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PAPER ROBOT: A DESIGN ACTIVITY TO INCREASE BEGINNER'S PROTOTYPING CONFIDENCE WITH MICROCONTROLLERS

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Abstract: This paper describes a creative design activity to introduce engineering students to mechatronic prototyping. Our goal was to find a creative task to increase student confidence and skills in mechanical design, electrical circuits, microcontrollers, and programming. We present the Paper Robot exercise, a design activity that blends everyday materials such as cardboard, with electronic components. This activity was introduced during the 2010-2011 academic year, and has been repeated every year since, in a global, industry-sponsored design course at Stanford University. The Paper Robot exercise resulted from the observation that students were intimidated to create functional prototypes with microcontrollers. The teaching team needed a way to quickly introduce tools for programming electronic components and to encourage creative experimentation early in the course. Results include a 100% task performance rate of students that successfully made a robot meeting the minimum requirements. 76% of students reported an increase in knowledge in programming microcontrollers (Arduino), and 69% increased their knowledge in creating electronic circuits out of raw components. This activity may be modified to introduce younger students to mechatronic platforms in STEM education curriculum.

Keywords: *Rapid Prototyping, Interaction Design, Electronics Toolkits*

1. Introduction

The Paper Robot activity ("P.bot" for short) fulfils an educational need to increase student's confidence and proficiency in prototyping with electronic components. This activity was initially developed for ME310, an academic yearlong course, at Stanford University. This multidisciplinary class typically consists of first-year graduate students in the Department of Mechanical Engineering; however a few students each year are from different disciplines not limited to Physics, Electrical Engineering, Computer Science, Education, Management Science, and Product Design. The course is structured such that the students work in teams with a company sponsor and industry liaisons that follow their progress on a design project based on a prompt supplied by the company. Past sponsors include SAP, Panasonic, Toyota, Volkswagen, BMW, Siemens, and Autodesk among many others. In the last several years, the course has included a global network of schools, some of which are paired with the local students to work on the corporate project. At the end of the 9-month course, students produce a final functioning prototype, with a high enough resolution that it appears polished and marketable. During the course, the students make several prototypes on various ideas, conduct needs-finding interviews and point of view analysis to define their customers, and present their findings and designs to the teachers and liaisons.

Although the students had various backgrounds and skillsets, the teaching team recognized that many students struggled with common barriers when it came to prototyping with electronic components. These barriers are currently decreasing with low-cost tools with large community support such as Arduino microcontrollers (Mellis, 2007) and the Processing programming language (Reas, 2007). The objective of the Paper Robot activity was to introduce students to such tools so that they could more easily and quickly start prototyping with microcontrollers for the corporate projects.

Figure 1. Examples of some Paper Robots created by students in 2013.

The approach of using paper as a prototyping medium has been demonstrated with the course's well-known "Paper Bike" activity, in which student teams build paper vehicles to compete in specially devised Paper Bike sports. The Paper Bike project is at the beginning of the course curriculum, introduced as a "warm-up" group design activity. Teams work for approximately 4 weeks to build a vehicle to carry a human rider and participate in the final competitions. The design process, specifications and final prototypes are documented by the students for a graded report at the end of the activity. This activity is not only a warm-up introduction to the design process, but it is also an "equalizer" across the students' experiences and skills. Very few people come into the class with experience building large scale functioning systems out of paper (or in this case, heavy cardboard tubes and boxes of different sizes that are scavenged from various outlets.)

Paper also offers a valuable medium that is especially suited for prototyping early in the design process. It is easy to construct and to manipulate paper. When used with electronics, it allows for the blending of high and low resolution materials while encouraging rapid prototyping and experimentation (Houde, 1997).

Since the Paper Robot's introduction in the 2010-2011 academic year, four classes of local students and many students in schools across the globe have participated in this activity. This report documents the methods and materials of the P.bot design exercise and the results from surveys that 29 students took during the second year of its introduction.

