The Development of the PaperBots Robotics Kit for Inexpensive Robotics Education Activities for Elementary Students

A thesis

Submitted by

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Abstract

In this thesis, I describe an electronics kit that enables robotic education activities that make use of readily available classroom materials. The developed product, PaperBots Robotics Kit, opens up accessibility to robotics education for users who formerly could not afford many of the available options. The design considers cost for the intended stakeholders, teachers, and usability for the end users, students, as well as test group feedback and production. This tool kit enables students to build their robot utilizing paper, cardstock, craft sticks, tape, straw and other craft materials common to a classroom. The controller is an Arduino based development board that is programmable by either the Arduino environment or with LabVIEW. Test groups of kindergarten to six grade students successfully constructed robots using paper, craft materials, and the PaperBots Robotics Kit. They were able to intuitively construct with the materials and the kit and program their robots using a provided LabVIEW interface. The participants also enjoyed their experiences with the product while gaining some experience in engineering principles. The first two design iterations of the PaperBots Robotics Kit and their subsequent testing are described in this report along with suggestions for further development of the product.

Acknowledgements

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To my advisor, Chris Rogers, thank you for PaperBots and allowing me the freedom to run with it. This idea has turned into something amazing and I plan to run with it for as long as I can. Your enthusiasm for educational technologies has been addictive and I plan to put that excitement to good use in the years to come. Thank you for your continued support and I look forward to working with you in the years to come.

And finally I would like to thank all of my friends and family for supporting my decision to quit my job and go back to school. There are times I miss Kollmorgen E/O and I will forever appreciate the experience I gained there but I have never been happier in my life. Pat Mallette, thank you for always being there to help me talk through these major life decisions and helping me to stay sane at KEO. This has been the longest and greatest LNR I've ever experienced. Mom, I wouldn't have had the courage and conviction to take this step without your love and support. Thank you for everything.

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Chapter 1: Introduction

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 rather 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." (Bers 2008). 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 (Douglas, Iversen and Kalyandurg 2004). 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 (Beer, Chiel and Drushel 1999). 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 billion. (Training Magazine 2001, Training Magazine 2012).

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 (IFR International Federation of Robotics 2012). 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.

Robotics education

To address these concerns over the lack of knowledge about technologies, how it works, its purpose and potential use or more simply "technological fluency", more curricula are adopting standards pertaining to technology and engineering education. (Bers 2008) Existing guidelines for such curricula recommend they involve hands-on learning for more context based curriculum with emphasis on the social good of engineering and its relevance to the real world, interdisciplinary approaches which involve multiple subjects, mapping the activities to existing state standards such as in math and science, and to find ways to make engineers “cool” to attract a wider range of constituencies (Douglas, Iversen and Kalyandurg 2004). Educational activities involving robotics achieve many of these goals.

The concept of complementing academic curricula with robotics has been discussed since the mid 1970s (Trotter 1973). Robotics activities require students to confront the non-ideality of real-world devices. It offers an inherently interdisciplinary activity, tending to attract students of a variety of disciplines and therefore providing an opportunity for students to engage with other students of varying perspectives. Participants develop specialties in the many subtasks essential to robotics and the engagement in these activities provide experience developing the interpersonal skills necessary to communicate with one another to consolidate their individual specialties and ideas (Beer, Chiel and Drushel 1999). Educational robotics products and activities are available for a wide range of ages and even young children have had successful engagements with them, exposing them to both math and science principles as well as better preparing them for this increasingly automated and technology driven world (Goldmann, Axhar and Sklay 2007). Robotics programs have been shown to be effective for transferring skills in understanding the scientific method and/or the engineering design process, applied math and reasoning, computer literacy, technical communication, creative or lateral thinking, vision and leadership, work ethic and initiative, goals and project/time management, and team work (Nelson 2012). Lastly, robotics provides a fun learning experience for students and has a certain “cool factor” associated with them (Eguchi 2012, Holahan 2011, Yong 2009, Foerst 2005).

Existing Technologies

Several robotics platforms exist which specifically market themselves for education. Bee-bot, shown in figure 1.1, is a simple mobile platform that is programmed by push buttons on the top of the robot (Terrapin 2013). K-Team produces The Hemisson and Activemedia produces the Amigobot, shown in figures 1.2 and 1.3 respectively, two educational robots designed as preassembled units ready for the addition of different sensors (Miller, Nourbakhsh and Siegwart 2008).

Fig.1.1. Digital image of the Terrapin Bee Bot. (Image available from www.terrapinlogo.com)

The products shown in figures 1.4 and 1.5 are the LEGO Mindstorms NXT and its predecessor, the LEGO Mindstorms RCX. They utilize a programmable “brick” computer base along with modular sensors and motors that work with standard LEGO pieces for added mechanical prototyping to the activity (Miller, Nourbakhsh and Siegwart 2008). Tetrix by Pitsco and The Vex Robotics Design System, displayed in figures 1.6 and 1.7, utilize more heavy-duty aluminum hardware with standard, or more real-world, nuts and bolts for its building platform (Eguchi 2012). The iRobot Create, shown in figure 1.8, is an educationally geared variation of the iRobot Rumba, the most

Fig. 1.2. Digital image of the K-Team Hemisson. (Image available from www.k-team.com)

Fig. 1.3. Digital image of the Activemedia Amigobot. (Image available from http://www.zsoltkira.com)

Fig. 1.4. Digital image of a LEGO Mindstorms NXT project. (Image available from Parekh, Alan 2006, http://hackedgadgets.com)

Fig. 1.5. Digital image of a LEGO Mindstorms RCX project. (Image available from www.microworlds.com)

common robot in the world, which has added interfaces to encourage experimentation (Miller, Nourbakhsh and Siegwart 2008).

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 (Nagel 2010). Providing robotics platforms to those budgets would drastically increase them. The Hemisson costs $250 per kit without software (Generation5 2003) and the Amigobot sells with its software suite for $3,095. The LEGO Mindstorms NXT currently retails for $279.95 with the software sold separately (LEGO Education 2011). Also without software, TETRIX retails for $871.95 for the basic kit (LEGO Education 2011) and the most inexpensive Vex Robotics Design System kit costs $399.99 (VEX Robotics 2012). The iRobot Create is the least expensive example at $129.99 each (iRobot 2012).

Fig. 1.6. Digital image of a project made from Tetrix by Pitsco. (Image available from www.pitsco.com)

Fig. 1.7. Digital image of a project made from the Vex Robotics Design System. (Image available from www.vexrobotics.com)

LEGO Education and their signature product, LEGO Mindstorms, are the most well known and popular among the previously mentioned products. LEGO Mindstorms has been integrated into classrooms around the world (The LEGO Group 2011). The cost of their product is one of LEGO's biggest obstacles in entering more classrooms. For a standard U.S. classroom size of about 24 students, rounded up from the real average of 23.1 students (Rampell 2009), 8 kits would be needed for effective use assuming teams of 3 students. This requires an approximate $2,650 investment per class, which includes the LEGO Mindstorms Education NXT software site license (LEGO Education 2011). Less expensive building kits, such as the iRobot Create, would still carry a hardware cost of approximately $1300. These costs all far exceed the budget of the average K-12 teacher, making many of them cost prohibitive. Outfitting the classrooms with these technologies commonly requires the added effort of seeking additional financial support such as grants or community donations.

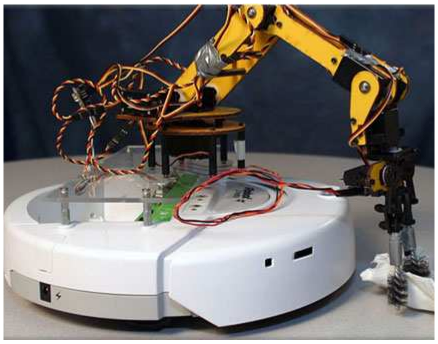


Fig. 1.8. Digital image of a project made using the iRobot Create. (Image available from store.irobot.com)

Other products exist that have not been marketed for classroom use until recently. Makey Makey is a product that turns ordinary objects like bananas or people into a digital contact sensor or “key”. The $49.95 standard kit includes the Makey Makey human interface device(HID) and the basic hardware required for its use (Sparkfun Electronics 2013). Although much less expensive than the previous products, the Makey Makey is not a robotics platform, just a sensing platform capable of mimicking a keyboard or mouse. For a less expensive robotics platform, Arduino products offer inexpensive microcontroller development boards. The Arduino Uno R3 costs $29.95 each but the Sparkfun Inventor’s Kit for Arduino includes the Arduino Uno R3 and hardware needed for getting started with programmable electronics for $94.95 (Sparkfun Electronics 2013). This is a more affordable option but is not designed with K-12 engineering education in mind.

PaperBots seeks to provide a more accessible means for students to participate in hands on science, technology, engineering, and math (STEM) activities and emphasizes creativity, engineering principles, team collaboration, and communication. By designing the platform to utilize common classroom materials, it hopes to provide a more affordable robotics activity. Through design with elementary students in mind, it intends to be an accessible and relatively simple robotics platform to be implemented in classrooms that otherwise would not be capable of implementing robotics education.

Chapter 2: Background

Goals

The goal of this thesis is to develop and test an electronics kit that would enable robotic education activities that make use of readily available classroom materials. This kit serves as an advancement of PaperBots, a product that focuses on using inexpensive materials, specifically paper, office and craft supplies already taken into account as a part of a school's existing budget to provide and implement cost effective engineering education for classrooms that would otherwise not be able to afford the existing educational technologies. By providing an inexpensive means for engineering education, we hope to expand the implementation of engineering education in lower income regions throughout the United States and the rest of the world.

Initial Idea

Masao Ishihara, President of Learning Systems Co. of Japan and Managing Director of Robert Rasmussen and Associates of Japan, presented an interesting problem to Dr. Chris Rogers of Tufts University and its Center for Engineering Education Outreach (CEEO). Learning Systems Co. was founded in 1997 to distribute educational tools such as LEGO Mindstorms to schools and after school programs in need of more STEM education programs and products (Ishihara 2013). Expansion into the India marketplace proved difficult for Mr. Ishihara due to the limited budgets in many of the rural areas. This brought about the question, "What can be done to provide effective and interactive design activities in schools with restricted budgets?"

Mr. Ishihara quickly noted that paper is available in all schools. This realization led to the main question behind PaperBots: How can we provide engineering education lessons using paper as our primary material? Dr. Rogers provided this question to two of his ME94 undergraduate research students, Marina Bagot and Abigail Spencer, in 2011. They produced a kit, which they entitled “Francesca the Fly”, that contained a $10 non-programmable control unit constructed from a motor, button, on/off indicator led, and battery; construction paper; double sided adhesive paper; and basic designs to cut out using a digital craft cutter. They estimated this kind of activity would cost a classroom about $400.00, their cost estimate being based on the initial cost of purchasing a $249.99 CraftRobo digital cutter and 10 kits for $15 each. Compared to the purchase of 10 base NXT Mindstorm kits for $279.95, they estimated a savings of $2400 at the time (Bagot and Spencer 2011).

Research

Building off of this initial idea, I expanded it into PaperBots, an inexpensive means for engineering education. There are numerous approaches to making education more affordable. Many organizations exist who believe the engagement of students in activities that promote creativity and allow them to express themselves. Some have worked to democratize educational technologies; specifically those intended to engage students in electronics, computers and robotics. Through use of the materials students already have, like paper and craft supplies, and introducing them to new materials and electronics, these organizations help to lower the cost of engineering education.

The use of paper has an obvious association with origami, which has been used as an educational tool for many years. It’s mainly been associated with mathematics at the early educational levels to date (Boakes 2009, Yuzama, et al. 1999, OrigamiUSA 2013). Researchers of the High Low Tech research group of the MIT Media Lab have used shape memory alloys to animate origami figures, an example of which can be seen in figure 2.1. (Qi and Buechley 2012) and created paper based electronic sensors that are used in interactive pop-up books (Qi and Buechley 2010). This research group has also been integrating electronics and craft materials in hopes of introducing new communities of people to technology production. They have done this through programs and workshops that use conductive ink for drawn circuits on paper as well as using copper tape for the same means, mounting of microcontrollers and other electronics on craft materials, and emphasizing the skilled use of tools and craft materials to create the electronics. These workshops mainly pull from the local MIT community though for participants so they range in age anywhere from 20 to 60 (Mellis, et al. 2013, Perner-Wilson 2011).

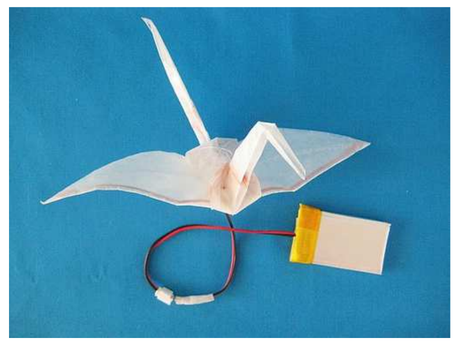


Fig. 2.1. Digital image of origami bird made with shape memory alloy to animate it (Image available from hlt.media.mit.edu)

The High-Low Tech research group has also done some work using craft based electronic activities with younger participants. The Arduino Lilypad, shown as part of the Lilypad Arduino Toolkit in figure 2.2, is an Arduino-based development board designed to be sewn to fabrics and has a suite of associated electronics also designed for wearables and e-textiles. It was designed and developed by a member of that research group who utilized two eighth grade girls as the initial pilot study participants (Lovell and Buechley 2010). It is currently an available product that has also been advocated for workshop and classroom use (Sparkfun Department of Education 2013).

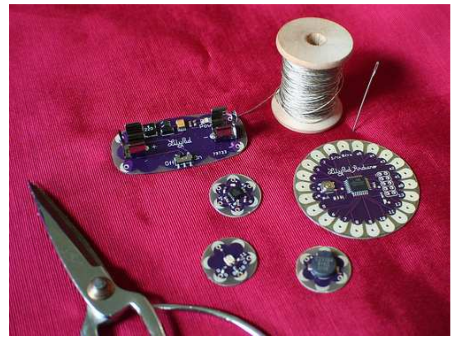


Fig. 2.2. Digital image of the LilyPad Arduino Toolkit (Image available from hlt.media.mit.edu)

Another research group from MIT Media Lab is Lifelong Kindergarten. There they created the Picocricket, a product that utilizes a programmable controller with modular sensors and motors that can be connected together through provided cables, represented in figure 2.3. This product enabled young people to design and program electronics that are designed to be combined with craft materials for added light, sound, music and motion to their artistic constructions. During this research, they saw that the combination of those craft materials, mechanical parts, and programmable devices offered a more universal appeal to both boys and girls than products like LEGO (Rusk, et al. 2008). During an informal assessment among a group of fifteen 9-12 year old girls, they showed prolonged engagement with the product over 10 weeks of activities as well as interest in more advanced programming concepts in the informal assessment (Rusk, Berg and

Fig. 2.3. Promotional image of The PicoCricket Kit (Image available from www.playfulinvention.com)

Resnick 2005).

