PaperBots, An Inexpensive Means for Engineering Education

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abstract

Due to economic issues, many school budgets are extremely strained by just the basic necessities of an educational institution. These budget limitations inhibit access to educational technologies that may promote engineering principle development within K-12 classrooms. PaperBots is a product that focuses on overcoming budget-driven limitations by utilizing materials like paper, office, and craft supplies already accounted for in a school’s budget. By effectively providing activities promoting abstract, design-based thinking and creativity in the classroom—like other products in the educational technology marketplace, such as LEGO Mindstorms—but at a much lower cost, PaperBots can be utilized by many budget constricted schools. Through combination of those available materials with inexpensive electronics and an Arduino based control unit known as the PaperBots Robotics Kit, students can be challenged with interesting and entertaining engineering activities in the classroom. In October of 2012, a small focus group of fifteen fifth- and sixth-grade students assembled for a workshop utilizing the PaperBots robotics kit. This activity was observed and documented to make a qualitative determination of the effectiveness of this product.

technology driven world

In the last few decades, technology has become an increasingly predominant aspect of our world. We no longer design on large drafting tables with pencil and ruler but make use of computer aided design software to design in 3 dimensional virtual environments. The mechanical controls within vehicles have become modified and at times replaced by computer sensors and controls. Marina Bers notes “Computers and electronics are as much a part of our world as gears and mechanical structures.” The world becomes more and more technologically driven as technology continues to saturate our everyday lives. The Library of Congress is the largest library in the United States. The information housed there and much more is now accessible by the smartphones many of us carry in our pocket. Over the course of a single day we can come into some form of digital contact with hundreds of people from around the world. This type of information access and communication was unimaginable just a century ago.

Preparing for this advancing world requires arming students with the technical literacy and an engineering-minded outlook to handle the continuous innovations they will face. It has been noted in recent years that we are not doing this to the extent necessary to meet demand. Students, in general, are not being prepared to tackle problems requiring integrated approaches: the problems they’re presented with do not expose them to the real-world issues they’ll face, teamwork in problem solving is rarely encouraged, and the opportunities for critical thinking are also rare. This failing is seen in industry by the United States spending $55.8 billion on necessary training for employees when in 1982 spent $7.02 billion, Value is corrected for inflation from $2.95 billion21,22.

One of those technologies is robotics, which has become more prevalent in recent years. From 2010 to 2011, the total number of professional service robots sold increased by almost 10% from 15,027 to 16,408 units valued at $3.6 billion. The number of personal and domestic service robots increased by 15% to 2.5 million in 2011 valued at $636 million. Projections for 2012-
2015 expect approximately 93,800 new professional service robots to be installed\(^8\). These trends indicate that robotics has become an important part of industry as both a manufacturing tool and an end product. They also indicate an increased association with everyday life. The students of today will need to be prepared for these and other technologies they’ll eventually encounter as they begin to further permeate our day to day lives.

There do exist several robotics platforms made specifically for the educational market. K-Team produces The Hemisson and Activemedia produces the Amigobot, two educational robots designed as preassembled units ready for the addition of different sensors. The LEGO Mindstorms NXT and its predecessor, the LEGO Mindstorms RCX, utilize LEGO pieces for added mechanical prototyping to the activity\(^{13}\). Tetrix by Pisco and The VEX Robotics Design System utilize more heavy-duty aluminum hardware for building\(^5\). The iRobot Create is an educationally geared variation of the iRobot Rumba, the most common robot in the world, which has added interfaces to encourage experimentation\(^{13}\).

All these systems offer robotics activities that benefit the classroom by providing some form of robotics education but also have an initial cost to outfit the classroom. A study done by the National School Supply and Equipment Association (NSSEA) showed that, in the 2009-2010 school year, teachers spent an average of $936 outfitting their classrooms. $398 was spent on general supplies and $538 on instructional materials\(^{14}\). Providing robotics platforms to those budgets would increase drastically increase them. The Hemisson costs $250 per kit without software\(^7\) and the Amigobot sells with its software suite for $3,095. The LEGO Mindstorms NXT retails for $279.95 with the software sold separately\(^{10}\). Also without software, TETRIX retails for $871.95 for the basic kit\(^{11}\) and the most inexpensive VEX Robotics Design System kit costs $399.99\(^{23}\). The iRobot Create is the least expensive example at $129.99 each\(^9\).