2. Related Work

The P.bot activity combines the use of paper and electronics prototyping in education. As mentioned, the use of paper as a medium for electronics prototyping offers a low intimidation material that is easy to start building with and modify. Few engineering education courses teach an introductory method to working with electronics in a way such that students can easily start a project with electronics outside the classroom without an instructor's guidance. Many engineering students find it difficult to work with electronics. Students may need to struggle with mechanical, electrical, and software components (Giurgiutiu, 2005). Introducing paper as a method to contain electronics and build structural mechanisms reduces the barrier to start prototyping with mechanoelectrical components (Qi, 2012).

Furthermore, robots and devices made of paper can promote social interaction due to their cute and inviting appearance, as demonstrated by Tweenbot (Kinzer, 2009) and Boxie (Reben, 2011). Tweenbot is a social art project that featured a robot that needs human interaction to help direct it to its intended location, and Boxie is a small robot for collaborative video recording.

As explained by Qi (2012), paper can be a friendly and open-ended material, which gives learners "full freedom to be expressive without the technical and aesthetic constraints of pre-designed kits or pre-fabricated electronic systems." Hence, in a course that is meant to foster creativity and innovation, the use of paper in an electronics-based learning activity is a suitable design choice.

3. The Paper Robot Activity

The Paper Robot assignment is 1.5 weeks long and presented about 3 months into the design course. At this point, students are narrowing down their ideas for their final prototype and shifting focus from exploration to implementation in their corporate projects.

The activity has three primary objectives:

1. To present students with a platform for prototypes involving electronics, and to introduce them to tools for developing embedded devices.
2. To influence corporate project success and increase functionality in the design teams' final prototypes.
3. To increase students' confidence in starting projects using electronics on their own.

The students were introduced to the activity and the Arduino programming environment in a single 50 minute long lecture. Then multiple office hours were held during the build week by the teaching staff. Before the start of the assignment, a tutorial was posted on the course webpage describing the assignment components. The tutorial also included example code for demonstrating some basic Arduino functions, controlling various electrical components, and implementing a software serial communication protocol.

3.1. Description of Activity

The learning objectives can be further broken down into the technical skills that the Paper Robot activity taught, including:

1. Soldering.
2. Building basic circuits.
3. Reading and writing analog/digital inputs/outputs.
4. Establishing communication between devices.
5. Programming a microcontroller.

First, students had to assemble their Arduino compatible microcontroller boards. The robots were required to have 4 types of inputs that could be triggered (sensors, switches, etc.) to send a message, and 4 types of outputs for display (LEDs, servo motor motions, etc.), which were controlled based on a received message. A sample robot was presented for students to interact with (Table 1, Figure 2).

The instructions to students were to:

1. Use "sensors" (of any kind, including switches) to detect an input state that is imparted to the P.Bot by a naive human user.

2. Communicate with others of its kind in a predefined standard format and protocol. In this activity, we will be using a software serial library, which simulates UART communication on standard digital pins.
3. Interpret received messages and do something physical to reflect the received messages as output that naive users can recognize and enjoy.

Table 1. Example Paper Robot inputs, outputs and communicated messages used for instruction of the activity.

Input Sensor	Output Display	Associated Message
Squeeze force-sensing resistor on left hand.	Large LED on heart lights up.	Happy (h)
Squeeze force-sensing resistor on right hand.	Right arm is waved by a servo motor.	Sad (s)
Bend forward neck, triggering a flex sensor.	Robot dances (turns in circle) by a DC gear motor.	Excited (e)
Press push button on nose.	Small LEDs on eyes light up.	Angry (a)
None / unclear.	No wave, eyes off, heart off, not dancing.	Default (?)

Students followed instructions under the following constraints:

1. Naive users should be able to manipulate (e.g. move, assemble, push, twist) the P.bot to put it into a desired state.
2. No text and no alphanumeric labels in any natural language are allowed for the input or output, or anywhere on the P.bot. There can be no instruction manuals. Operation has to be achieved by finding "intuitive" motions, graphics, lighting, sounds, and so forth. Icons and graphics are also permitted.
3. The P.bot systems need to be able to send and receive messages in a standard format, using the SoftwareSerial library. Everyone will use the same pins for receiving and transmitting data (digital pin 3 and 4) at a baud rate of 9600.