Stakeholders

As part of PaperBots development, examination of the market and stakeholders helped to provide support for continued development of the product. The educational technology market is a $7.5 billion industry in the United States alone (Watters 2011). Both industry and government have made increased investments in this market over the last few years. The Silicon Valley, home of the world's largest technology companies, invested $177 million into educational technology companies in 2010, three times the investment made in 2007 (MacMillan 2011). The American Recovery and Reinvestment act of 2009 provided $650 million specifically for educational technology (United States Department of Education 2009).

This investment is also seen in existing policy. Engineering skills and knowledge are included in the academic standards of 41 states' standards (Carr, Bennett IV and Strobel 2012). Current Massachusetts state guidelines require 90% of all teachers to be using technologies in the classroom for activities such as simulations, data analysis, communication and collaboration and to integrate technologies that heighten student interest, analysis and creativity by 2015 (Massachusetts Department of Education 2010). These technologies are expensive and teachers are the ones being required to implement them. They will likely prefer relatively inexpensive options.

Teachers are the ones who are required to meet these upcoming standards. They will make the initial and greatest investments in both time and money to bring such technologies into the classroom. Administration, parents, and aids are also stakeholders because they are interested in the product's educational results as well as how it works in the classroom. It has become an accepted practice among school districts to expect teachers to spend a significant amount of their own money each year on classroom resources. The NSSEA study showed that 92% of U.S. teachers spent money out-of-pocket to provide for their classroom. That amounted to $3.5 billion outside of their provided budget in the 2009-2010 school year, $1.3 billion of which was from their own money instead of other sources. That's an average of $356 per teacher spent on supplies and instructional equipment not provided by their school district, through grants, or from parent or PTA support (Nagel 2010). These expenditures are commonly written off in taxes but this does not always fully reimburse the teacher. Anything with an overall cost above these levels may be cost prohibitive especially for classrooms with little administrative and community support.

Conclusion

Based on this information, there is a need to make engineering education more accessible. Other research groups have already shown interest in finding new and interesting ways to implement these types of activities. Massachusetts state education standards require teachers to include engineering skills and knowledge within their curriculum. The existing educational technologies exceed the individual budget of the average teacher so affordable alternatives would be a welcome option for these stakeholders.

Chapter 3: Implementation

Implementation

With backing for the educational and financial potential of utilizing craft materials for engineering education activities with students, I further examined the capabilities of paper and existing paper craft projects leading to development of some simple mechanisms, such as structures, cams, ratchets, cranks, and levers out of paper, shown in figure 3.1. Creation of working mechanisms out of paper was relatively simple after gaining some experience with paper craft, but that was only after acquiring some skill for use of the material and having prior knowledge about the mechanisms and devices being

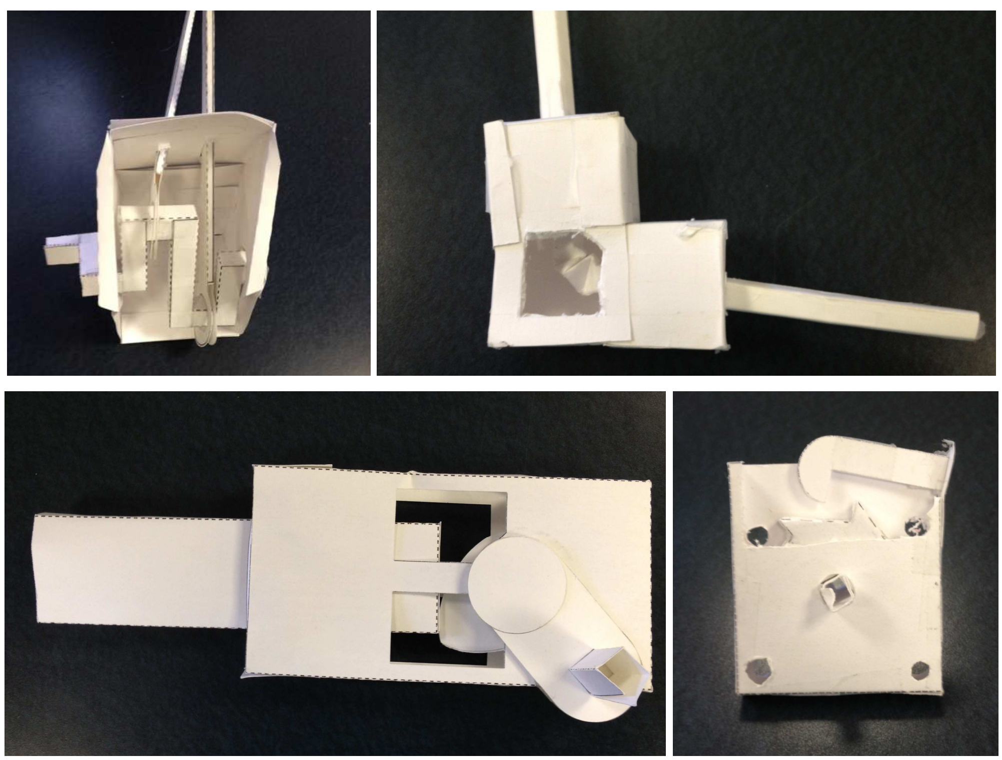


Figure 3.1: Examples of simple mechanisms created by papercraft. *Top left*, A double piston with camshaft made from cut cardstock and tape; *top right*, an origami universal joint made from paper in a cut paper and tape housing; *bottom right*, a ratchet and crank made from cardstock and tape; *bottom left*, cam and piston made from cardstock and tape. (Photos by author)

made. Creating such devices seemed very difficult for a student without such prior knowledge. With help of a team, including graduate students from mechanical engineering and human factors, these initial creations were developed into educational activities. Through further assistance from feedback from undergraduate test groups, high school summer interns, teachers, and kids, these activities became more properly suited for inexperienced students and teachers.

Initial PaperBots Activities

This initial research and development led to three activities which are capable of being implemented only using common classroom materials: The Pull-Up Man, The Rubber Band Car, and The Rube Goldberg Machine. Each activity increased in build difficulty while building on engineering principles that were presented in prior lessons. The Pull-Up Man is the first of the PaperBots activities, the completed assembly shown in figure 3.2. Within this activity students learn about cams and other mechanisms as well as assembly design. While the lesson plan for this activity does provide detailed instructions there may still be room for design errors, such as component overlap. If errors occur, the student has the opportunity to test their mechanical knowledge by inspecting the assembly to identify the error and carry out

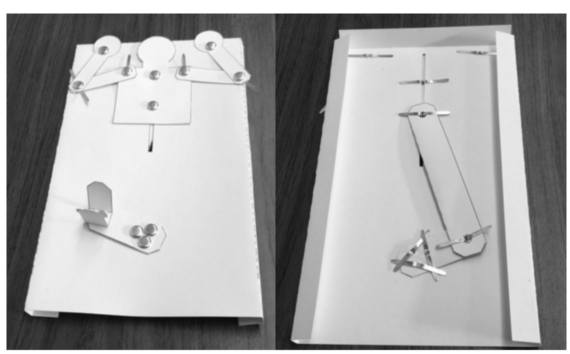


Fig. 3.2. Images of the completed assembly from The Pull-Up Man activity. Left, front of completed assembly showing crank and character which is animated by the action; right, rear of completed assembly showing rotational arm attached to cam shaft. (Photos by author)

modification accordingly.

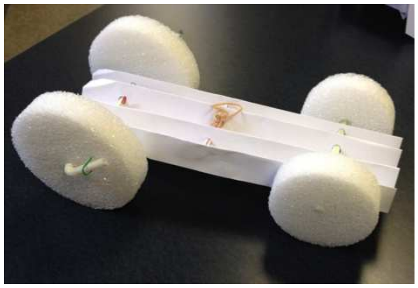


Fig. 3.3: An example of a project from the Rubber Band Car activity (Photo by author)

The Rubber Band Car is the second PaperBots activity. An example from that activity is shown in figure 3.3. This activity introduces students to the concept of free form design and energy transfer as well as the iterative design process. Ultimately, the intention is for students to iterate the mechanical design of the car to maximize the internal energy transfer of the rubber band to the car’s motion.

The third activity requires students to construct a Rube Goldberg machine using paper and other classroom objects. Within this activity the classroom is split into teams of two or three students. Each team is assigned to a defined square that fits into a larger project pattern, creating an environment for inter-team communication and collaboration. The team is required to build a mechanism that will interface with the mechanisms of the teams on either side of their square. The goal for the group is to have a marble start at the first team’s station and to have a marble end in a cup placed in the last team’s station. This activity requires students to be creative and take on a problem-solving attitude. Each team needs to be aware of how they impact and interact with the larger group. Transparency of each team’s work and goals as well as the effective communication and collaboration between groups is imperative for the success of the overall design. The Rube Goldberg activity also emphasizes iterations, testing, and the concept of learning from failures to strengthen the final design.

Figure 3.4 shows an example of a developing fourth activity in the PaperBots series, the HexaBot. The HexaBot activity will allow the children to experience a more complicated build as well as construct a walking machine. It will later serve as the base of a robot that incorporates simple sensors and responses. Other future activities involve a greater range of mechanisms, mechanical computing, Boolean logic, and structures. The ideal would be that PaperBots would provide an activity to support every state standard and behavioral issue. Further development of these ideas and concepts into lesson plans and activities will be future work for the overall project.

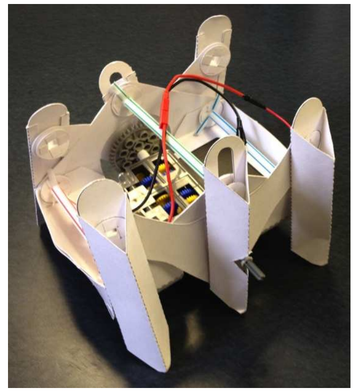


Fig. 3.4. A prototype design for the Hexabot activity. (Photo by author)

PaperBots Robotics Kit

Up to this point, design had concentrated on engineering education activities that involved only standard classroom materials (with the exception of the Hexabot that utilizes a motor like the “Francesca the Fly” kit). The rest of this thesis concentrates on the design, manufacture and testing of the PaperBots Robotics Kit that includes a programmable controller and peripherals designed for construction with common classroom materials and by elementary students. Before this product, PaperBots was only providing mechanism and design based engineering activities within controlled instruction, free form design, but no sensor input or use. The robotics kit intended to provide for the implementation of more creative and robust activities, specifically in robotics education.

Chapter 4: Design

The PaperBots Robotics Kit went through 2 major design iterations. Each consisted of a programmable controller, a light sensor, a gearmotor (gearbox with brushed DC motor), and a set of alligator clip test leads. This goal of this kit is to provide the electronics necessary for the construction of a robot. It is intended to easily achieve electrical connections between the components using alligator clip test leads and to be able to interface with a structure, or robot body, that has been constructed from paper and other craft materials.

Prototype 1

The first prototype for the PaperBots Robotics Kit was constructed with the overall thesis in mind. The design considerations are mainly based on existing products, suppositions of user capabilities, and cost.

Wiring

The first major concern of the design was how to solderlessly interconnect the electrical components as easily as possible. In terms of ease of physical use for young students, banana jacks and alligator clips were the top choices. Alligator clip test leads were chosen because they were less expensive than banana jack test leads, $2.95 for 10 as opposed to $4.95 for 2 on Sparkfun.com (Sparkfun Electronics 2013) and the Makey Makey, which was designed for use with alligator clip test leads, was recently released and had proven to be a popular and successful item on Kickstarter (Silver 2012).

Motor

The gearmotor is a Solarbotics GM3 224:1 gearbox with low-current motor available through polulu.com at $5.95, shown in figure 4.1. This gearmotor was selected due to affordability and its low operating voltage and low current of the motor. The built in safety clutch is also a strength since it prevents students from damaging it by binding up due to material interference or manually turning the output shaft, two events considered very likely when dealing with elementary students. The dual output shafts held appeal due to the versatility and orientation options they offer and since other systems, like LEGO Mindstorms' motors, utilize a similar configuration (Pololu Co 2013).

Fig. 4.1. Digital image of the Solarbotics GM3 gearmotor with a US quarter for scale. (Image available from www.pololu.com)

The gearmotor was modified for use with paper materials and the alligator clip test leads. Figure 4.2 shows the modified unit. The motor was encapsulated by a 3D printed housing which included two access holes for the alligator clips. The motor's solder tabs were soldered to copper wire that was wound around the diameter of those access holes for

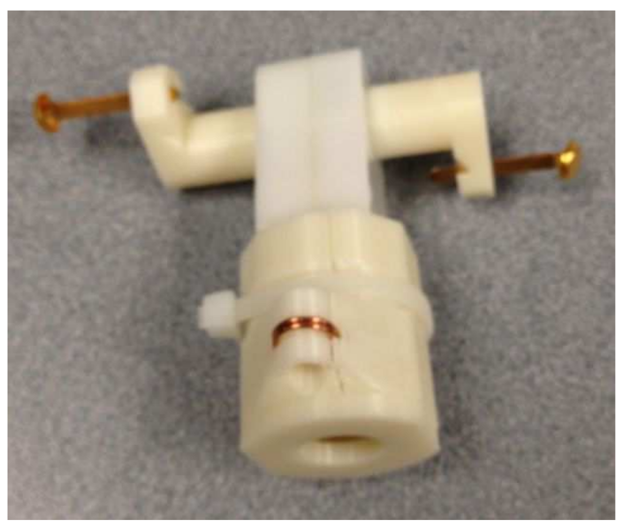


Fig. 4.2. PaperBots Robotics Kit Motor, modified from Solarbotics GM3, with added housing and hubs. (Photo by author)

the alligator clips to contact with. For the output shafts, offset hub arms were designed and also 3D printed. The ends of the arms contained a mounting slot sized for a standard brass fastener. Molded wheels and cast hubs with screw mounting holes do exist for this product but were thought to be inappropriate for use with paper and craft materials as well as guide design towards cars if the motor came with attached wheels or round hubs. The arms had slots sized for brass fasteners, a commonly available office supply, and are offset by 180° in hopes of presenting a better design challenge for the students.