PaperBots

With those costs and the available funds for them in mind, a new educational technology was designed. PaperBots utilizes the available classroom materials, such as paper and other office and craft materials, to provide engineering activities in the classroom. Currently PaperBots provides lesson plans and the associated templates allowing for teachers to print them up and the students to make items like cams and articulated joints from paper. These initial lessons provide activities about design and mechanisms with no more cost than that of some cardstock and brass fasteners for the cam activity and similarly for the others\(^{16}\).

Those existing lessons only require already available classroom materials but are limited in scope. The PaperBots robotics kit is specifically designed for use with classroom materials to augment those activities with inexpensive electronics and a microcontroller to allow for student construction of robots. The combination of these inexpensive materials, mechanical components, and programmable controllers has shown promise in promoting creativity and the familiar materials help cultivate a more comfortable and productive experience\(^{17}\). A testing group was assembled to assess if the first version of the PaperBots robotics kit functions as suggested by such findings and this paper examines the results of that case.
PaperBots robotics kit

The first version of the PaperBots robotic module was custom shield for a Teensy, an Arduino based microcontroller, and a reference image for the module is provided in figure 1. The shield was designed for single motor control as well as simple interface to the microcontroller using relatively inexpensive, simple and reliable means. The module contained six surfaces along the edge of the shield that act as the external interface of the microcontroller. These surfaces were designed for simple connection to with alligator clips. This method of connection was thought to be the simplest and most inexpensive way for elementary aged students to make the electrical connections to the microcontroller. There are connections for a single motor, two digital contacts, one analog contact and a ground contact. The teensy is capable of many more connections but limiting the available connections is intended to keep the design options to a manageable level for young students. Also, the hope is that the principal that constraint breeds creativity will further challenge the students and produce some interesting design choices\textsuperscript{12,20}.

![Fig. 1. PaperBots Robotics Module Reference Sheet](image)

The PaperBots robotics kit contains the PaperBots robotics module version 1. It also contained a low power motor modified for use with alligator clips and a photocell module also designed for use with alligator clips. Five alligator test leads were also provided with the kit.

product testing workshop

For this testing group, participants were recruited from the Tufts University Center for Engineering Education and Outreach’s email list of parents interested in sending their children to available workshops. The test group was limited to fifth and sixth grade students, of which, 9 were in fifth grade and 6 were in sixth grade for a total of 15 participants. One of the participants was home schooled. Their ages ranged from 10 to 12; eight 10 year olds, six were 11, and one was 12. There were 2 female participants and the rest were male.
The workshop was for 3 hours on a Saturday morning from 9 to 12. The participants were separated into 5 groups of 3 chosen by the participants. Two appeared to know each other but the rest chose based on where they had initially seated themselves. Each group was provided with a PaperBots robotics kit. The participants were assigned a Rube Goldberg type activity with the purpose of lighting an LED jack-o-lantern, chosen due to the upcoming holiday, Halloween. This is an activity that offers a single objective via a collaborative experience and one that I have used with other groups with success. A grid was placed on the floor of five approximately 1.5 ft by 1.5 ft squares. Each group was assigned a square and instructed that the only criteria for the activity was to utilize the PaperBots robotic kit, stay within the confines of your square, have your robot triggered by the previous robot and will then have it trigger the next, with the obvious exceptions of the first and last square. The final setup of their PaperBots Rube Goldberg system is shown in figure 2.

Along with the PaperBots robotic kits, the materials made available were paper, cardstock, construction paper, craft sticks, brass fasteners, aluminum foil, duct tape, masking tape, office tape, and string, scissors, hole punches, pens, pencils, and markers were also provided. Due to the short time period available for the activity and the learning curve associated with line based programming languages like Arduino, 4 prebuilt codes were made available to the students; a code that turned on when a digital signal is triggered on D1 or off when digital signal is triggered on D2, a code that goes forward when digital signal is triggered on D1 and backwards when digital signal is triggered on D2, a code that turned on when an analog signal on A1 was above a certain threshold, and a code that turned on when an analog signal on A2 was below a certain threshold. It was determined that the physical usability of the kit was more important at that time since the programming abilities of the students within that age range had long since been established.