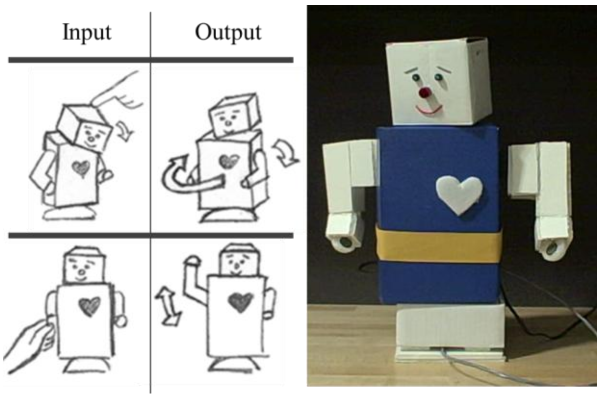


Figure 2. Select inputs and outputs and a photograph of the example Paper Robot.

The first two constraints are to foster creativity in interaction design of the Paper Robot, and the third constraint provides guidance, so that all robots will communicate with each other in the same way.

3.2. Choice of Tools

The Really Bare Bones (RBB) board (Modern Devices, 2014) was chosen as the microcontroller board for the course due to its Arduino compatibility, low cost, and the need for assembly. Students were encouraged to have their team members with the least soldering experience assemble the boards, to increase their knowledge and confidence in soldering skills. Some schools participating in the design activity chose to use other Arduino boards that did not require assembly for the interest of time.

For the communication between robots, a software serial protocol was implemented using the SoftwareSerial library (2014). A software based serial protocol was chosen because the standard Atmel ATmega328 chip on the RBB board has only one hardware UART port set on its TX and RX pins. If these pins were used for communication between P.bots, they would not be able to be used during continuous debugging.

Wired communication was implemented with standard 4-pin RJ-11 jacks on each robot, and cross-over cables between the robots to properly direct transmitted and received messages. A wired serial protocol was chosen because it was quick to implement, with less uncertainty involved in wireless communication protocols (such as cross talk, range limitations, etc.).

4. Study Design and Evaluation

The Paper Robot activity was evaluated by means of self-assessment surveys given to the students immediately before and after the assignment. The task performance was measured in terms of whether or not the students were able to complete the task of building a robot with 4 inputs and 4 outputs, while sending and receiving messages. Confidence in the technical areas of prototyping with microcontrollers, programming, and building circuits was assessed before and after the activity. Students were also asked about whether or not they believed their knowledge had increased in the technical areas.

Written surveys were taken by 29 students as per Intuitional Review Board approved Human Subject Research Protocol No. 22639. The pre-activity survey assessed students' experience, interest, and comfort level in certain technical areas including: working with microcontrollers, Arduino programming, other programming languages, building circuits, mechanical component design, and implementing communication protocols between devices. The pre-activity survey assessed students' knowledge and incoming skillset regarding the technical areas. The post-activity survey assessed students' knowledge gain and confidence in the technical areas, while also assessing the specific skills learned from and time spent on the activity. Responses included choices such as "Very Confident, Fairly Confident and Not Confident"; and "Expert, A Lot, Some, Little, and None", which were linearly normalized to a 5-point Likert scale. The data gathered were from 29 students in the design course. The students' average age was 23.8 years old, in the group of 9 female and 20 male students.

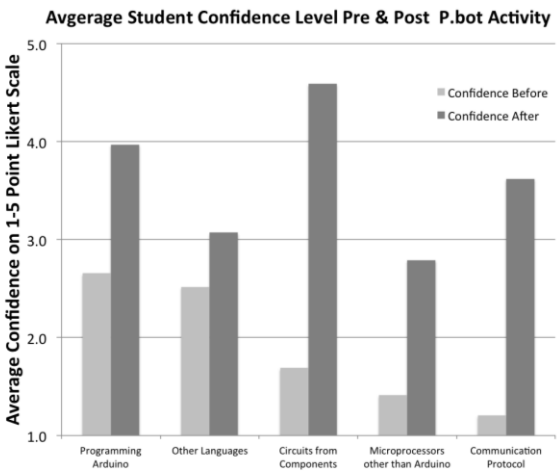
Although this data were gathered from one class at a local US university, the P.bot activity has been taught in satellite courses across the globe, including universities in Finland, Mexico, Colombia, and China, over the course of the last 4 years.