Light Sensor

An analog light sensor is included in the kit, shown in figure 4.3, since one of the major functions of a robot is sensing and the two types of signals are digital and analog. Although digital sensors can easily be made from classroom materials like aluminum foil, analog sensors made from classroom materials require more prior knowledge of those material properties and some ingenuity to take advantage of those properties (Perner-Wilson 2011). This sensor is meant to be an introduction to analog sensing for the students. It consists of a photoconductive photocell (PcP) in a 3D mounted housing. The PcP is an Advanced Photonics Inc product available on digikey.com for $1.86 each (Digi-Key Co. 2013). The housing, like that of the motor's, is 3D printed and has two access holes for the alligator clips to connects with and copper wire wound around the edge for the alligator clips to

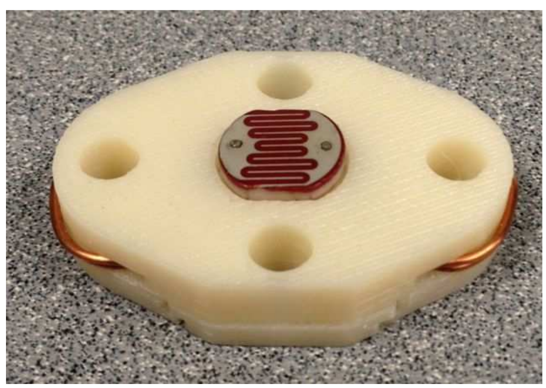


Fig. 4.3. The PaperBots Robotics Kit Light Sensor. (Photo by author)

contact with.

Controller

The controller for the first prototype of the robotics kit is a custom shield for a Teensy 2.0, which can be seen in figure 4.4. The Teensy is an Arduino based USB development board selected for its low cost of $16. The shield contains several electronic components mounted to a custom printed circuit board (PCB) enabling its function: a 9V battery holder, a button press momentary single pull single throw (SPST) switch, a slide double pull double throw (DPDT) switch, a 5V voltage regulator, a 10K ohm resistor, and an integrated circuit (IC) of a quadruple half-H driver (H-bridge). There are 6 exposed scallops on the shield’s board that the user can clip to using the alligator clips test leads and 3D printed plastic components to protect the mounted electronics.

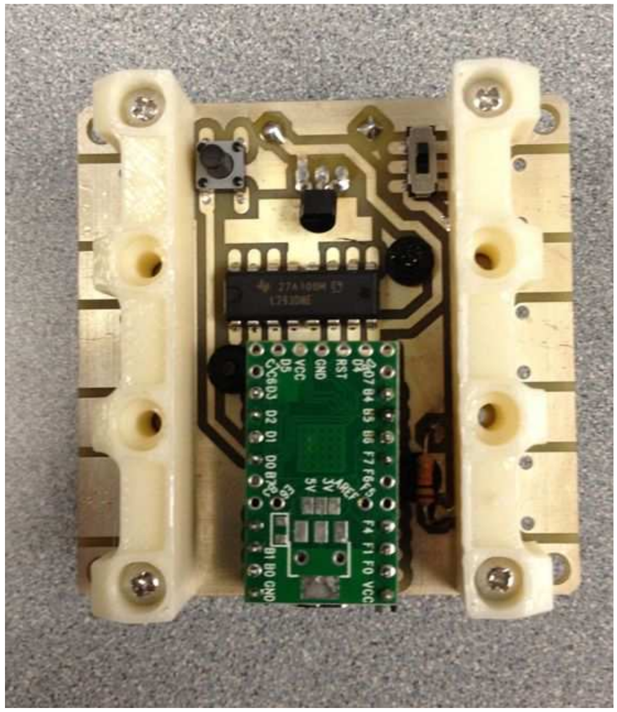


Fig. 4.4. Component side view of the PaperBots Robotics Kit Controller. (Photo by author)

A 9V battery powers the entire unit. This was chosen due to it being a readily available product, also available in rechargeable, and has a high voltage to volume ratio.

The 9V supply is used to power the motors and is regulated to 5V to power the H-bridge, which has a 7V max input, and the Teensy, which functions at 4.5 to 5.5 V.

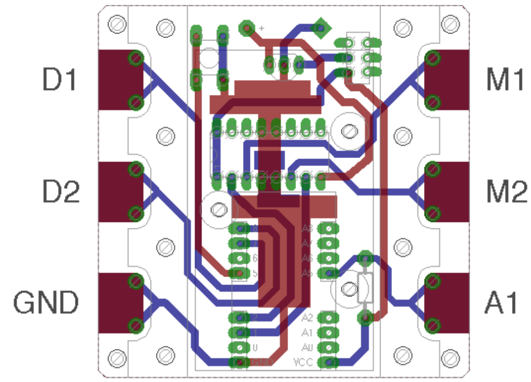


Fig. 4.5. Electrical traces of the PCB with labeled contact scallops. (Image provided by author)

The scallops provide the user with interface to the Teensy, shown labeled in figure 4.5. Scallop D1 and D2 connect to digital pins 7 and 8. Scallop A1 connects to analog pin A5. The 10K ohm resistor bridges scallop A1 to the 5V supply to serve as a pull-up resistor for that connection. Pins 7 and 8 have internal pull-up resistor capabilities within the AVR Atmega328, the microcontroller of the Teensy 2.0, so they did not require additional resistors added to the shield. The ground (GND) scallop is to ground out the signal since the other pins are stably held high due to their pull-up resistors.

The H-bridge used is Texas Instruments L298. It controls the motor outputs, scallops M1 and M2. Figure 4.6 shows the pinouts for connection to and from the H-Bridge. It controls the 9V feed to the motor based on the values of pin 1 and pin 2 of the Teensy as compared to the 5V being fed to the enable pin of the H-bridge. These are 2 digital pins only capable of sending a high (5V) or low (0V) signal to the H-Bridge. Although capable of variable output, by only utilizing digital pins, the motor is only capable of reverse, forward or stall. The logic behind

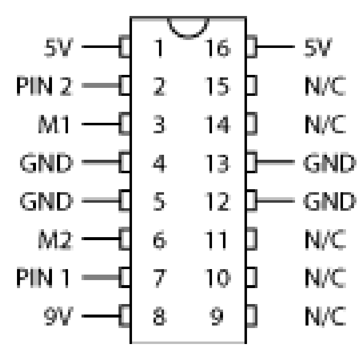


Fig. 4.6. The pinouts for the H-Bridge. (Image provided by author)

these commands is shown in table 4.1. The GND pins are connected to a heat sink plane included in the design of the PCB in order to dissipate any heat generated within the IC as a standard safety precaution.

Table 4.1: H-Bridge Logic Table for Prototype 1

Pin 1	Pin 2	Motor
Low	Low	Off
High	Low	For
Low	High	Rev
High	High	Stall

The slide switch serves to disconnect the power so the battery is not drained if left in the unit. The tactile switch provides an accessible standard sensor for the user to utilize. It connects to digital pin 5. This is the interrupt pin 0 for Teensy. Interrupt allows for emergency disruption of the programming, if this functionality is included in the code.

The shield was specifically designed for minimal sensor input, 2 digital options and 1 analog, and a single motor control. The Teensy has 25 input/output (I/O) pins, 12 of which are analog. Figure 4.7 shows how the pins connect out to the other components on the shield. Limiting the available connections is intended to keep the design options to a appropriate level for young students. The choices were based on assumptions that with 2 digital I/Os, one could be for turning the unit on or go forward and the other for turning it off or go in reverse, and a single analog I/O would be usable for a threshold based control, that the unit would turn on if the signal is above or below a threshold and off otherwise. This was determined to be the bare minimum needed and therefore a good limit for a student's initial experience with robotics. There is also the

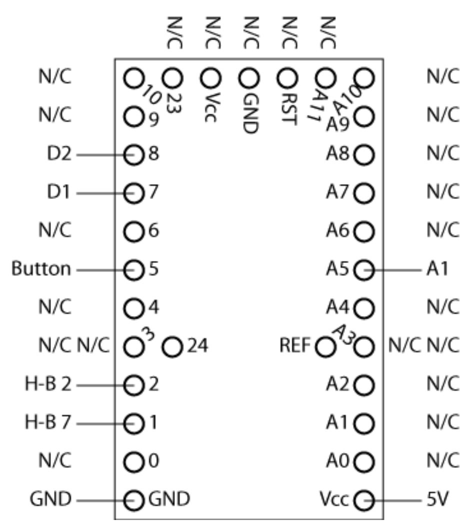


Fig. 4.7. Pinouts for the Teensy USB development board. (Image provided by author)

assumption that the principle that constraint breeds creativity will further challenge the students, in hopes of producing some interesting design choices (Stokes 2001, Lehrer 2011).

Prototype 2

During testing of The PaperBots Robotics Kit Prototype 1, no issues were identified with the cabling, motor, or light sensor that demanded redesign. The clip interface of the motor and light sensor caused no issue for the first test group. The participants were able to attach to the hubs of the motor using craft materials. Since no issues came up with physical interface to either the light sensor or motor, no changes were made to those components. The group also had no major difficulties with the alligator clip test leads so that method of interconnection was maintained.

The controller was the only component that required redesigns. It had several known and discovered issues to it. By having a removable microcontroller, the Teensy, it risked loss or damage. The through hole mounting components are useful for prototyping but bad for manufacturing. They also caused some confusion among the participants of the test group when the 5V regulator was mistaken for an actionable switch due to their similar visible affordances. Protective features like surge capacitors for the motors were excluded from prototype 1 to keep the initial design simple. The second prototype controller was going to be a complete “build from scratch” design so more opportunistic features were added to improve functionality.

Controller

The second prototype for the PaperBots Robotics Kit contained an updated programmable controller. The second prototype controller is a fully independent Arduino clone; meaning that it is a single unit development board based on existing an existing Arduino development board instead of being a shield to an existing development board. Building the unit from the PCB up allowed for full control of the components being installed. It is also a step closer to what a production unit would actually be, which allows for a more accurate cost estimate for a production run. The component locations have more freedom of location since mounting and connecting to a secondary development board does not define connection points.

The PaperBots Robotics Kit Prototype 2 Controller is based on the Arduino Pro, which is designed and manufactured by SparkFun Electronics and retails for $14.95 (Sparkfun Electronics 2013). This board was selected because of its low cost compared to the other available Arduino boards. The PaperBots control module version 2 utilizes the same schematic as the Arduino Pro with some alterations and a modified layout of the PCB for alligator clip test lead interface. Connections for external power were removed and replaced with a 9V battery holder. They were removed to reduce overall cost by not having auxiliary components for power since an on board source has been made available. The power switch remains as well as the 6-pin programming header, requiring a USB to Serial cable to program the unit.

Small size surface mounting device (SMD) components were used since those style components are becoming more popular and available in industry, therefore less expensive due to their mass production. As mentioned, there was also an unforeseen issue with through hole components being mistaken for actionable switches in the first test group. Two different groups mistook the through hole voltage regulator of the first prototype, seen in figure 4.8, as a switch and began bending it back and forth. This misconception was discovered and corrected before permanent damage occurred. With SMD components, these misconceptions are very unlikely to occur.

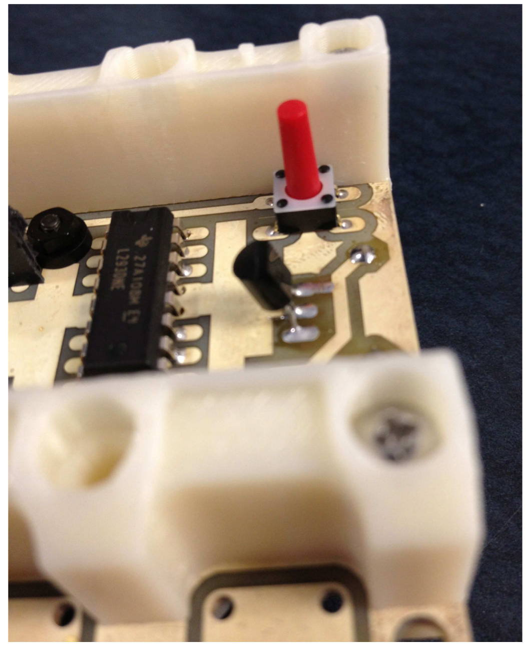


Fig. 4.8. Magnified image of the 5V Regulator on Prototype 1. (Photo by author)

Mounting hole patterns for two servomotors has been included on the PCB design. Figure 4.9 shows the locations of these added hole patterns as well as the other added features. The participants of the first study described options they would like in future motors, mainly angle control, that would be serviced by a servomotor. The base kit does not include a servomotor at this iteration so they were left unpopulated to continue to keep

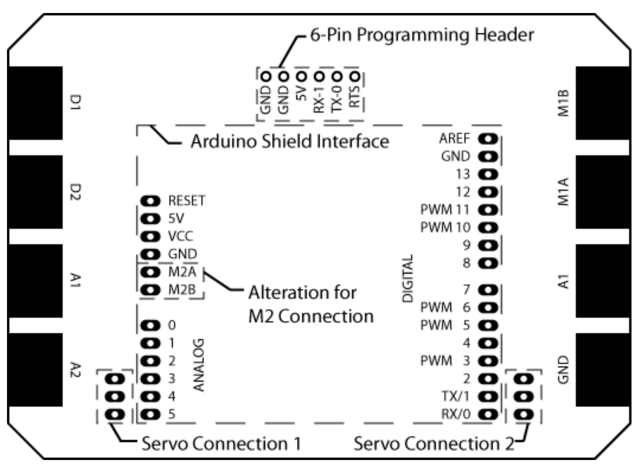


Fig. 4.9. Pinout diagram for the PCB of the Paperbots Robotics Kit Controller prototype 2. (Image provided by author)

cost down. Servomotors usually come with a standard 3-pin power and control cable so the design accommodates user addition of the mating connectors for those devices. One of the servomotor patterns is connected to analog pin A2 and the other is connected to analog pin A3.

This design has 16 digital I/O pins, 6 provide pulse width modulation (PWM), and 6 analog inputs, all accessible from the standard Arduino shield interface pattern and seen in figure 4.9. Scallops D1 and D2 are connected to digital pins 2 and 3, pin 3 is PWM capable. Scallops A1 and A2 are connected to pins A0 and A1. A SMD equivalent of the H-bridge used in prototype 1 has been added to the board. The H-bridge is connected to digital pins 5, 6 and 7, which controls motor 1 and connected to scallop M1A and M1B, and digital pins 8, 9 and 10, which control motor 2. Pins 5 and 10 are PWM capable, enabling speed control of the motor, another requested feature from the first test group. A ground and battery pin of the Arduino shield interface pattern is replaced with pin outs for motor connections for a second motor, M2A and M2B. The ground pins of the H-bridge are connected to a heat sink plane designed into the PCB. Surge capacitors were added to the motor connections to ease directional transitions of the motor; preventing "jerky" starts and stops of the motor. These also suppress sparks and surges caused by the motor backlash during these transitions that could harm the IC.

