ 4.94	$2.96
	Toggle	$ 3.31	$1.99
	Prolonger	$ 3.31	$1.99
	Splitter	$ 4.26	$2.56
	Wireless transmitter	$ 5.53	$3.32
	Wireless receiver	$ 5.49	$3.29

detects light, the eBlock will send a "yes" packet through its output port. The green LED on the top of the eBlock pulses as long as light is detected, providing a visual cue to users to the "yes" status of this block. Similarly, the red LED will activate when "no" light is detected by the photosensor, indicating that the eBlock is currently sending "no" packets through its output port. The yellow LED indicates users that the eBlock is in error state and is not functioning properly.

With the low-level implementation issues transparent to the user, coupled with a simple interface, users are able to quickly and easily develop custom applications by snapping together a variety of fixed-function blocks and the order in which the blocks are connected specifies the systems functionality.

eBlocks are not just a conceptual platform, rather these building blocks have been implemented in hardware to test the feasibility and usability of this platform as a whole. Over the past several years, we have prototyped more than 100 blocks with approximately 20 different building blocks that fall into one of the following three general categories:

- *Sensor blocks* - monitors the environment, including motion sensors, light sensors, buttons, contact switches, and so on;
- *Output/display blocks* - provide stimuli, and include light-emitting diodes (LEDs), beepers, relays, etc.;
- *Intermediate blocks* - computation blocks that perform basic logic transformations (e.g. AND, OR, NOT) or basic state functions (e.g. prolong, toggle, trip, pulse) as well as blocks to enable wireless point-to-point communication

A Harvard Business School project estimated parts cost in moderate volume to be between $3 and $6, and between $2 and $4 in higher volumes with costs decreasing each year due to technology trends, and lower costs for higher volumes [31]. Table I provides a breakdown of cost for several of the block types currently available within the eBlock platform. The sensor or actuator utilized contributes to the majority of the cost of each node, thus we must be mindful when developing new nodes.

A wide variety of systems can be constructed utilizing the same set of eBlocks. To date, we have explored the use of the existing eBlock platform with approximately 500 subjects, representing a wide range of age groups and backgrounds [7]. Participants have been observed utilizing the existing eBlock platform to create and implement a variety of applications. On average 55% these participants were able to successfully build an application within just 10 minutes of being introduced to the platform without any training or assistance.

As the goal of this project is to develop a project module targeted toward middle school environments, we have also performed additional usability experiments specifically with two local middle schools where students were able to work with the platform in three to five one-hour sessions. In the first session, students were provided with a 30 minute introduction to eBlocks. In the subsequent sessions, student were provided with project booklets that asked them to utilize the eBlock platform to achieve a pre-specified goal, such as detecting room temperature and sounding an alarm or counting the time a button is pressed. Overall, students demonstrated an average success rate of 89% [22] which shows improvement compared to experiments in which no training was provided.

While the platform contains components suitable within the scope of the smart home project, the main limitation of the platform is also its strength, the use of pre-defined fixed function blocks. The fixed function blocks remove any need to program block functionality. However, as the functionality becomes more complex, the number of blocks similarly increases. Additionally, if the desired functionality is not already available, users must try to manipulate existing blocks. Studies indicate that programming constructs need to "cognitively fit" with the user to be utilized effectively [29]. Users who were asked to develop an eBlock system to detect whether a value was within a pre-specified range performed poorly, achieving a success rate of 54%, when provided with comparison blocks (<, >, or == operations available) which needed to be combined with other blocks to achieve the desired range functionality. In comparison, users who were provided with a block specifically designed to detect range (high < x < low) achieved higher success rates of 81%. Additional usability experiments similarly follow the above trend when users were asked to manipulate blocks for a functionality not specifically designed for that intended purpose.

Currently platform extensions are being evaluated to enable specification of custom functionality through the use of a tangible programming language. Developing applications with tangible programming languages is an interactive activity where an algorithm is perceived as a physical shape composed by objects that represent digital information. The manipulation of these objects results in the manipulations of the digital information they represent. Tangible programming languages can provide novice users with a mechanism to express algorithms without ever having to learn complex language syntax. The programming language syntax can be embedded in the shapes of the language objects allowing objects to be connected together only if they make syntactical sense, similar to the PicoBlocks graphical programming language shown in Figure 4 used to program the educational microcontroller PicoCricket [30] and the Lego Mindstorms RCX [16]. Previous works have introduced several tangible educational platforms [13][19][20]. However, these platforms do not address the needs of resource-constrained schools because they either depend on a host computer and other expensive equipment such as a digital camera for their program's compilation or because of their high acquisition prices. We must adapt these techniques to ensure that an intermediate desktop computer or other expensive equipment is not required to compile and download the new eBlock behavior specification while keeping the platform's cost low. The overall goal is to provide a low-cost platform with the flexibility found in software-specified applications, while having physical blocks that a user can manipulate and interact with to develop block-level and system-level functionality.

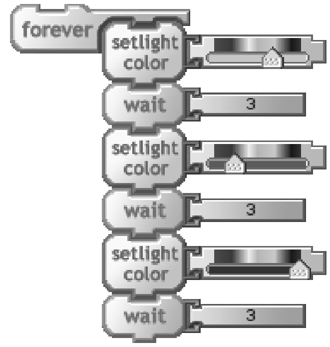

Figure 4. PicoBlock program that continuously pluses and LED between three different colors.

IV. CONCLUSIONS

We are continuing to work toward developing instructional materials that provide guidance to teachers to introduce middles school students to engineering. In particular, we focus on resource-constrained middle schools and strive to limit the cost and expertise associated with the activities developed. Furthermore, to complement these materials we are also working toward a low-cost physical platform feasible for most educational settings. By providing students with an opportunity to interact with these technologies we hope to build confidence early, resulting in better performance and more opportunities to participate in accelerated math and science programs at the high school and college level and stimulate their interest in engineering as a possible career.

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