Fig. 2. Final layout of the PaperBots Rube Goldberg system made by the participants of the workshop. (Photo by author)
The kits were then demonstrated by first engaging the motor with a digital signal by touching two alligator clips momentarily contacted and then by connecting the photocell with the unit programmed to turn on the motor when a shadow is cast over it. Instruction specific to the use of the PaperBots Robotics Kit was intentionally limited to see how intuitive the product’s use is and to avoid influencing the outcome of their designs. They were not given an opportunity to ask about the PaperBots Robotics Kit’s operation after the demonstration but were asked to ask questions that arose during construction of their robots. The activity was then described to them along with the available programs they could choose from. No encouragement was given for particularly unique or novel ideas, just to achieve the goal. They were reminded on several occasions to confer with other groups to assure their robots interact properly.

Within the given time, approximately 2.5 hours adjusting for instruction and final demonstrations, each group was able to build a robot that would sense the previous step and actuate the next. This had been demonstrated at least once for each robot. As a full Rube Goldberg setup, it did not function fully, being interrupted once during each of the two trials. Figure 3 shows the robot designed and built by the first group, a swing arm that is triggered by a digital signal from contacting two pieces of tin foil together. The motor is mounted to a heavy base in order to anchor it in place and the controller is tethered to it. The arm swings from their square to the next, knocking a paper dome off the next bot.

The second group’s robot was a crawling hand tethered to the PaperBots module and is shown in figure 4. It has the light sensor mounted to its top with a paper dome loosely placed over it. Once having the dome knocked off of it, exposing the light sensor to the ambient light of the room, the motor engaged and used the existing hubs on the PaperBots motor to propel it forward in a waddling type motion. It would crawl forward and cover the light sensor of the next bot with the fingers of the hand.

The third group’s robot was similar to the first robot. It was another swing arm setup. As shown in Figure 5, they had set up a platform built off the PaperBots controller to position the light sensor where required by the previous group. Once covered, the arm swings around and knocks over a piece of cardstock, exposing the next robot’s light sensor.

The fourth group’s robot was a car, shown in figure 6. They used PlayDoh container lids taped to the motor hubs to act as wheels. The light sensor is mounted to the back of the vehicle with the aforementioned piece of cardstock leaning against it to shade it. Once the light sensor was exposed to light, it began to move forward. On the front of the vehicle was a feature designed to insert itself into a receptacle on the next robot.

Fig. 3. Group 1’s robot. (Photo by author)
The fifth group’s robot was a drag sled, shown in figure 7. In the receptacle feature on its back end, they installed the light sensor. When the fourth group’s robot plugs into that receptacle, the sensor activates on the robot. Using Popsicle sticks attached to the motor hubs, the robot drags itself forward. The bottom of the sled is made of aluminum foil so when it drags itself over two wires taped to the ground, it completes the circuit and lights the LED Jack-o-lantern.

The participants were asked to take a survey before and after the activity. 11 participants elected to take the pre-activity survey and 14 took the post-activity survey. Some participants did not want to take part in the surveys. The pre activity survey was intended to gauge the participant’s experience with engineering activities and their average use of these robotics and craft materials entering into the workshop. The survey showed that the participants had good confidence in their abilities with robotics. When asked on a scale of “very poor” to “very good” (quantified as from 1 to 5) about this ability, the average answer was a 4.18. The lowest rating was a 3 or “neutral” response. The average use of robotics was indicated as “once a month” but “once a week” for craft materials.

The post activity survey was used to gain their opinions of the activity and those responses are provided in table 1. To corroborate the participants thinking, the survey included positively and negatively phrased versions of the same questions; for
example, “I thought the activity was very easy.” and “I thought the activity was very hard.” The answers were limited to “No”, “Not really”, “Maybe”, “Sort of” and “Yes”. These answers were weighted from 1 to 5 with 5 being the most positive response to the question. The post activity survey also included short answer responses. These involved questions about their enjoyment about the activity and what was easy or hard about the activity. Responses will be discussed in sections.

evaluation

The PaperBots Robotics Kit Prototype 1 was evaluated based on observations of the first testing group, their survey results and the robots they were able to produce. Using the observations and survey data, conclusions on the usability and the effectiveness of the product are made. The robots are evaluated as a sign of the creativity available using this type of robotics education implement. Shah, Smith and Vargas-Hernandez identify four types of outcome based metrics for evaluating design creativity: quantity, variety, quality, and novelty\textsuperscript{18}. These metrics are intended for examination of generated ideas as well as produced artifacts. Due to the lack of structured and documented idea generation activity from the workshop, the available artifacts serve as the examined population and were measured according to these metrics. Quantity examines the total number of ideas generated and was not recorded.