Code

The first test group complained of not having the ability to program the units. Using the Universal Robot Application Programming Interface (URAPI) developed at the CEEO, a LabVIEW based user interface (UI) was developed for the second test group.

The second testing group was a daisy scouts troop, the initial level of Girl Scouts of America. The girls' ages were varied from 5 to 7 and were in kindergarten and first grade. Keeping their age and presumed experience in mind, the user interface was kept simple and can be seen in figure 4.10.

The color scheme and decoration of the UI shown in figure 4.10 were selected to appeal to young girls, consisting of shades of pink, purple and blue. It has 3 selectable icons that display options for each; one for "sense", one for "think", and one for "act". This is an attempt to reinforce the "sense-think-act" paradigm as the operational definition of a robot. Figure 4.11 shows the images used for the icons. Each has an associated field with it that alters with the command, describing how each command functions. For images of each available command field, see Appendix C. The sense icon allows the user to select which sensor connection will be used; D1, D2, A1, or A2. An

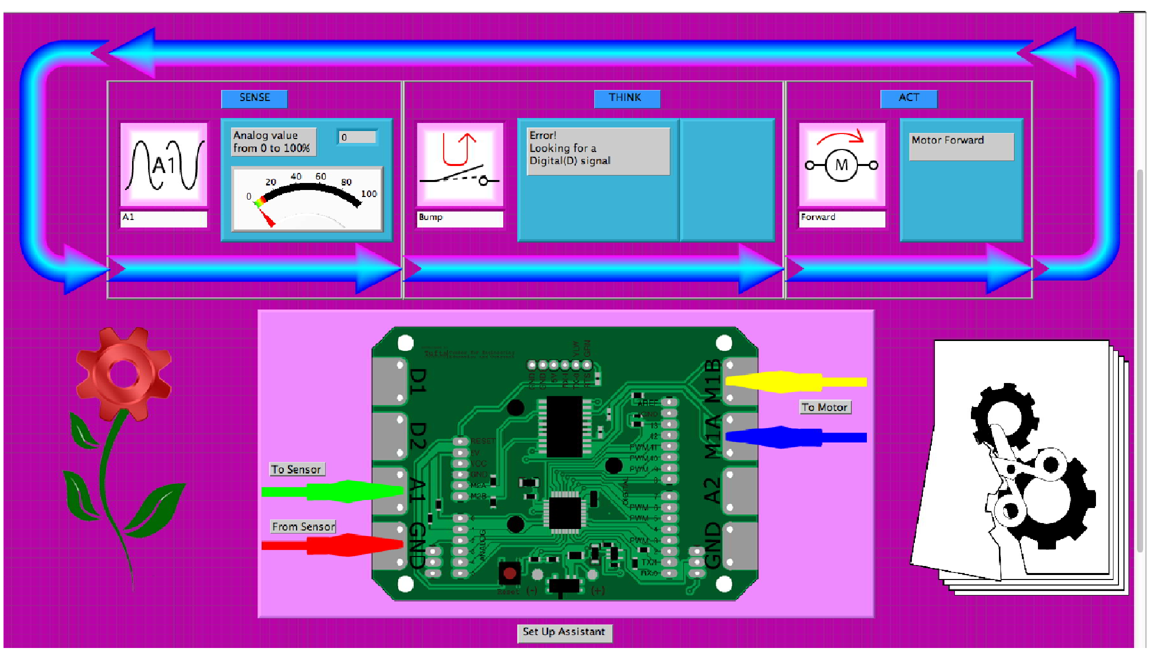


Fig. 4.10. Front panel of the LabVIEW UI developed for Testing Group 2. (Image provided by author)

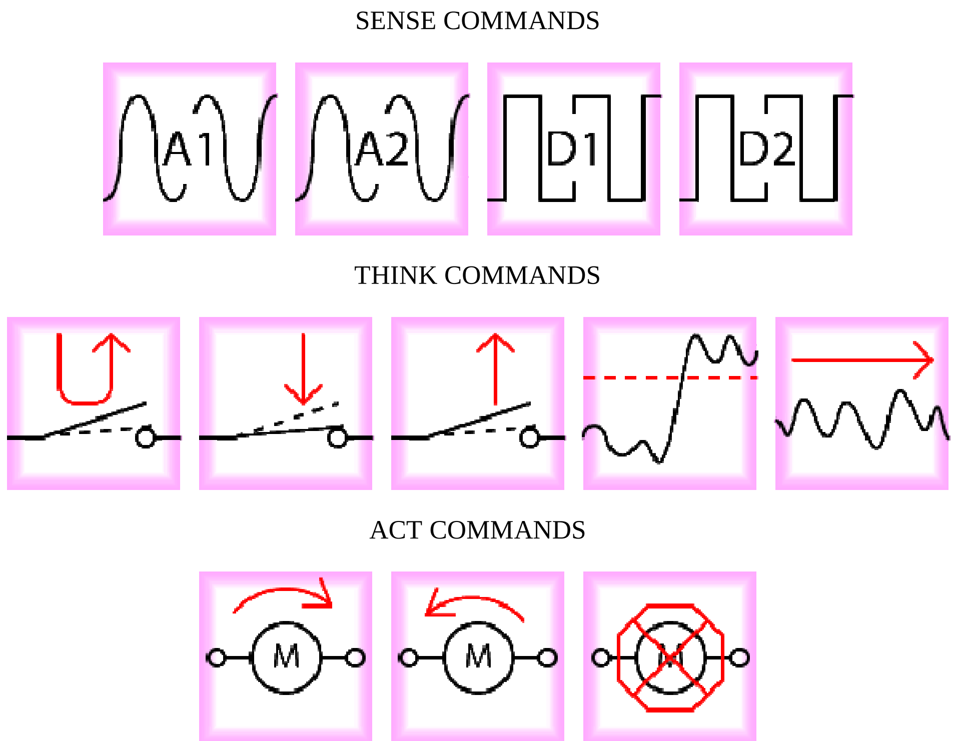


Figure 4.11: Icons used for the various command options of the LabVIEW UI. *Top left,* icon for analog signal A1; *top second to the left,* icon for analog signal A2; *top second to the right* icon for digital signal D1; *top right,* icon for digital signal D2; *middle left,* icon to sense for a bump of the signal; *middle second to the left,* icon to sense for a held signal; *middle middle* icon to sense for a released signal; *middle second to the right,* icon to sense for a signal threshold; *middle right,* icon to leave signal unchanged; *bottom left,* icon to command motor reverse; *bottom middle,* icon to command motor forward; and *bottom right,* icon to command motor to stop.

image of a square wave was used to represent the digital signal and that of a sinusoidal wave for analog signals since these are the general waveforms commonly associated with the those signal types. The field below the icons is also controlled by the selected “Sense” command. The field changes to indicate how the test leads should be connected to the controller by displaying an image that depicts alligator clips attached to the necessary scallops.

The think command gives the participant options on how to process the sensor information. For a digital signal, D1 or D2, the options are either a “Bump”, single press and release of the digital connection, will trigger an action, a “Hold”, a maintained contact of the digital signal, will trigger it or a “Release”, a disconnection of the digital contact, will trigger the action. The “Bump” option has a reset button as part of the UI to turn off the action since there is no other sensing option available in the code that would serve that purpose. For each of those icons, the standard schematic symbol for a switch was combined with some arrows representing the associated action to engage it.

For an analog signal, A1 or A2, the “Think” options are “Threshold” and “Signal”. “Threshold” allows the user to select a threshold that, when the signal either rises above or goes below depending on the selected options, will trigger an action. The “Signal” option sends through the analog signal and calibrates it to a useful range for controlling the motor speed. The range of speed is dependent on the minimum or maximum sensor value accumulated during the program’s current run so the signal gets calibrated to that range, therefore utilizing the full speed range of the motor instead of some small subset. The icons for those two commands are variations on the sinusoidal wave used to represent A1 and A2 in the “Sense” command. The “Act” command provides the option for how the motor will react to command: “Forward”, “Reverse”, or “Off”. For each icon, the schematic symbol for a motor with added symbols to representing the “Action”.

Chapter 5: Testing

PaperBots Robots Kit Prototype 1 was tested at the CEEO among of a group of elementary students. Participants were recruited from the CEEO's email list of parents interested in sending their children to available workshops. The workshop was held in the CEEO's workshop room. 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 and the rest attended public school. 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.

Prototype 1 Testing

The workshop was held 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 5.1.

Along with the PaperBots robotic kits, common classroom and office 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 A1 was below a certain threshold. It was determined that the physical usability of the kit was more

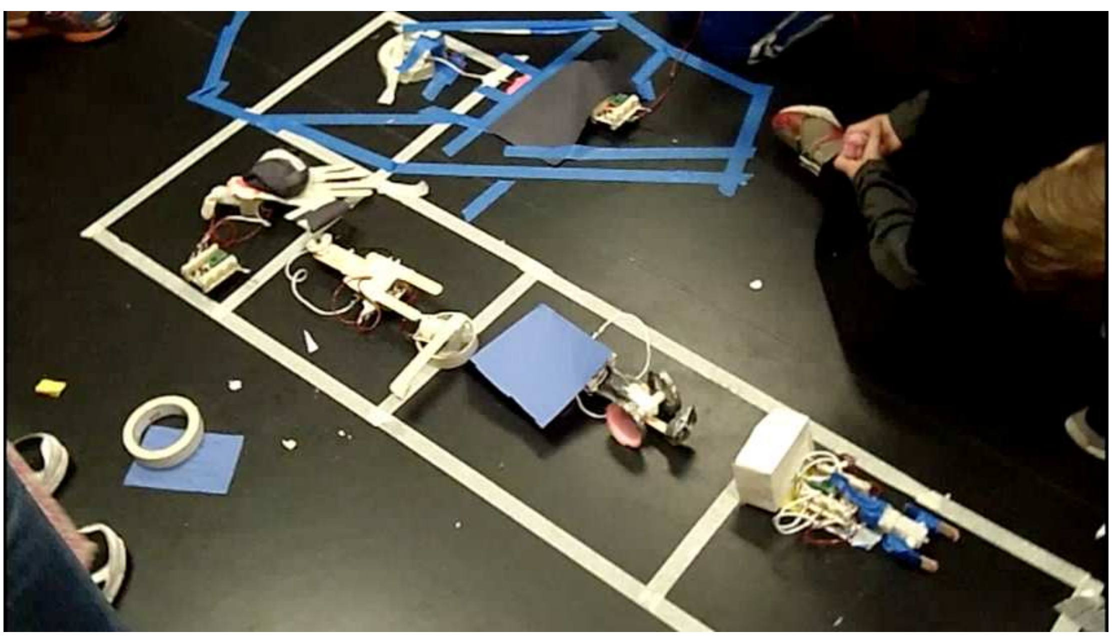


Fig. 5.1. Final layout of the PaperBots Rube Goldberg system made by the participants of the workshop. (Photo by author)

important at that time since the programming abilities of the students within that age range had long since been established (Erwin, Cyr and Rogers 2000, Bers 2008, Rusk, et al. 2008, Benitti 2012).

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.

Robots

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 due to misalignment between two of the bots and one forgetting to turn theirs on before one of the tests. Figure 5.2 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.

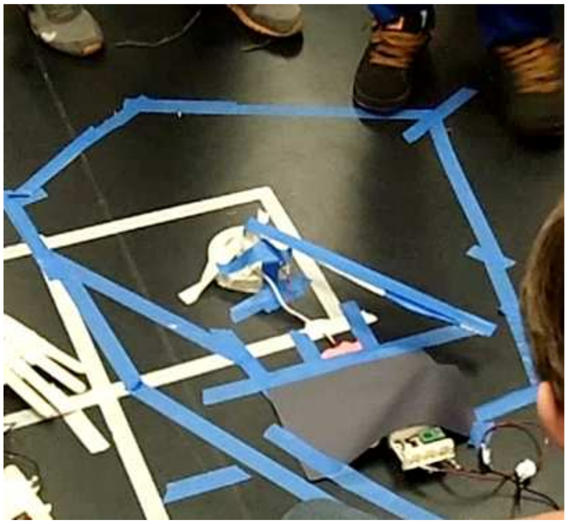


Fig. 5.2. Group 1's robot from October 2012 testing workshop. (Photo by author)

The second group’s robot was a crawling hand tethered to the PaperBots module and is shown in figure 5.3. 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.

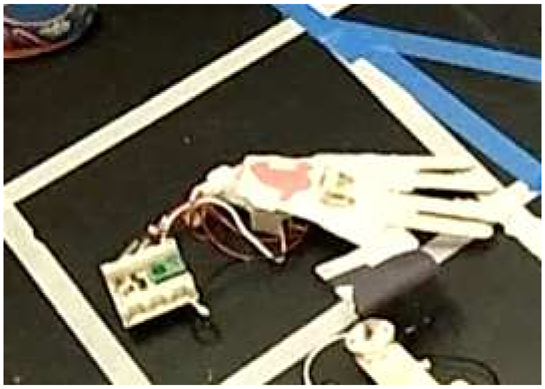


Fig. 5.3. Group 2's robot from October 2012 testing workshop. (Photo by author)

The third group’s robot was similar to the first robot. It was another swing arm

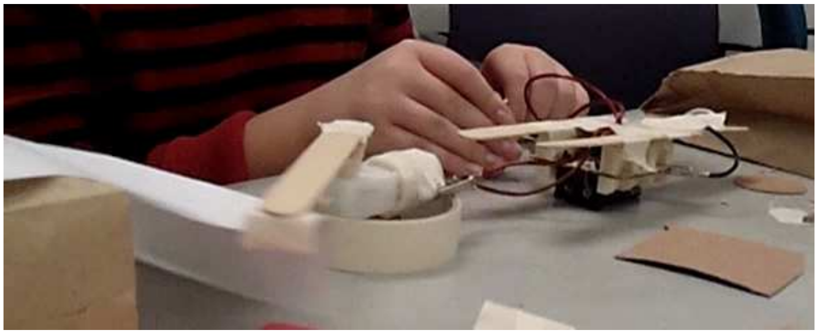


Fig. 5.4. Group 3's robot from October 2012 testing workshop. (Photo by author)

setup. As shown in Figure 5.4, 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 5.5. 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.

The fifth group's robot was a drag sled, shown in figure 5.6. 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.

Fig. 5.5. Group 4's Robot from October 2012 testing workshop. (Photo by author)

Fig. 5.6. Group 5's Robot from October 2012

Survey

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 5.1. To corroborate the participants thinking, the survey

Table 5.1. Average responses to the Post-Activity Survey by the workshop participants.

