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A pilot biomedical engineering course in rapid prototyping for mobile health

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SECTION I INTRODUCTION AND COURSE DESIGN

Mobile health (mHealth) is “the practice of medical and public health, supported by mobile devices” [1]. Electronic mobile devices like cell phones and patient monitors are often thought of, but mobile devices may also include microfluidics devices or public health toolkits arranged in a backpack (e.g. polio vaccination coolers).

Rapid prototyping refers to the construction of physical objects that can be used to test functionality of devices. It often specifically refers to the use additive manufacturing technology such as 3D printers. When designing our course, we used a much broader definition for this term, since a prototype can include Proof-of-Principle, Form Study, User Experience, Visual, and Functional Prototypes [2]. We also included software prototypes in our definition to address the growing trend toward developing new software applications that build upon working open source code instead of “from scratch”.

Free and open-source tools for rapid prototyping have reached a level of sophistication such that little training is required to design useful products inexpensively. We anticipate growth in custom-built devices from very cheap components. For examples of such devices, see recent issues of Make Magazine. Some of these device designs may develop into commercial successes.

Rapid Prototyping for Mobile Health (RPMH) is designed as a structured laboratory with a research design component. We allowed broad enrollment of students from many majors and grade levels, but students were required to meet with the instructor before registering to get a permit for the class. This gave us an opportunity to test the students willingness to take a course that was in a pilot phase. Our goal was enrollment of about half biomedical engineering students and half students from other departments (e.g. biology, computer science, electrical and computer engineering, and industrial design). There were no prerequisite courses, but the permitting process emphasized a strong personal interest in health and medical device design.

RPMH comprised of four lectures, nine self-guided laboratory assignments (each designed to take six hours to complete) (see Fig. 1), and a six-week team project with a literature review deliverable and presentation of prototypes. Eleven students enrolled in the pilot.

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During the first lecture, each student chose a different childhood chronic disease (from a list of 25) to serve as a common thread to link all of the labs together. Then, when forming teams, each member had different ideas to present based on what they had learned about their chosen disease over the first 10 weeks. The course was offered for only one semester.

A. Grading

Each of nine completed labs counted for 5.6% of the final grade. The final project counted for 50% of the final grade, composed of a literature review, a presentation score, a prototype quality score, and a participation score partly based on peer review grades from team members. The peer review rubrics were derived from Newstetter et al [3]. Two extra credit points were awarded to students that attended a local Maker Faire event held on campus.

SECTION II RAPID PROTOTYPING TECHNOLOGY DESCRIPTIONS

In this section, we describe the four technologies that were ranked the highest by students as most interesting and useful for prototyping. Table 1 gives shorter descriptions of the other four technologies as well as the average rankings. Labs are sorted by average student ranking (1–9). The standard deviation of the rank scores is in parenthesis under the average and if less than 11 students attempted the lab, the number responding is given below that. The agreement between biomedical engineers and industrial designers was high, especially among the top three labs.

A. Arduino Microprocessor

The Arduino open-source microprocessor was developed to re-introduce electronics as a hobby to the modern generation of high school students [4]. Students can easily learn to write firmware for prototypes and low-speed applications. The Arduino development community encourages code sharing through a publicly editable wiki site [5]. Arduino is a single-board microcontroller that can be paired with external modules (called "shields") to make the process of using electronics in multidisciplinary projects more accessible. The hardware consists of an Atmel AVR processor and on-board input/output support. The software consists of a standard C based programming language compiler and the bootloader program that runs on the board.

Arduino was ranked highly by the RPMH students due to the wide variety of projects that it enables, including sensors, robots, and devices that communicate with mobile phones or the internet wirelessly. Google has announced that their Android operating system for mobile phones will provide supported application programming interfaces (APIs) for devices built using the Arduino microprocessor. This means that complex data storage and network connectivity issues can be outsourced to mobile phones, making mobile medical device design even simpler.