usability

Within a 3-hour time period, the participants completed an assigned engineering task utilizing a product with which they had no prior experience and the provided paper and craft materials. Completing the task to the satisfaction of the requirements is indicative of some amount of intuitiveness within the product. The survey questions 5 and 10 asked directly about how hard it was to build. Questions 2, 4, 7 and 8 more indirectly relate to the ease of the activity by asking about it overall and the time allotted for it. (Table 5.1) The average survey score of those

<table>
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<th>Question</th>
<th>Score</th>
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<td>1  I thought the instruction were very easy.</td>
<td>4.3</td>
</tr>
<tr>
<td>2  I had enough time to finish the activity.</td>
<td>4.8</td>
</tr>
<tr>
<td>3  I think the activity helped me understand problem solving and robotics concepts.</td>
<td>4.3</td>
</tr>
<tr>
<td>4  I thought the activity was very hard.</td>
<td>3.6</td>
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<td>5  I thought the activity was very easy to build.</td>
<td>3.2</td>
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<tr>
<td>6  I thought the instructions were very confusing.</td>
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</tr>
<tr>
<td>7  I thought it was really hard to finish in the time I was given.</td>
<td>4.3</td>
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<tr>
<td>8  I thought the activity was very easy.</td>
<td>3.2</td>
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<tr>
<td>9  I am more confused about the problem solving and robotics topics after I finished this activity.</td>
<td>4.8</td>
</tr>
<tr>
<td>10 I thought the activity was very hard to build.</td>
<td>3.6</td>
</tr>
<tr>
<td>Average</td>
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questions is 3.8 out of 5.0, a generally positive response to the activity. Two other mechanical engineering graduate students assisted in the workshop as well, providing assistance and helping to observe and record the proceedings. They described the activity as just as successful as some LEGO based workshops have been. They observed that the participants engaged in conversations about how their robot would function and how they would work together. There also noted that there were conversations similar to those they’ve come across in LEGO and Arduino projects about how they would hook up the components and how would they attach the parts to the structure they were building\textsuperscript{15,19}.

The participants were also asked open-ended questions as part of the post-activity survey. “Building” was a common response to “What part of the activity did you find hard?” but with regard to using the provided materials. When asked “What part of the activity was easy?”, three participants identified the assembly of the PaperBots robotics kit components. The video data also shows many of the participants making the electrical connections properly and with ease.

creativity

As part of a single workshop where 15 participants produced 5 artifacts for examination, no definite direct correlation between the PaperBots Robotics Kit and its inherent promotion of creativity can be made. This thesis examines those available artifacts as a case study of what students are capable of producing and experiencing using PaperBots under the provided conditions. Examination of larger populations utilizing several different educational tools, including PaperBots, would be required for more viable evidence of increased creativity due to the technology.

To generalize the five robots; two would be considered vehicular, having all components fully integrated into a single body with rotational driven motion; two are stationary arm system, where the motor is stationary and appendages are driven to actuate the next robot, and the last is a hybrid system, where the motor and sensor unit are mobile but tethered to the controller. Important to mention again, the offset motor hubs of the PaperBots motor are intended to be a barrier to simple wheeled motion. Two of these groups overcame that issue through unique use of craft and found materials, achieving a common type of motion in spite of the designed barrier.

variety

Variety indicates of the explored design space through examination of the how each function is satisfied. Figure 8 and figure 9 show the genealogy trees for the primary functions of the robots, to sense the previous robot and to actuate the next. Calculated out using the formula \( M_v = \sum_{j=1}^{m} f_j \sum_{k=1}^{4} S_k b_k / n \) where \( m \) is the number of functions evaluated, \( S_k \) is the score for level \( k \), \( b_k \) is the number of new branches for that level, and \( n \) is the number of ideas, artifacts in this case. The values of \( f_j \) were chosen based on the apparent options made available.
Since the instruction and demonstration may have biased the participants towards using the light sensor, a value of 0.25 was assigned to that function and 0.75 for the actuation function. With values of $S_k$ suggested by Shah, Smith and Vargas-Hernandez\textsuperscript{18}, the value of $M_Y$ was calculated to be 7.3; a 10 would result from all robots having a different physical principle. This indicates a high variety among this small sample.