	Question	Score
1	I thought the instruction were very easy.	4.3
2	I had enough time to finish the activity.	4.8
3	I think the activity helped me understand problem solving and robotics concepts.	4.3
4	I thought the activity was very hard.	3.6
5	I thought the activity was very easy to build.	3.2
6	I thought the instructions were very confusing.	4.0
7	I thought it was really hard to finish in the time I was given.	4.3
8	I thought the activity was very easy.	3.2
9	I am more confused about the problem solving and robotics topics after I finished this activity.	4.8
10	I thought the activity was very hard to build.	3.6
	Average	4.0

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 (Shah, Smith and Vargas-Hernandez 2003). 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. Of the survey questions in table 5.1, 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. The average survey score of those 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 (Noble 2012, Smith 2012).

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 5.7 and figure 5.8 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

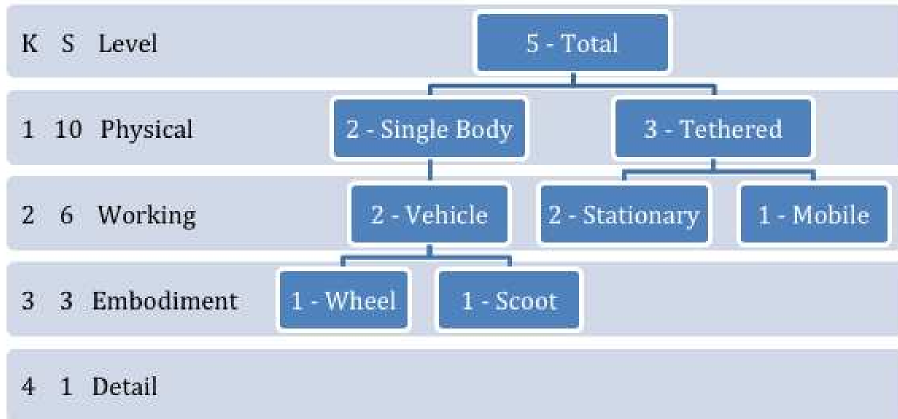


Fig. 5.7. Genealogy tree for the actuation function of the robots from the workshop.

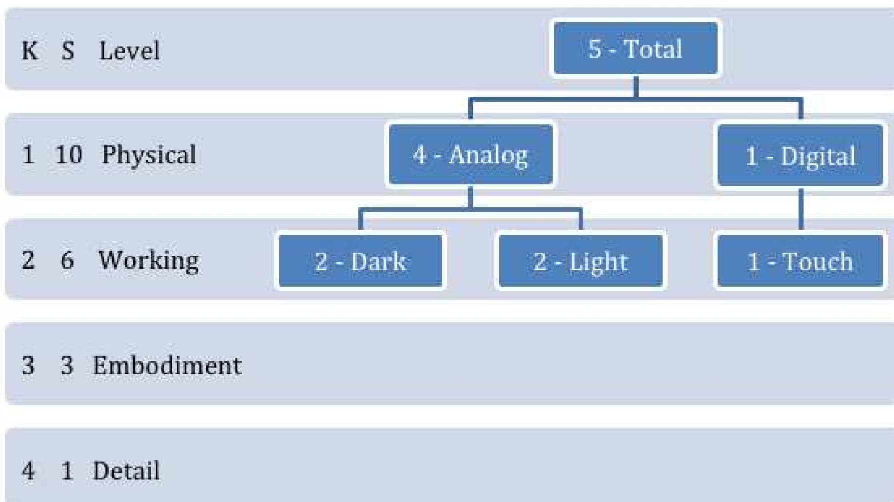


Fig. 5.8. Genealogy tree for the sensing function of the robots from the workshop.

evaluated, is the score for level k, is the number of new branches for that level, and is the number of ideas, artifacts in this case. The values of 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 suggested by Shah, Smith and Vargas-Hernandez (2003), the value of was calculated to be 7.3; a 10 would result from all robots having a different physical principle. This value is on the higher range of the possible values, which was taken as an indicator of a high variety among this small sample.

Novelty

Novelty measures 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 $S_{1jk} = \left(T_{jk} - C_{jk}\right)/T_{jk} * 10$, each feature was scored for its novelty and shown in table 5.2. 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 $M_g = \sum_{j=1}^{4} f_j S_{gj}$. The group is represented by g and f_j is the weight assigned to that function. Table 5.3 shows the novelty scores for the artifacts. For a group this size, a novelty score of 8.00 would be

Table 5.2: Posteriori feature counting and values

Sensing	C_1	S_{g1}	Body	C_2	S_{g2}	Movement	C_3	S_{g3}	Actuation	C_4	S_{g4}
Touch	1	6.67	Tethered Static	2	3.33	Rotating Arm	2	3.33	Knock Paper	2	3.33
Light	2	3.33	Tethered Mobile	1	6.67	Waddle	1	6.67	Cover	2	3.33
Dark	2	3.33	Single Body	2	3.33	Wheel	1	6.67	Conductive Sled	1	6.67
						Scoot	1	6.67			

Table 5.3: Design Data and Novelty Scores

Group	Sensing	Body	Movement	Actuation	Score
	Wt = .2	Wt = .2	Wt = .3	Wt = .3	
1	Touch	Tethered Static	Rotating Arm	Knock Paper	4.00
2	Light	Tethered Mobile	Waddle	Cover	5.00
3	Dark	Tethered Static	Rotating Arm	Knock Paper	3.33
4	Light	Single Body	Wheel	Cover	4.33
5	Dark	Single Body	Scoot	Conductive Sled	5.33

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 5.4, 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

Table 5.4: Success Rates

Fn	**Sensing**	**Actuation**	**Score**
Wt	0.5	0.5	
1	2	1	.75
2	2	1	.75
3	2	2	1.0
4	2	1	.75
5	1	2	.75

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 posttests 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. After 3 hours, 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 (Noble 2012, Smith 2012).

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.

Prototype 2 Testing

This test group was one of opportunity. Their troop mother had contacted me and asked to have a PaperBots activity at one of their meetings and agreed to allow it be part of this research. The testing took place at a suburban elementary school in a classroom where the Daisy Troop met weekly. There were 14 girls in the group. I had them for an hour after school, from 3:20 to 4:20, on a Monday afternoon. Due to the short time period and their young age, participant pre and post surveys were not done. A premade PaperBots display was presented to the girls to demonstrate a working unit as well as an example of the task they’ll be undertaking. The use of alligator clips to connect to the controller and how to select options in the LabVIEW UI were demonstrated to the participants. Digital sensing was demonstrated by touching two alligator clips together to turn on the motor and then the light sensor was demonstrated by allowing it to vary the motor speed as I shaded it.

The task assigned to the girls was to make a robot animal that simply moved when it sensed something. Time for questioning was not given but the participants were asked to start and then ask questions as they went along. The troop mother was the only other adult available to the participants for assistance and had no prior experience with

Arduino, LabVIEW or the PaperBots robotics kit. I went around to each group at the beginning to give them a closer demo of the program and answer any initial questions.

Test Groups

The girls were asked to split into groups and were allowed to choose their own groups; creating two of 3 and two of 4. Group 1 consisted of the 4 kindergarteners of the troop and did not produce a robot. They made paper butterflies without using the PaperBots Robotics Kit. Group 2 consisted of three members and built a robot chicken. Group 3 was also made up of three members and built a robot unicorn. The fourth group had 4 members and made a robot butterfly.

Group 1 – Paper Butterflies

The first group consisted of 4 girls of age 5. The troop leader spent the most time with this group at the beginning. After the program had been demonstrated to them, they did not make any changes to the program after. They quickly picked up on how to interconnect the board based on the image on the UI. They had trouble actuating the clips though due to lack of finger strength and dexterity and needed help physically clipping the alligator clips. Without an image of how to connect the motor or sensor though, they didn't think to connect to them. They began discussing what animals they would like to make and how they wanted it to move. There was an understanding that the motor was needed to actuate their creation; one student holding up the motor and saying, "We need this to make it flap its wings."

The troop mother helped them to connect to the motor and the light sensor upon noticing this oversight. The girls did not interact with the robotics kit after this point. The only people to touch the light sensor after the system was working were the troop mother and I. By the time I made it back to this table again, the girls had lost interest in making a robot. They had begun making paper butterflies; moving to an adjacent table by direction of the troop mom to give them space to work and leaving the laptop and robotics kit behind.

Group 2 – Robot Unicorn

The second group consisted of 3 girls in first grade. They quickly decided to make a unicorn that moved its head up and down. They waited at first before interacting with kit and the program until I came around, one girl exclaiming, “We’re supposed to wait.” During that time though, they began discussing the board and comparing it to the image on the UI, indicating the cables that should be connected to the board based on the cable color and the ones on the UI. After they were walked through the program, they were aware of how to hook it up based on the options selected on the screen: “So you put the green one on D1 one and it goes to the sensor…What happens if I do this? [Changes sense command] Oh you put it at D2 because we changed it.”

There was still some confusion on how to get the entire system to work. A second walkthrough of the program was needed, with them describing what they want their robot to do and I guiding them on which options to select to achieve that. After this, they became comfortable with the program, changing options and seeing how those change the motor reaction. After another few minutes of this they settled on a program and became comfortable enough to start building.

The majority of the rest of their time was spent building their unicorn. With only minutes left, they realized they did not consider the motor in their build, mounting the unicorn's head to the body in a manner that the motor rotation would tear it off. At this point I asked them a few questions about whether they had fun, if they felt they figured out the kit and if they liked the kit. One was very excited simply about figuring out how to use the kit and had fun, another group member was ambivalent and the last begrudgingly agreed she figured out the kit but was very disappointed. I reassured them that this isn't a failure, just a lesson in considering the motor next time, cheering them enough to move on. This last individual found inspiration from the next table; "Wait a second, I bet somehow we could make the wings move."

They took on this with great excitement. With the motor loosely taped to the back of the unicorn and wings taped to the hubs as seen in figure 5.9, they tried their bot. There was another disappointment when the tape bound up but I fixed this issue for them. Once their robot worked in accordance with their updated idea, wings flapping as soon

Fig. 5.9. Daisy troop group 2's unicorn. (Photo by author)

as a paper jewel was picked up and another group member puts the 2 alligator clips together for the digital signal. It fell apart after a few showings but they were still very proud of their work, with exclamations like “Yes, it’s moving. Yay.” and “We did it guys, we did it.”

Group 3 – Robot Chicken

The third group dove into the project quickly with one member taking leadership over the laptop, another grabbing the robotics kit, and a third taking an observational role. All of these participants were in first grade as well. This was the first group I checked up on so they did not have much time before I gave them a personal demonstration of the program. After I moved onto another group, they quickly began connecting and disconnecting clips to see how that changed things. Each time they got it working again, one exclaimed “Awesome” and they began trading turns trying it.

After 5 minutes of tinkering with the robotics kit, they began talking about what to build. They eventually decided on a chicken, which can be seen in figure 5.10. The building offered them no issue but they struggled to include the motor. Once given permission to tape to the motor though, they progressed quickly. Having made a tin foil ice cream cone for their chicken and having the wings directly attached to the hubs, they couldn’t decide how to signal the bot

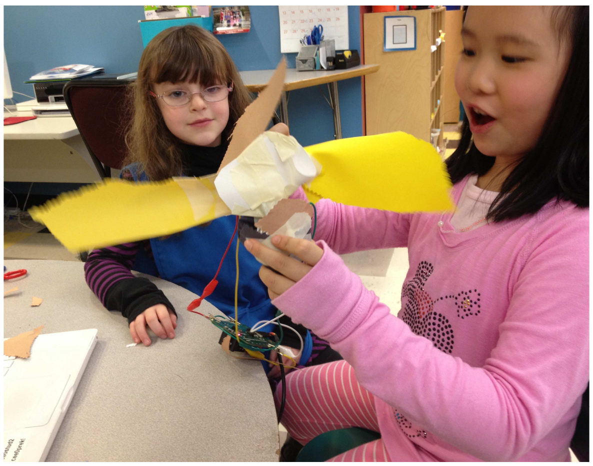


Fig. 5.10. Daisy troop group 3's robot chicken. (Photo by author)

to “flap” its wings. I gave them the suggestion of clipping to the tin foil and attaching another clip as the beak so when they touch that provided them with a digital signal.

Group 4 – Robot Butterfly

The fourth group had also begun using the laptop and kit before I made it to them. This group consisted of 4 first grade students. They had not associated the image on the UI with the board and had randomly clipped all test leads to the controller’s sides. The required more time to dissuade this misconception, properly connect the kit, and navigate the UI. Although their time to understanding was longer, they were the first group to create a functioning robot, shown in figure 5.11. After observing how the motor hubs would push up on a piece of paper that had accidentally been tossed on it, they decided to use that motion to actuate the wings. I did provide the suggestion to reinforce the construction paper wings with cardstock since they were disappointed with how “floppy” they were beforehand. They spent the remaining time decorating and taking turns showing their robot to other daisy troops and parents.

Evaluation

Due to the small volume of functional robots and the amount of intervention the participants needed, this test group was evaluated more on the usability of the kit and the enjoyment of the girls. Every group had varying degrees of issue with

Fig. 5.11. Daisy troop group 4's robot butterfly. (Photo by author)

the alligator test leads. They understood how to connect them but had trouble with the dexterity and strength needed to manipulate the clip and attach it to the controller. Each group as well as the troop leader associated the test leads with color. The UI image of the connected controller shows different color clips and every group placed great emphasis on connecting the “right” color clip to the scallop indicated. With that though, they were able to associate the image on the UI to the physical kit before them, enabling them to try different options and reconnect the kit without supervision, with the exception of group 1 who didn’t try any other program configurations after the initial set up. The three groups who completed the task felt that they were able to figure out and utilize the kit to make what they envisioned as a robot within the limited time they had been given. These groups were able to navigate the UI to program the controller, properly connect to get the results the envisioned, and build using craft materials to complete their robot.

When asked about their experience, many of the students had positive responses. The participants cheered when their robots first functioned and were eager to show their robots to others. When asked if they had fun, many responded “yes”. The only “no” response came from the disappointed group member of group 2 but this question was asked before their redesign. After they changed their scope and succeeded there, she was the one cheering, “Yes, it’s moving. Yay.” Group 4 engaged in discussions about when and how they would show their robot to their parents as well. These behaviors suggest a pride and enjoyment in the activity.

Chapter 6: Conclusion

Prototype 1

The participants of the first test group were capable of building a moderately functional PaperBots based Rube Goldberg machine. Individually, each group built a robot that reacted to the stimulation of the previous bot and then would actuate the next. 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 robots that could sense, think and act. With regards to the creativity metrics, they were used to provide some quantitative measures for evaluation but baseline scores of similar activities were not available. Therefore I decided to consider scores that were in the upper half of the range to be acceptable since these measures were only meant to serve as a spot check. The variety and novelty metric scores of the artifacts as compared to the ideal score for a population of this size were therefore considered passable scores, 7.3 out 10.0 for variety and a 5.33 max out of 8.00 for novelty.