B. Makerbot 3D Printer

Makerbot is an open source 3D printer than can be purchased in parts and built by the owner or purchased fully assembled. Builders with access to the necessary machine shop capabilities can fabricate a Makerbot using openly available diagrams and computer numerical control (CNC) files. Makerbot electronics are all based on the Arduino open hardware standard. The printing device is paired with open- source software capable of making simple adjustments to a 3D model and a package called Skeinforge which converts the model into instructions for moving the print head. The Skeinforge process can be tuned with over 100 parameters governing print speed, accuracy, and plastic consumption.

3D printers extrude heated plastic through a small nozzle to build objects in ~0.2 mm layers (see Fig. 2). 3D printers introduce interesting design constraints because they can only place plastic on top of pre-existing plastic. Making a model with significant "overhangs" (e.g. a 3D sphere) requires a model with 2 connecting pieces. The Makerbot lab extension (counting as an additional optional lab) required a design with multiple connecting pieces. Students were also encouraged to search for public models to print on the Thingiverse web site [6].

C. Bamboo Online Lecture Kit

The Bamboo tablet facilitates electronic design and prototyping by capturing free-hand drawing at a detail level much higher than previous stylus technology. The tablet detects not only the location of the stylus when touching the pad, but can also detect 1024 different haptic pressures and can detect when the stylus is hovering just above the pad. The founder of the education non-profit and web site Khan Academy uses this device as an inexpensive electronic blackboard while recording online lectures covering complicated math, science, and finance topics. For RPMH, students were asked to record a 4-minute background lecture on the chosen chronic disease with accompanying blackboard drawings.

D. Google Sketchup

Google Sketchup was originally provided as a tool to allow community contributors to upload models of buildings in their area to improve the 3D realism of the Google Maps interface. However, the tool has been adopted by a wide variety of designers as a free alternative to more expensive computer aided design (CAD) programs. It is useful for architectural modeling as well as product prototyping. For RPMH, students explored the application of Sketchup to three different areas of product development: documentation of device design, packaging design for 3D printing, and modeling of 3D characters or graphics for branding and marketing. The Sketchup lab was a prerequisite for the Makerbot lab so students would have their own 3D model to print.

SECTION III PROJECTS PROPOSED BY STUDENT TEAMS

At week 10 of the course, students chose their own project teams based on technology and disease interests. Extra points were awarded for forming multidisciplinary teams, with the positive result that all 3 teams contained an industrial design major. Here we present two ideas proposed by these project teams.

A. PainPal

The goal of this design project is to develop a device that records pain levels over time through the use of a quantifiable pain scale [7]. The device should encourage children to report their pain on a regular basis, as well as be quick and easy to use. Doctors should then be able to use the recorded data to monitor patients' pain levels and correctly diagnose any future treatments.

The device targets pediatric pain sufferers between the ages of 6–12 years old who are unlikely to own a smartphone device. Implementing Arduino and an RFID with tokens corresponding to different levels of a modified Faces Pain Scale, a simple, portable device was constructed that allows the child to report pain quickly and with relative ease. The two prototypes presented were the bracelet and the RFID detection circuit (Fig. 3).

The child would wear a bracelet, constructed using the Makerbot, with the RFID tokens placed inside of the bracelet, and a label for each token would be visible on the outside of the bracelet. The child would then be trained to record his/her pain level at a certain interval by holding up the part of the bracelet corresponding to their pain level to the RFID device. The type of token that was used would be stored using a Micro SD Card, and later accessed by a health care professional on a computer. Code was developed to interpret the RFID token used by modifying open source code for Arduino.

This device allows for pain reporting to be actively contributed by the child and for the pain records to be moved from a verbal or written format to an electronic format, making data analysis easier for the health care professionals. While it was originally designed for children affected with sickle cell disease, this device can be easily modified for other target groups or uses.

B. Breath of Air

An asthma attack is usually caused by a certain number of known triggers, including dust, smoke, plants, animals and weather change. Effective management of asthma can reduce symptom-days down by 21 days per year [8]. It involves adequate knowledge of one's surrounding and detection of allergens where possible. To facilitate the detection of allergens immediately, we propose a tool called 'A breath of Fresh Air' to alert the user in the presence of dust and smoke.