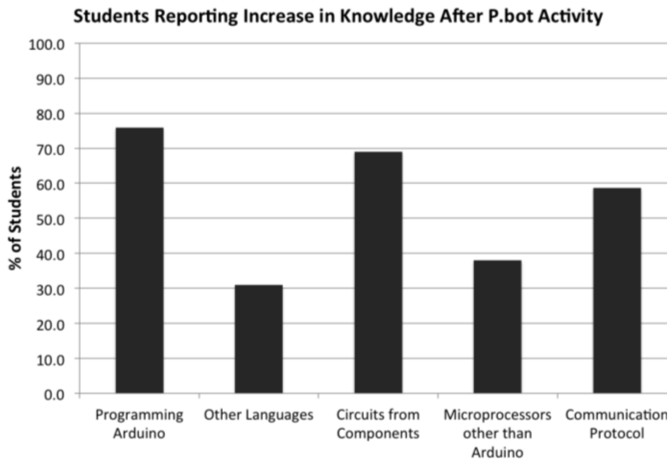
33% percent of students in the surveyed class also participated in an extended post-survey which was administered 6 months later at the end of the course, which assessed the complexity of their teams' final prototypes and whether knowledge gained from the Paper Robot activity was useful to the corporate projects.

5. Results

From the class of 32 students in their 8 design teams, all students made a Paper Robot with 4 inputs and 4 outputs as described in the instructions, and were successful in integrating mechanical, electrical and software components. Figure 3 shows the reported confidence level (normalized to a 5 point Likert scale) before and after the activity in specific technical categories. Figure 4 shows the percentage of students that reported they had gained knowledge in the specific technical categories. 76% of students reported an increase in knowledge in programming microcontrollers (Arduino), and 69% increased their knowledge in creating electronic circuits out of raw components. Table 2 outlines the breakdown of time spent on the Paper Robot activity, averaged across all students' self-reported answers.

Students that completed the third survey at the end of the course reported using the following new knowledge from the P.bot activity in their corporate projects: soldering, rapid prototyping, teamwork in electronics activities, building simple circuits, programming digital I/O, and implementing serial communication. Mechatronic components used in final prototypes for the corporate projects included: LEDs, servo and stepper motors, resistive and capacitive sensors, proximity sensors, accelerometers, tilt sensors, photo-resistive sensors, WiFi shields, RFID cards, IR cameras, and LCD displays. Programming languages used included: HTML/HTML5, PHP, CSS, JavaScript, MySQL, Ajax, C/C++/C#, Arduino and Python. Control hardware utilized in the final projects included Arduino, custom electronics with Atmel-based chips, mobile devices and computers.





6. Discussion

The results show that although students came into the activity with less confidence in the technical categories, at the end of the course, average confidence increased greatly. Even confidence in microcontrollers and software other than those introduced by the P.bot activity had increased. This shows that the Paper Robot assignment was successful in encouraging confidence in the general areas of electronics prototyping and enabled students to have the confidence to learn and implement such prototypes on their own, without guidance, and on new platforms. It was not obvious to us whether student confidence would decrease in response to technical frustrations, but our evaluation shows that successfully making a working paper robot appears to balance these frustrations. Knowledge gain also showed positive results, although not as drastic as the change in confidence. It is reasonable to assume that students' confidence level may be higher than their knowledge of certain aspects, which is also an indicator of willingness to learn and gain unfamiliar skills.