The participants also 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. Their interactions in the video data also show the enjoying themselves with few signs of frustration. The final test of the Rube Goldberg setup is filled with laughter and cheers and the participants began showing their robots off to their parents once they had the chance.

Prototype 2

Due to the simple demands on the prototype 2 testing group, make a robot animal, and the few robots produced, there were not enough functions, features, and artifacts to effectively utilize the same creativity metrics as used on the prototype 1 testing group's resulting robots. Therefore prototype 2 was evaluated on the usability of the kit and enjoyment of the participants of the second test group. Within the hour that they had available, the participants were able to navigate the UI and associate it with the functionality of their PaperBots Robotics Kit Prototype 2. Three of the four groups were able to complete the task to produce a robot animal. The behavior of the participants and their responses to inquiry indicate that they had a positive experience. They cheered when their robots first functioned and were eager to show their robots to others.

Robotics Kit Cost

The end user cost of the robotics kit cannot be exactly determined at this time due to the variety of factors that go into the retail price. The parts cost based on an estimated 5000 units would be $8.76 each if sourced from SparkFun Electronics, Digi-Key Electronics and Sunstone Circuits. Based on an estimated retail cost being 4 to 5 times the bill of materials (BOM) cost, the controller would cost $35.04 to $43.80. This cost seems very high, being 2.5 to 3 times the cost of the board it is based upon, but is based upon a SparkFun Electronics general rule of thumb and could change based on product market, packaging, instructions, and wholesale component purchases (Seidle 2013).

Applying the same estimate to the light sensor would price it $7.25 to $9.05. The motor retails at $5.40, at bulk price, but required modification. Existing hubs and a gearmotor housing from the same vender cost less than the price of the motor (Pololu Co 2013). Assuming the addition of the developed plastic housing and hubs would no more than double the cost of the unit, the PaperBots robotics kit motor would cost $10.80. A set of 5 alligator clip test leads costs $3.05 (Digi-Key Co. 2013). The entire kit may cost anywhere from $56.14 to $66.70.

Conclusion

During a 3 hour time period, the first test group intuitively utilized the product, created a range of artifacts and enjoyed the experience of doing so. Their responses and behavior indicate they enjoyed this workshop and were able to utilize the PaperBots Robotics kit with little issue. The robots they produced also functioned individually, albeit not consistently when combined as a complete system.

The majority of second testing group was able to program and set up the kit in a working manner as well as build off of it to create robots as they intended. With some assistance, they created working robots. They showed many signs of enjoyment throughout the activity and great pride in what they produced.

The current cost of the robotics kit is low enough to be within the range of what most teachers have spent on classroom resources. A controller, motor, light sensor and test leads would cost $56.14, assuming the price stays on the low end of the estimate. Enough kits for a classroom, approximately 8, would cost approximately $560; a cost that is below the $936 average spent by teachers to outfit their classroom reported by the NSSEA.

Through examination of the two testing groups utilized for the first two iterations of this product, the PaperBots Robotics Kit has provided evidence to be an effective elementary engineering education tool for inexpensive classroom activities. Although some uses are challenging for the younger participants of these groups, all were able to use it to some degree in relatively short time periods. The cost of the product in its current state is well within the limits of affordability. The PaperBots Robotics Kit has potential as an affordable option for robotics education.

Future Work

Design improvements

The PaperBots robotics kit prototype 2 controller was oversimplified to a fault. Basing the design off of the Arduino Pro was a move intended for cost savings but requires the purchase of an FTDI breakout board or cable, adding a cost. The 6 pin connection of these cables is also complex for students inexperienced with these types of interfaces and that, along with general use, could lead to damage of the connection. Other Arduino products, although more expensive, utilize a USB standard B connector; a more commonly used and more accessible means of electrical connection for young students.

Changing this feature would add cost to the unit due to the necessary addition of an FTDI USB to UART IC.

Shields for the unit would improve interface and versatility as well. A shield is already needed to access the second motor control. Additional shields for rechargeable power, wireless, Bluetooth and other options would greatly support the product.

In the other direction, downgrading the product would likely further decrease the cost. By taking a similar path as Digistump's Digispark, a less powerful microcontroller could be utilized. By limiting the controller to only being capable of as many I/Os as are necessary, the component costs will likely decrease and therefore decrease the overall cost.

Production

Production for these will also affect design. Input from the contract manufacturer may force change for manufacturing, assembly, component availability and other unknown factors. The motor modifications were done with 3D printed components but this is not a viable bulk process. Changes to the hubs and casing may be necessary due to injection molding practices and tolerances. Further analysis for these manufacturing and production concerns is needed.

Code

Most educational robotics products have their own software package for programming of their product. This kit takes advantage of the existing open source software package provided by Arduino but this program is not as intuitive as some of the others. Creating a LabVIEW based graphical interface similar to robolab is the logical direction after developing a simple UI through LabVIEW for the second test group. URAPI has limited autonomous program capabilities, due to the size of the code required to be loaded on the Arduino, which interprets the URAPI commands. This would need to be further streamlined to allow for larger autonomous programs. The much larger undertaking would be creating a LabVIEW toolkit that will compile to Arduino and upload that code to the controller.

Recent success has been had by other researchers at the CEEO in the controlling of robots through iPad programming apps. Adding a Bluetooth or wireless shield to the controller would allow it to communicate with an iPad. Building off of the work of this other research could lead to either directly using that app to control the PaperBots controller or the development of a PaperBots specific app. This will add to the cost but a wireless experience and a simplified graphical programming environment may be worth it to the end user.

PaperBots Activities

PaperBots currently has a few activities that include templates and lesson plans for educators to utilize. These currently available activities do not make use of the PaperBots Robotics Kit. Activities that do make use of the PaperBots Robotics Kit need to be developed to provide a structured introduction to the kit, its available functions, and its general use. I served as the organizer of the activities and as an informational resource during the test groups so that same information needs to be available to instructors and students in a more accessible and non-isolated form. Lesson plans and instructional information on the kit will be needed before this product's use can be expanded.

Further educational testing

Currently this product has been tested to only a small degree, enough to glimpse some potential. Before any definitive statements can be made of this product's effectiveness, a larger study will have to be pursued. Comparative analysis of this product being used in multiple classrooms would be necessary to provide backing to any inherent benefits the PaperBots robotics kit has on student learning. To make any definitive statements about this product in comparison to other robotics education systems would require testing against those other products in controlled environments.

Appendix A: Test Group Survey Data

Pre-Test

Post-Tes

ID	Age	Grade	Sex	thought the Instructions were very easy	instructions were very confusing	had enough time to finish	hard to finish in the time given	thought the activity was very easy	thought the activity was very hard	activity helped me understand problem solving and robotics concepts	more confused about problem solving and robotics topics after	activity was very easy to build	activity was very hard to build	Average Opinion of Activity
001	11	6	M	5	5	5	5	5	5	5	5	5	5	5.0
002	10	5	M	4	2	5	5	5	5	5	5	4	5	4.5
003	10	5	M	5	5	5	4	5	5	4	5	4	5	4.7
004	10	5	M	5	5	5	5	4	5	4	5	4	5	4.7
005	10	5	M											
006	12	6	M	4	2	5	5	1	1	4	5	2	2	3.1
007	11	5	F	5		5			2	5			2	3.8
008	11	6	M	4	4	5	4	2	2	5	5	4	4	3.9
009	11	6	F	4	5	5	5	2	4	5	5	2	4	4.1
010	11	6	M	4	4	5	5	2	4	2	4	1	2	3.3
011	10	5	M	5	5	5	5	5	4	5	5	4	5	4.8
012	10	5	M	5	4	5	4	3	4	4	4	2	4	3.9
013	10	5	M	4	5	5	5	4	3	5	5	1	1	3.8
014	11	6	M	3	3		2	1	2	3	4	3	2	2.6
015	10	5	M	3	3	2	2	3	4	4	5	5	4	3.5
			Average	4.3	4.8	4.3	3.6	3.2	4.0	4.3	3.2	4.8	3.6	4.0
			Available Answers	No Not Really Maybe Sort Of Yes	Yes Sort Of Maybe Not Really No	No Not Really Maybe Sort Of Yes	Yes Sort Of Maybe Not Really No	No Not Really Maybe Sort Of Yes	Yes Sort Of Maybe Not Really No	No Not Really Maybe Sort Of Yes	Yes Sort Of Maybe Not Really No	No Not Really Maybe Sort Of Yes	Yes Sort Of Maybe Not Really No	

Frequency of Use

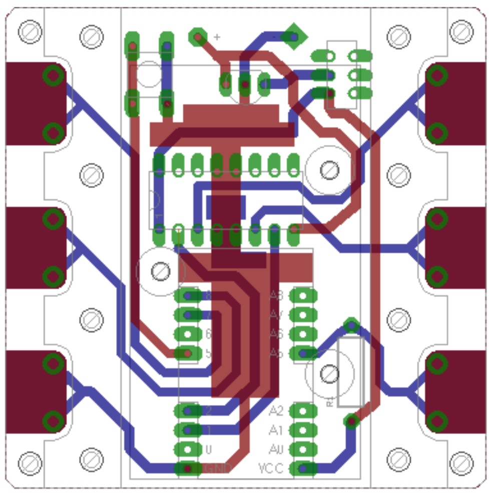
LEGOS/Tetrix	Crafts	Average Freq. of Use
-		
5	4	3.3
4	3	3.7
5	4	3.7
-		
4	3	3.7
4	3	3.7
3	4	3.3
4	5	3.7
3	3	3.0
4	5	4.3
-		
4	4	4.0
4	4	3.3
-		
4.00	3.8	3.6

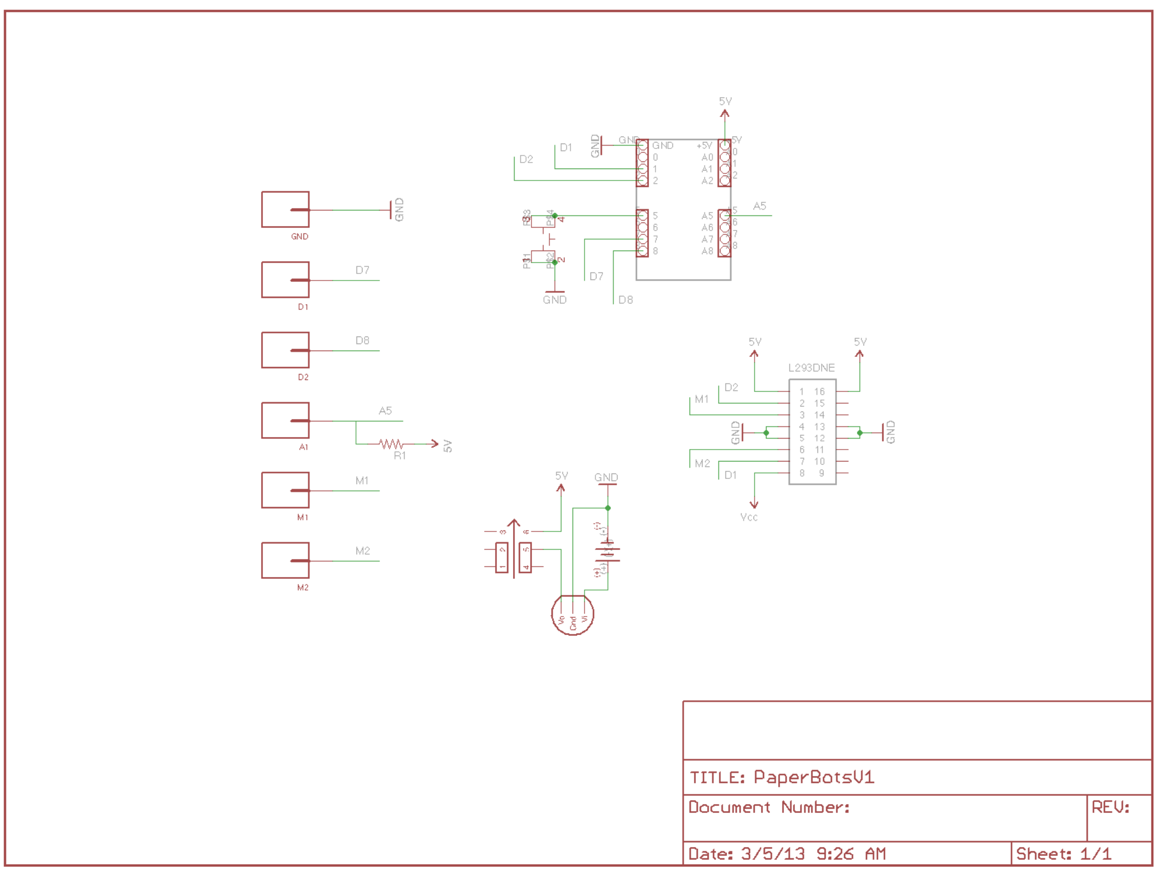
Answer Weights			
1	ever	Never	Never
2	nce a Year	Once a Year	Once a Year
3	nce a Month	Once a Month	Once a Month
4	nce a Week	Once a Week	Once a Week
5	nce a Day	Once a Day	Once a Day

ID	Age	Grade	Sex	What did you think of today's activity?	What part of the activity did you find hard?	What part of the activity did you find easy?	What would change for future activities?	How would you compare today's activity to other activities you have done in classes?
001	11	6	M	I thought it was cool	None.	Everything.	Nothing.	Way Better.
002	10	5	M	good	none	everything	no	good
003	10	5	M	I thought it was good	Building it	connectin the wires and robot pieces	nothing	very good
004	10	5	M	It was fun.	Finishing the "robot" before the tests	all	none	different. It is made of paper!
005	10	5	M	-	-	-	-	-
006	12	6	M	It was very fun and I would like to do it again	taking our plan and adapting it to the problems that came along	securing it to the ground	I would make premade wheels and gears	It was not at all like anything that I have done before.
007	11	5	F	It was extremely fun and a tad hard	getting it to work	figuring out how to make it work	nothing	more creative
008	11	6	M	Fun	Choosing what to make so making it was easy	Making it and taping it to the ground	more materials, premade wheels and gears	
009	11	6	F	It was fun and interesting	figuring out how to make my bot move	...none of it?	maybe partners instead of groups	nothing like activities in class
010	11	6	M	It was fun and hard	building	securing it to the ground, taping	No cars or rolling vehicles	much better
011	10	5	M	fun	other groups	the construction	more paper	very fun
012	10	5	M	good	making it work	thinking of an idea	if you could program	it had more all out building
013	10	5	M	Fun	Building	turning it on	no	good
014	11	6	M	It was fun but difficult	making the bot move	making the bot not move	slightly more structured	
015	10	5	M	It was fun!	The part with all the wiring.	The making of the hand	nothing much	so-so I would say