The device is an Arduino-based dust detection device. The two prototypes presented were the detection module and the child-friendly packaging (Fig. 4). It uses a commercial optical dust sensor with fans to direct the flow of air to the sensor. The air quality information is continuously recorded to an inbuilt microSD flash memory chip, from which information can be retrieved when required. If the amount of particulate matter in the air increases beyond a threshold, an alarm is sounded. This alarm indicates that the room is not safe for the asthma sufferer.

SECTION IV DISCUSSION AND LESSONS LEARNED

Rapid Prototyping for Mobile Health was a successful class with positive reviews by students. However, some modifications would be necessary if is expanded into a regularly-listed course in biomedical engineering. First, most of the labs were performed and debugged by the authors before being assigned to students. However, a troubleshooting section was added to the end of each lab description document to describe problems encountered by students and their solutions. The two labs that required the most troubleshooting were Makerbot and Google AppEngine. Problems encountered with Makerbot stemmed from the physical nature of plastic extrusion. Many models experienced warping as the plastic cooled, sometimes leading to total failure of the build. We allowed students to substitute three failed build objects for one good build. Also, students were advised to scale their models to the smallest size possible. The Google AppEngine lab was a valuable test of student time management skills because of the daily quotas enforced on free accounts. Students that didn't start this lab early were sometimes forced to pay to release their quotas.

SECTION V CONCLUSION

Rapid prototyping training extends the standard hands-on instrumentation labs that help biomedical engineers understand medical device development. The most common feedback from students in the course was they wish that teams and team projects were assigned earlier so they could spend more time to develop their ideas. This curriculum could be integrated with existing instrumentation labs or offered as an elective course. If offered as an elective, it is recommended that students of different majors be invited to participate in order to emphasize the interdisciplinary nature of product development. If notice of the course can be coordinated between departments, many students should show interest due to the current potential of biomedical devices and mobile health.

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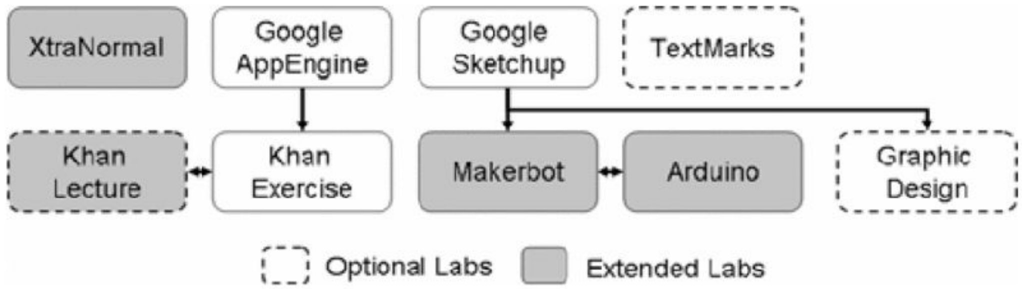

Figure 1.

Rapid Prototyping Class Overview. Nine labs were assigned in a pseudo-random fashion, taking into account the dependencies indicated above. Students were given the choice of substituting an optional lab by performing a more advanced version of an extended lab