**Novelty**

Novelty measures of how unusual or unexpected an idea is in comparison to other ideas. Previous solutions to a problem may be used to define what is not novel and help with evaluation since this was the first trial for the PaperBots Robotics Kit; the ideas are again limited to those created in this individual case. For this reason, posteriori classification of the artifacts was done. Calculating from $S_{1jk} = \left( T_{jk} - C_{jk} \right) / T_{jk} \times 10$, each feature was scored for its novelty and shown in table 2. $T_{jk}$ being the total number of ideas for that function ($j$) among the entire artifact population and design stage ($k$) and $C_{jk}$ is the amount of instances of that individual solution. This activity only considered a single design stage so $k$ is ignored.
Individual novelty scores for the artifacts are calculated from $M_g = f_j S_j$. The group is represented by $g$, and $f_j$ is the weight assigned to that function. Table 3 shows the novelty scores for the artifacts. For a group this size, a novelty score of 8.00 would be the maximum if each robot had a unique feature for all functions ($C_{jk} = 1$ and $T_{jk} = 5$ for all functions).

### Quality

Quality relates to the performance of the artifact. Each artifact has been scored, which are shown in Table 4, based on whether they performed their two main functions, to sense the previous robot and to actuate the next. This was only considered for their performance during the two trial runs at the end of the workshop. Using equation $M_g = \sum_{j=1}^m S_j f_j / n$, $S_j$ is the score for that function, in this case being the amount of successful attempts. $f_j$ is the weight of the function, $n$ is the number of trials, and $m$ is the number of functions. They have an average quality score of .80 based on assigning a 1 for each successful function. This is a disappointing quality for a Rube Goldberg machine that expects each component to perform its function consistently but is only over 2 trial runs. This metric should not be based purely on the robot’s functionality. In an elementary engineering education setting, I believe the success of the artifact is not the only consideration; the experience of the student is a factor. When asked “I think the activity helped me understand problem solving and robotics concepts.”, the average answer was 4.3. In classroom trials, more in depth pre and post tests would be needed to evaluate student experience but, although just a single data point, this is a positive indicator.

### Effectiveness

During the final trials of the assembled robot Rube Goldberg machine, all of the participants were laughing and cheering even when some robots did not engage properly. As a simple check, this evidence suggests the participants’ enjoyment and engagement in the activity.
many of the participants were still very much engaged in their design while some had already moved on to building new robots just to fill the time. Only 2 of the participants’ attention spans had been visibly exhausted. During post activity interviews, the other graduate students observed that there was “a lot of back and forth” between the students, referring to the amount of interaction between the groups about how their robots would interact within the system. Video observations of one of the groups showed that during the first hour of their build time, one of that group’s participants was in discussions with the group before them and the group after them for a third of that time. One noted that even though there was some “goofing around” by the participants, they all seemed very engaged with the materials and problem. The surveys also included open-ended questions. When asked, “what did you think of today’s activity”, 10 of the participants surveyed described it as “fun” while the others referred to it as “good” or “cool”. When asked about the activity in comparison to their normal classroom activities, 10 of the participants described it in more positive terms like “more creative” and “much better”. The others used general descriptive terms but none indicated it as less enjoyable than their classroom activities.

conclusion

The participants of this workshop were capable of building a moderately functional PaperBots based Rube Goldberg machine. They did so within 3 hours of being introduced to the product and with great autonomy. Although they indicated that the “building” was the hardest part, they had little issue making the electrical connections necessary to make artifacts which sense, think and act. Examination of the variety and novelty metric scores of the artifacts as compared to the ideal score for a population of this size show passable scores, 7.3 out of 10.0 for variety and a 5.33 max out of 8.00 for novelty. Future test groups will have to include a documented idea generation session in order to compare the inherent abilities of the participants to their produced artifacts using the PaperBots Robotics Kit in order to gain better understanding of the product’s influence. The participants left the workshop with a positive opinion of the experience. Their survey responses indicate that they enjoyed participating, had little trouble with the product, and gained more understanding of problem solving and robotics concepts. This test group intuitively utilized the product, created a range of artifacts and enjoyed the experience of doing so. These results of this case study indicate that PaperBots can be an effective tool for engineering education. Further studies among larger and more varied populations would be required for any definitive proof but this case study offers a positive view of the potential of PaperBots.

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