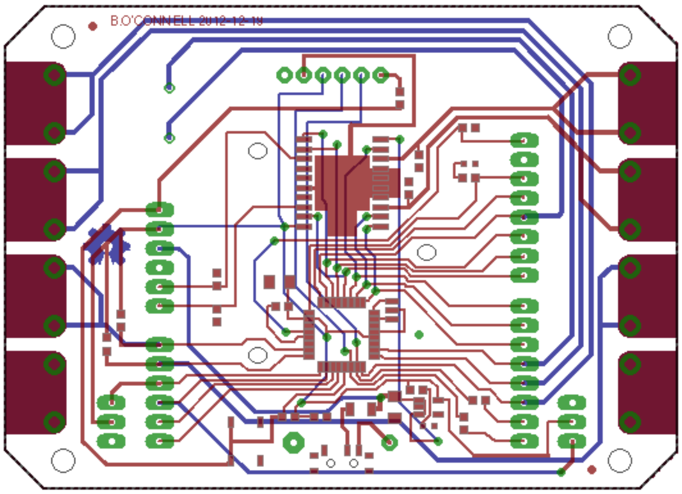
Appendix B: Schematics and Artwork

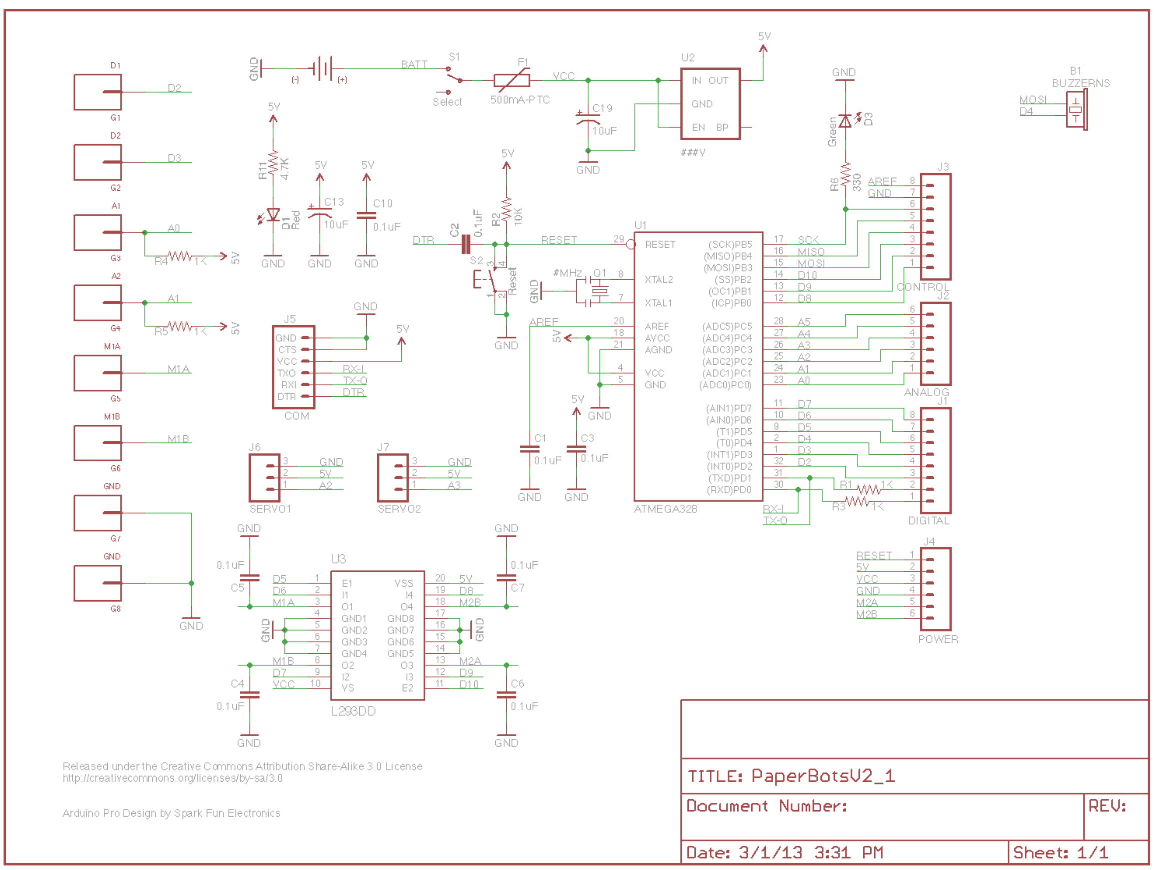
Prototype 1





Prototype 2

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Document Number:
REV:
Date: 3/1/13 3:31 PM
Sheet: 1/1
Released under the Creative Commons Attribution Share-Alike 3.0 License
http://creativecommons.org/licenses/by-sa/3.0
Arduino Pro Design by Spark Fun Electronics
ATMEGA328
L293DD
BUZZERNS
CONTROL
ANALOG
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POWER
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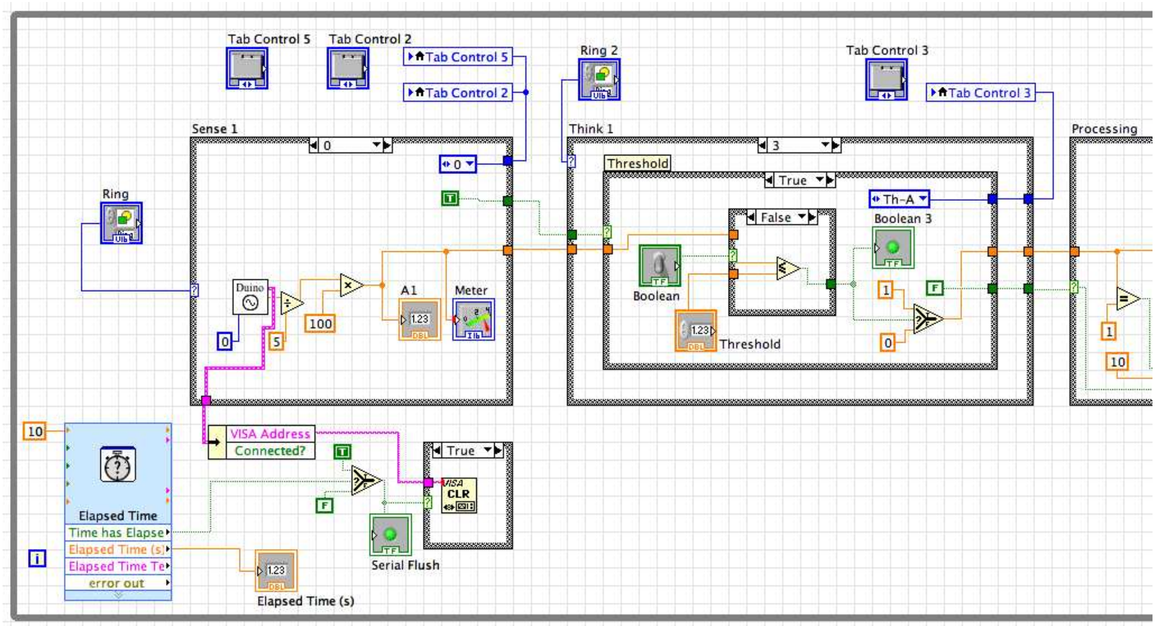
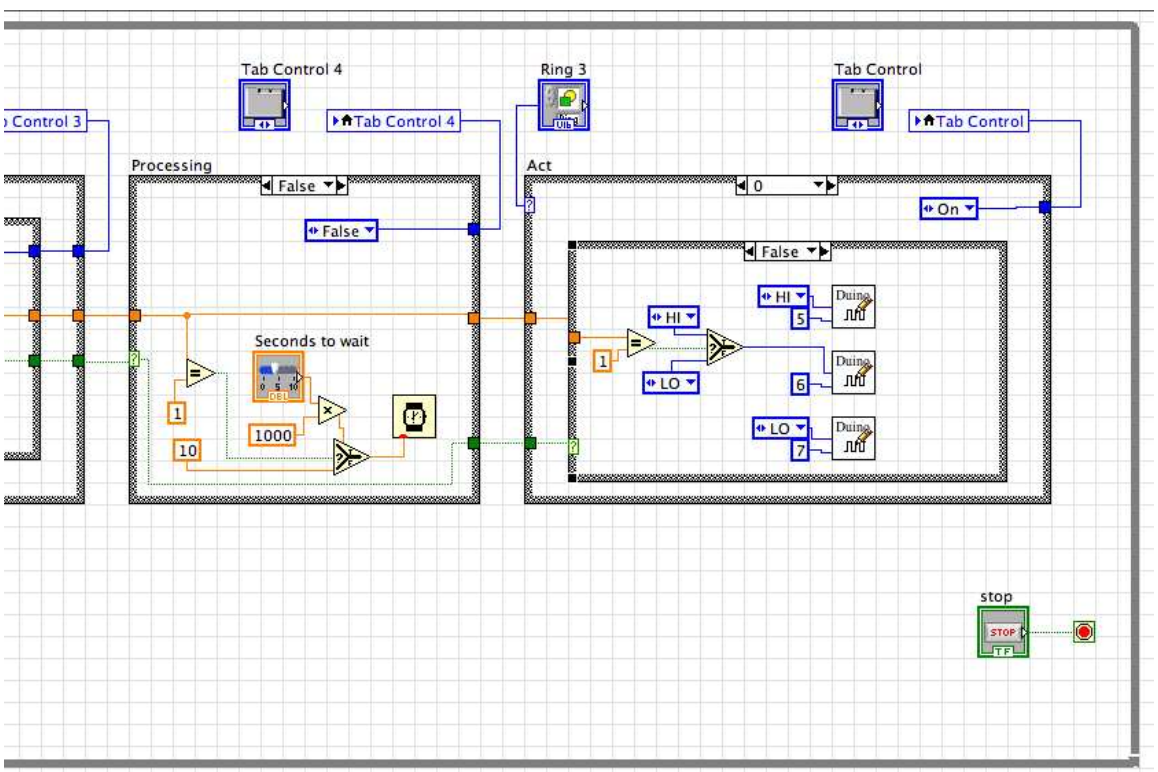
COM

Appendix C: LabVIEW UI

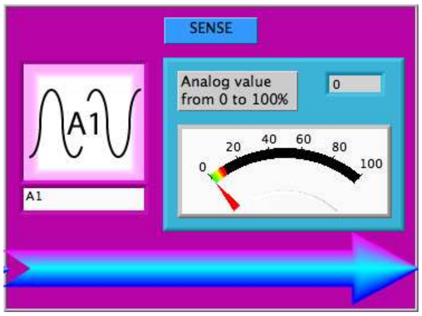
Code Overview

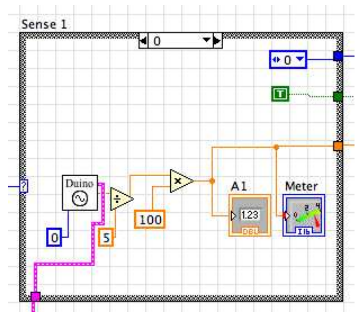




Sense Commands

A1





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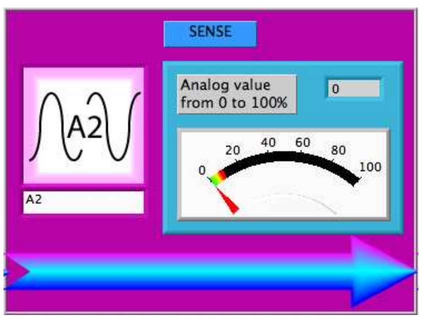
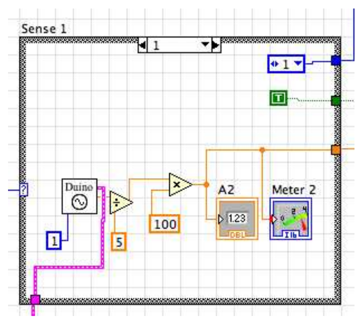
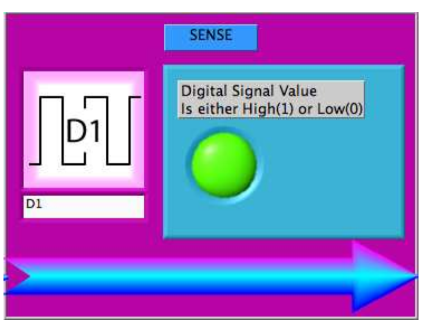
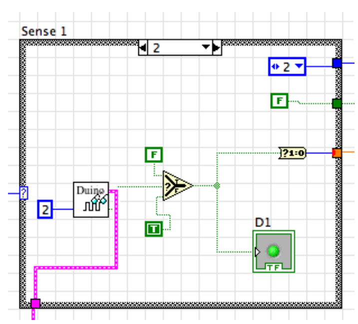