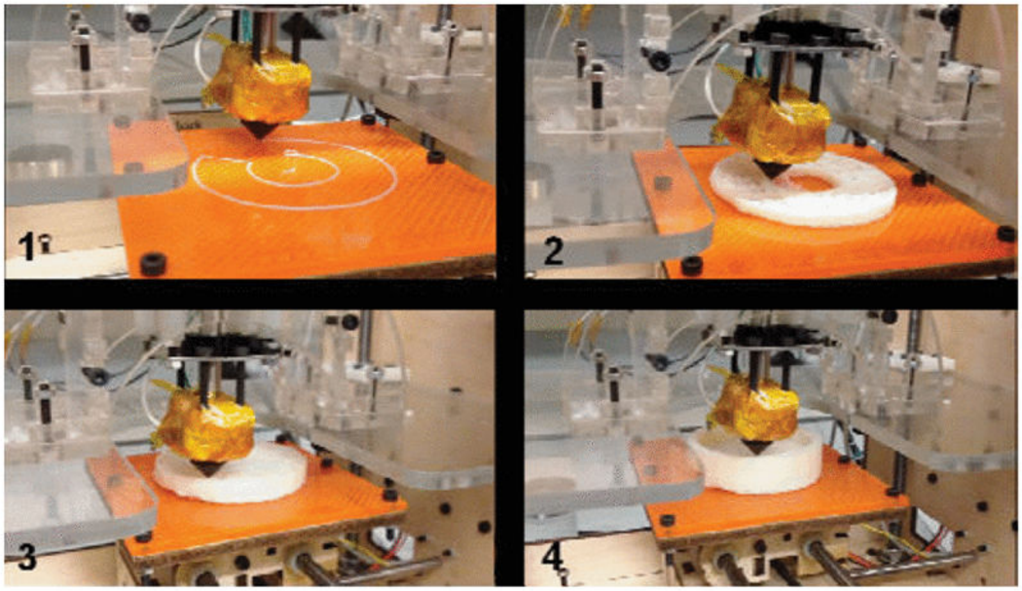

Figure 2.

Time Series Images of Makerbot Printing. The print head of the Makerbot is wrapped in insulation and yellow heat-resistant tape (above the white model). The print head only moves in the Z plane. The orange build platform movies in the X, Y planes to ensure the plastic extrudes to the correct location

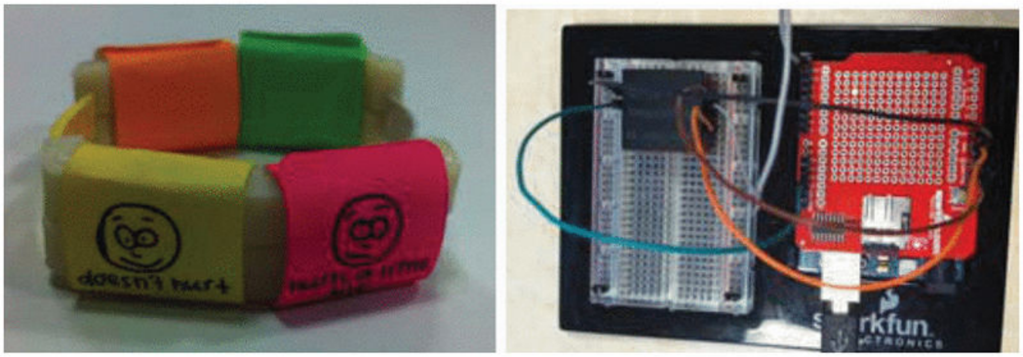

Figure 3.

The PainPal Prototypes. The image on the left shows the bracelet containing RFID tokens that a child would wear and use to record his/her pain level. The image on the right shows the RFID and Arduino connections