Many students commented on their "likes" about the P.bot activity; common themes included making the final P.bot, learning mechatronics, the ability to be creative, and the social debut in which the P.bots were connected to each other at the end of the activity. Most of the "wishes" centered on the following themes: desire for more tutorials/instruction, time pressure on other assignments in the course, programming issues, serial communication issues, and team issues. It was helpful for teachers to have done the activity, and present an example robot during the introductory lecture.

Some recommendations for the activity include establishing a clear communication protocol, and providing test robots for students to continuously debug before the final P.bot social. Unclear interaction protocols are a reoccurring issue for human-machine interfaces in the course. A protocol establishes, for example, what happens if a robot issues a message and there is no response, or if robot gets into a loop that causes it to repeatedly broadcast messages without stopping to listen for incoming messages. Implementing devices that communicate robustly with each other may require more advanced concepts such as event-driven programming, but this may be challenging for a novice programmer to implement from scratch. A future toolkit for communicative P.bots could provide a minimal event-driven framework to decrease difficulty associated with sending and receiving messages.

Students reported that a large percentage (30%) of their time was spent on testing and debugging the circuitry of the robots. This means that the overall time of the activity could be compressed with improved debugging tools, and with components that have a reduced chance of error. Providing more modular electronic components for this activity may provide students with premade functioning modules that may be more easily incorporated into a design idea. For example, a tri-color LED light, or a light sensor module, that already has the necessary supporting circuitry, allows ideas to be swapped in and out in a modular building block fashion. This building block philosophy, which can be seen in novice toolkits such as LEGO Mindstorms, littleBits (littleBits Electronics, 2014), and Electronic Blocks (Wyeth, 2008) are effective ways to make the P.bot activity accessible to even younger age groups. Mindstorms and littleBits platforms are geared toward easing electronic interactions so that the user can focus on learning programming. Mindstorms, just like the P.bot, allows for visual debugging since they "embody state and behavior, physically modeling the structure of the programming solutions. Their activities are the concrete instantiation of program behavior. Students receive immediate visual feedback, allowing visual debugging since the program's state of execution is literally played out in front of them" (Powers, 2006). Prior work has shown that more modular platforms such as the Go-Go board (Sipitakiat, 2002), and d.Tools (Hartmann et al., 2005), have allowed increased focus on the creative design task, rather than technical learning. We are exploring how these ideas may be incorporated into a future P.bot activity, to encourage design and creativity while fostering electronics and programming skills.

Table 2. Breakdown of time spent on key stages.

Activity	Avg. % Time Spent
Soldering the microcontroller board.	12%
Brainstorming the idea/theme/components to use.	15%
Finalizing components, inputs and outputs of the P. bot.	18%
Testing and debugging the P.bot.	30%
Building the P.bot (chassis, assembly, integration).	27%

7. Conclusions

We present the Paper Robot activity as a way to encourage creative exploration with electronics and low-tech materials such as paper. Students reported a gain in knowledge and confidence across several technical categories relating to microcontrollers, programming, and building circuits after completing the Paper Robot activity.

Compared to traditional educational models, the use of paper as a means for fostering creativity, coupled with the project based learning activity, led to a successful curriculum in which students worked together in teams while enhancing their own knowledge. Over the last 20 years, capstone (Dutson, 1997) and project based courses (Frank, 2003) have been increasingly taught in university level engineering programs in order to provide students with more exposure to the design element of engineering as well as experience working in teams. Due to recent advances in technology, design education has shifted toward more active learning methods while allowing for the dissemination of knowledge through the Internet and the use of open source tools (Beetham, 2013).

Due to potential complications during implementation of the communication protocol, it is helpful for the students to have an example Paper Robot to interact and test with their own robots. Access to simple debugging tools and pre-established communication APIs may also be helpful.

Improvements to the study include using a larger sample size, assessing the influence of the activity on global schools, and measuring the long-term effects of prototyping confidence in microcontrollers. Continual studies across schools and class years may show insights on the learning styles of students as more project based courses are taught concurrently with ME310. More quantitative data could be gathered between ME310 partner schools to compare students' confidence and knowledge gain in different environments under slightly different P.bot activity goals, perhaps focusing on electronics, programming, or the creativity aspect more than others.

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