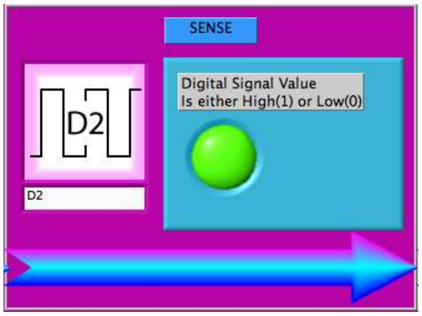


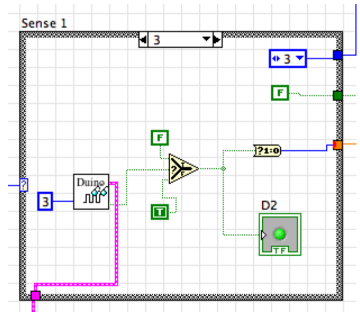
D1





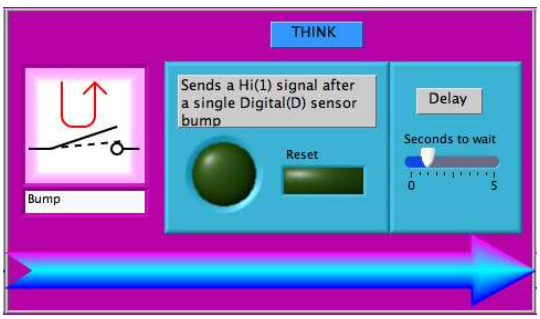
D2

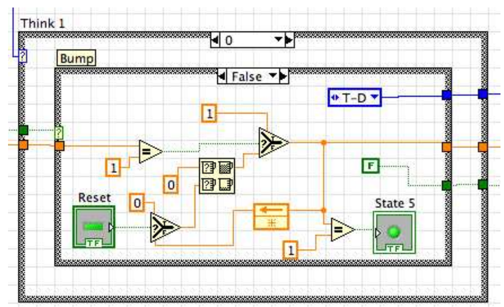




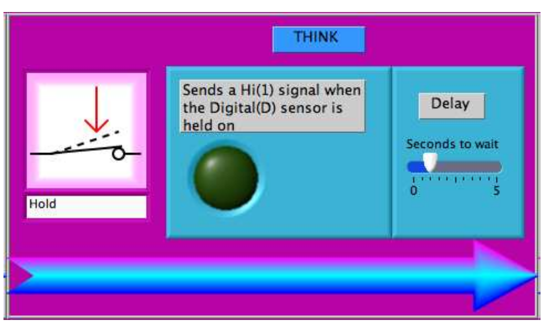
Think Commands

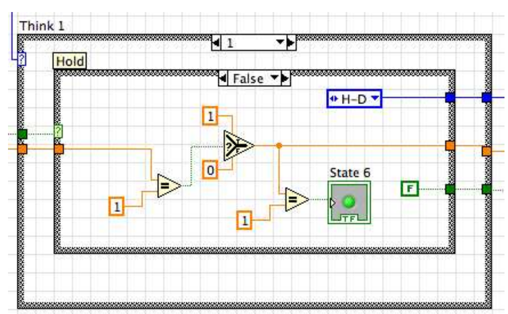
Bump



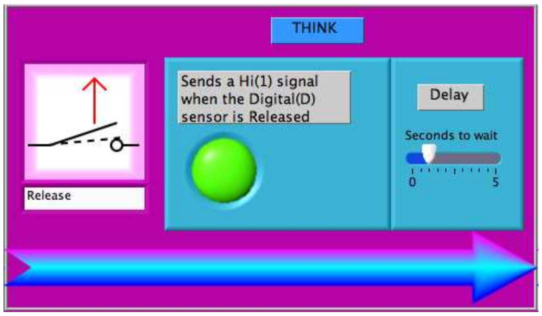


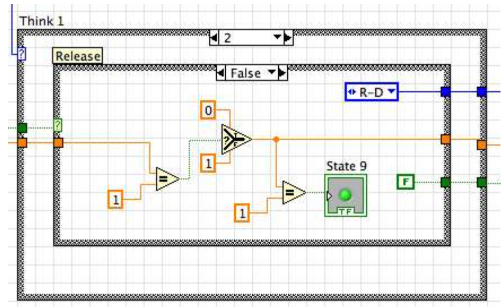
Hold



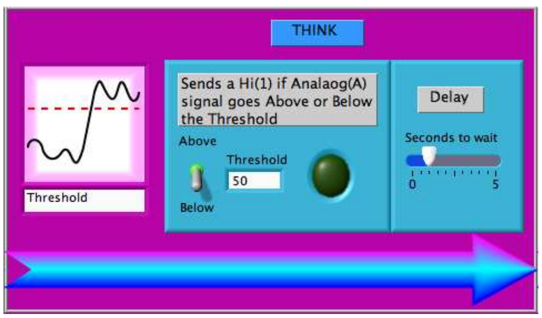


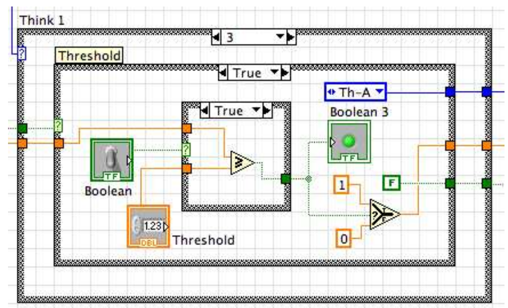
Release



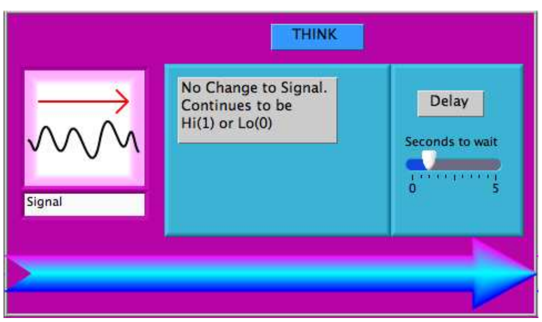


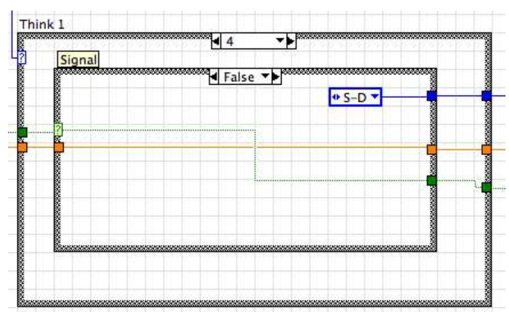
Threshold

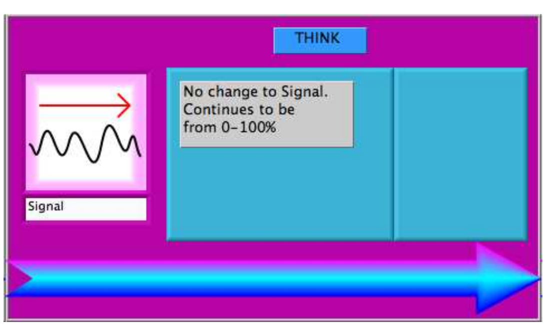


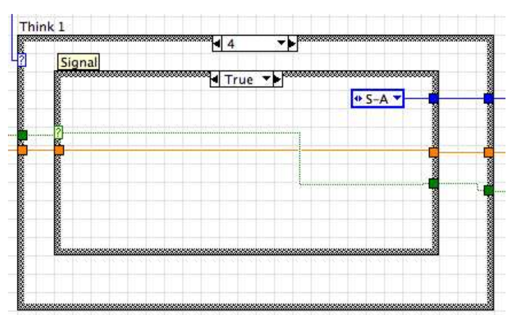


Signal

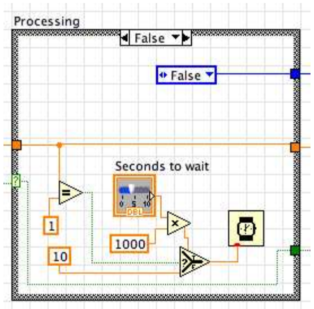




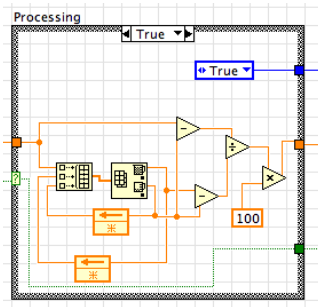




Digital Signal - Delay

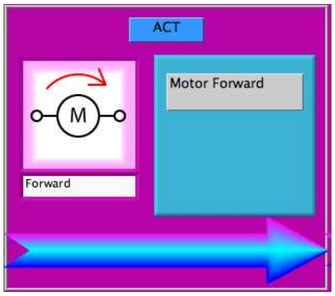


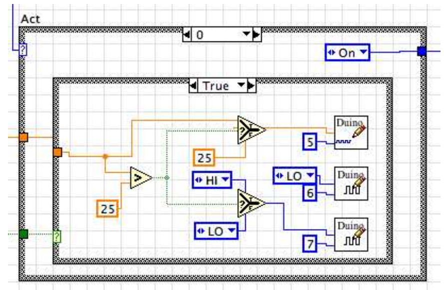
Analog Signal - Calibrating

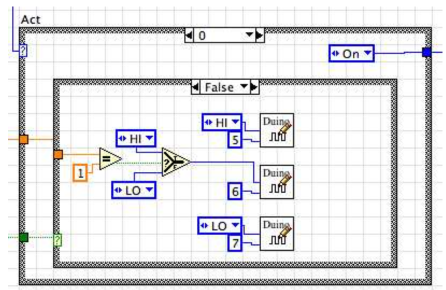


Act Commands

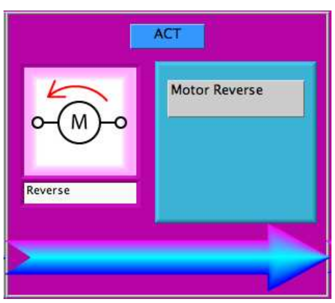
Motor Forward

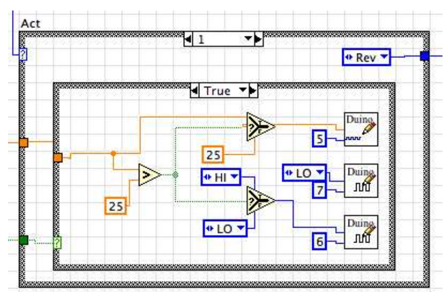


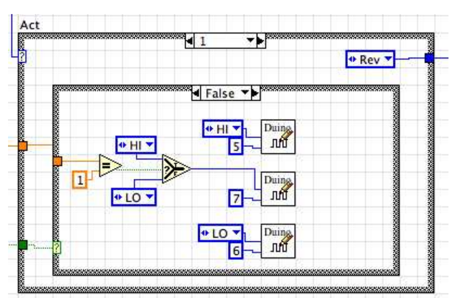




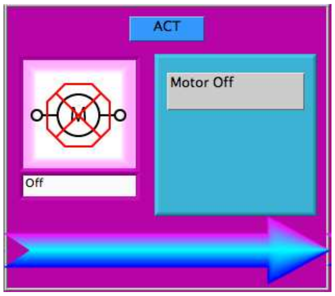
Motor Reverse

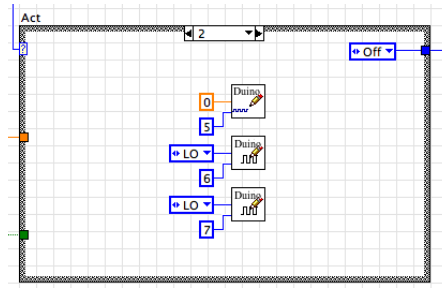






Motor Off





Appendix D: Bill of Materials and Cost

Bill of Materials for Prototype Units

		For 5 Prototype Units		
Ref Des	**Description**	**Source[1]**	**PN**	**Unit Cost**
C1	0.1uF Capacitor	SF	PRT-11245	$0.03
C2	0.1uF Capacitor	SF	PRT-11245	$0.03
C3	0.1uF Capacitor	SF	PRT-11245	$0.03
C4	0.1uF Capacitor	SF	PRT-11245	$0.03
C5	0.1uF Capacitor	SF	PRT-11245	$0.03
C6	0.1uF Capacitor	SF	PRT-11245	$0.03
C7	0.1uF Capacitor	SF	PRT-11245	$0.03
C10	0.1uF Capacitor	SF	PRT-11245	$0.03
C13	10uF Capacitor	SF	PRT-11244	$0.24
C19	10uF Capacitor	SF	PRT-11244	$0.24
D1	Red LED	SF	PRT-11248	$0.24
D3	Green LED	SF	PRT-11249	$0.20
F1	500mA-PTC	SF	PRT-11637	$0.30
Q1	16MHz Resonator	DK	CSTCE16M0V53-R0	$0.48
R1	1K Resistor	DK	P1.0KGCT-ND	$0.10
R2	10K Resistor	SF	PRT-11246	$0.04
R3	1K Resistor	DK	P1.0KGCT-ND	$0.10
R6	330K Resistor	SF	PRT-11247	$0.03
R11	4.7K Resistor	DK	P4.7KGCT-ND	$0.10
S1	SPDT Slide Switch	SF	COM-10860	$0.95
S2	Tactile Switch	SF	COM-08720	$0.95
U1	ATMEGA328	SF	COM-09261	$4.25
U2	5V Regulator	SF	PRT-11252	$0.90
U3	H-Bridge	DK	497-2937-1-ND	$3.63
U4	9V Holder	DK	BH9V-PC-ND	$1.49
N/A	Rivet, plastic	DK	3441K-ND	$0.24
N/A	Rivet, plastic	DK	3441K-ND	$0.24
N/A	Rivet, plastic	DK	3441K-ND	$0.24
N/A	PCB	SC	TBD	$31.25
			Total=	$46.44

[1] SF = SparkFun, DK = DigiKey, SC = Sunstone Circuits

Bill of Materials for Production Units

		For 5,000 Production Units		
Ref Des	**Description**	**Source**[2]	**PN**	**Unit Cost**
C1	0.1uF Capacitor	DK	490-1575-2-ND	$0.0037
C2	0.1uF Capacitor	DK	490-1575-2-ND	$0.0037
C3	0.1uF Capacitor	DK	490-1575-2-ND	$0.0037
C4	0.1uF Capacitor	DK	490-1575-2-ND	$0.0037
C5	0.1uF Capacitor	DK	490-1575-2-ND	$0.0037
C6	0.1uF Capacitor	DK	490-1575-2-ND	$0.0037
C7	0.1uF Capacitor	DK	490-1575-2-ND	$0.0037
C10	0.1uF Capacitor	DK	490-1575-2-ND	$0.0037
C13	10uF Capacitor	DK	587-1295-2-ND	$0.0462
C19	10uF Capacitor	DK	587-1295-2-ND	$0.0462
D1	Red LED	DK	754-1132-2-ND	$0.0620
D3	Green LED	DK	754-1121-2-ND	$0.0611
F1	500mA-PTC	DK	F2112TR-ND	$0.1884
Q1	16MHz Resonator	DK	490-1198-2-ND	$0.2289
R1	1K Resistor	DK	P1.0KGTR-ND	$0.0015
R2	10K Resistor	DK	311-10.0KHRTR-ND	$0.0017
R3	1K Resistor	DK	P1.0KGTR-ND	$0.0015
R6	330K Resistor	DK	311-330GRTR-ND	$0.0013
R11	4.7K Resistor	DK	P4.7KGTR-ND	$0.0015
S1	SPDT Slide Switch	DK	563-1102-2-ND	$0.3677
S2	Tactile Switch	DK	EG4387TR-ND	$0.4176
U1	ATMEGA328	DK	ATMEGA328-AURTR-ND	$1.6080
U2	5V Regulator	DK	497-3500-2-ND	$0.2263
U3	H-Bridge	DK	497-2937-2-ND	$1.6128
U4	9V Holder	DK	BA9VPC-ND	$1.1000
N/A	Rivet, plastic	DK	3442K-ND	$0.2420
N/A	Rivet, plastic	DK	3442K-ND	$0.2420
N/A	Rivet, plastic	DK	3442K-ND	$0.2420
N/A	PCB	SC	TBD	$2.0300
			Total=	$8.7584

[2] SF = SparkFun, DK = DigiKey, SC = Sunstone Circuits

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