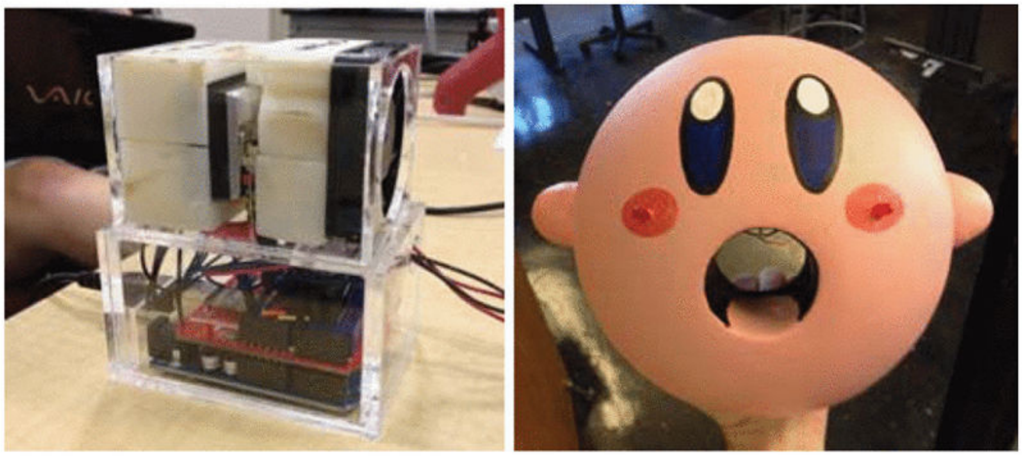

Figure 4.
The Breath of Air Prototypes. The image on the left shows the air handling unit (top), the dust sensor (top center) and the data processing and storage unit (bottom). The image on the right shows the packaging and the LED lights that display warnings

TABLE I

RAPID PROTOTYPING TECHNOLOGY SUMMARY

Technology	Source Company	Project Description	Cost	Student Ranking
Arduino	SparkFun Electronics (Boulder, CO)	Students constructed and tested 6 circuits from the SparkFun Inventor's kit. Evidence of completion was gathered using cell phone cameras.	$95	1.91 (1.7)
Makerbot	Makerbot, Inc. (Brooklyn, NY)	Students searched for object files in the Thingiverse web site or designed their own in Google Sketchup and learned to set up and troubleshoot a print job.	$1150	2.45 (1.3)
Bamboo Online Lecture Kit (with Camtasia Studio)	Wacom Tech. Corp. (Vancouver, WA) TechSmith Corp. (Okemos, MI)	Students worked with the same tools as the founder of Khan Academy to record a 5-min lecture about the cause of a chronic disease.	Tablet: $80 Software: $99	4.43 (1.8) 7 rspg.
Sketchup 3D Modeling	Orig: Google, Inc. (Mountain View, CA) Curr: Trimble Navigation Limited (Sunnyvale, CA)	Students explored the many features of Sketchup: drawing, camera positioning, 3D extrusion, importing from the 3D warehouse database, textures, styles, dimensions, animation, and exporting to 3D printer file formats.	Free	4.45 (2.1)
XtraNormal Desktop Animation	XtraNormal, Inc. (San Francisco, CA)	Students created scripts involving adolescents with chronic disease in social situations. They selected a set, characters and voices to produce a 3-minute animated video.	$25 (for limited sets & actors, unlimited vids.)	4.64 (2.0)
Graphic Design with Vector Graphic	Inkscape Administrators (open source software project hosted on Launchpad.net) (http://inkscape.org)	Students learned the difference between 2D vector graphics, raster graphics, and 3D graphics. Students learned about the open source algorithm Potrace for converting raster graphics into vector graphics. Students created scalable logos in 2D and 3D using Inkscape and Google Sketchup.	TotalVectorize software $40 (useful but not required)	5.3 (1.6) 5 rspg.
Social Games via SMS Text Messaging Gateway	Orig: TextMarks (San Francisco, CA) Curr: Google, Inc. (Google Voice) (Mountain View, CA)	Students created a state diagram to describe a social game that can be played using SMS text messaging on cell phones. They then converted the state diagram into database tables. Our lab has custom-built software in place to create a working system from the database. Students tested the system with their personal cell phones.	TM plans have monthly limits ($35–$100/mo) Google Voice is free for slow messages	5.6 (2.8) 5 rspg.
Google AppEngine	Google, Inc. (Mountain View, CA)	Students were introduced to the Khan Academy open source project. They learned how to set up a free account on Google AppEngine, how to reserve a URL, and how to deploy their system and do basic database maintenance.	Free	6.3 (2.0) 10 rspg.
Khan Academy Mastery Learning Exercises	Khan Academy (Mountain View, CA) (non-profit)	Students developed a 10-question knowledge quiz about their selected chronic disease. They were introduced to Javascript methods for randomizing questions and answers. The quizzes were uploaded to Google AppEngine to support a working Khan Academy-style web site.	Free (this open source project is no longer supported)	6.63 (2.3) 8 rspg