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A PROPOSED PLATFORM TO SIMPLIFY THE INTEGRATION OF ELECTRONICS INTO A MECHANICAL ENGINEERING DESIGN COURSE

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ABSTRACT

The interdisciplinary nature of engineering design and the pervasiveness of electronics in most products has made it necessary for practitioners of "design thinking" to understand electronics and embedded systems, in order to expand their concept exploration space. This poses a significant challenge for mechanical engineers, whose knowledge of electronics is typically limited. A course in mechatronics is available to enhance this knowledge, however it is taught separate from product design and CAD/Toy Design, and students often do not get the opportunity to combine these elements. With an open source microcontroller platform (Arduino^{TM}) that allows for easy programming, we see an oppportunity to blend design thinking into a larger domain of engineering. In this paper, we propose a platform that would simplify the incorporation of electronics into a design. The proposed platform will utilize the Arduino^{TM}, along with a modular architecture for designing electronic systems, as well as modular program segments for controlling these systems which can be easily customized to meet student requirements. This will enable students in a toy design course to integrate electromechanical systems into their designs, while at the same time providing useful electronic knowledge which can be used in their future careers. The toy design projects utilize a Problem-Based Learning [1, 2] approach that will allow students to familiarize themselves with the synthesis and programming of these systems. We describe two student test teams that were introduced to this electronic integration in an existing toy design course, and we use our observations to inform the design of the proposed platform.

INTRODUCTION

Motivation

Everyday more and more mechanical products are incorporating electronics into their design. For example, automobiles, which were once purely mechanical, are now being continually optimized with electronics [3,4]. With the incorporation of electronics, a higher degree of functionality can be achieved, resulting in more technologically advanced products. According to Giurgiutiu et al. [4], "Due to the accelerated growth of electronics, computers and information technology industries, a gap has emerged between the teachings of traditional non-Electrical Engineering education (e.g., Mechanical Engineering, Civil Engineering, Chemical Engineering, etc.) and the skills expected of non-EE graduates entering the job market". Thus, it is increasingly necessary for Mechanical engineers to have a basic knowledge of electronics, especially its integration into design architectures.

While our course teaches Computer-Aided-Design (CAD) and prototyping, there is also a focus on innovation and the design process. Tim Brown [5] states that today's designer needs to

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imbue "the full spectrum of innovation activities with a human-centered design ethos" – in general, the designer needs to think beyond the specifics of a product and think in terms of a larger system that interacts with people. Brown gives the example of Edison whose invention is not a specific product, but the modern R&D laboratory and experimentation, and uses the term 'Design Thinking' to describe the kind of thinking required to envision and design for such a system. One key aspect of the design process is ideation. When Mechanical Engineering students generate design ideas, many are limited to a purely mechanical scope. A basic understanding of the electronic tools available can provide a broader view of what is possible, which can result in not only a greater number of design ideas, but also an increase in the creativity and functionality of the designs.

Learning basic electronics is not trivial, as whole courses are typically dedicated to this task. This poses a problem for our design course, as Mechanical Engineering students typically have little to no experience with electronics. In addition, the students only have part of the semester to learn and implement these skills. Our solution is the aforementioned platform, which aims to expedite this process. The platform is the result of the 'design thinking' kind of approach, in that it aims to create a system which will lower the learning barrier for students so that they can bring about the next generation of innovation in toy design.

Educational Background

Bucciarelli [6] talks about the disjunction between designing and learning, stating that "unless faculty within a department or those responsible for prerequisites discuss themes and threads that intersect in their different courses, each course appears to students as an island apart from others". With increasing division and subdivision of disciplines as they become more and more specialized, this problem gets exacerbated over time. This poses a problem for undergraduate educators, where it is difficult in design courses to spend too much time training students in the technology required, like mechatronics, and in mechatronics courses, it is difficult to teach the subject in the context of design.

In recent years, there have been some efforts to teach mechatronics in a design context, especially to mechanical engineers [7–10]. Some of the courses lay emphasis on the learning of embedded systems and assembly language, while others lay emphasis on design, using higher-level language to reduce the students barrier to education. Both approaches have their strengths and purposes, and have to be chosen based on the goal or the intended impact of the course. At the same time, it is necessary to engage students in the learning process. Problem-Based Learning [1, 2] and Learning by Design™ [11] approaches have been established as effective for teaching design. It has been shown that creativity has strong relations to play [12], and tolerance of ambiguity [13]. Repenning et al. use this approach to engage students in learning programming through scalable game design [14].

Our capstone course on Computer-Aided Design and Prototyping (ME 444) was a natural choice for assessing our approach to integrate electronics, due to its unique position in integrating design and prototyping in the context of toys. The course has benefited around 2400 students to date, and has been directed especially towards developing a "self-paced"CAD learning content for students, with the experienced teaching assistant's knowledge in the subject providing additional support. The course was application-oriented in that the students learned CAD concepts, and applied them to a course project to design an "action toy"with significant geometric and mechanical complexity [15]. We have combined the models of Learning by Design™ [11] and creativity through play where students learn design and prototyping through a combination of collaborative workshops and laboratory sessions, culminating in a toy design project, where they form teams and design and prototype a toy. This course attempted to integrate electronics earlier, but showed a considerable barrier for learning due to the intricate knowledge of assembly language and circuit development required.

PILOT STUDY

As previously mentioned, ME444 culminates in the design and fabrication of a toy. Since this is a Mechanical Engineering course, the designs have tended to be purely mechanical. Our goal for the future of this course is to expand the breadth of the designs by enabling students to easily incorporate electronics. To accomplish this, we first conducted a pilot study involving two groups that built electro-mechanical toys with help from a TA.

Arduino™

The groups were informed that they would be using the Arduino™ [16] prototyping platform. The Arduino™was chosen because it provides an easy way to incorporate electronics into a design. It can read input from sensors and control many devices, such as motors and actuators. This is done via an Atmel microcontroller. Essentially, the Arduino™simplifies the incorporation of a microcontroller. The Arduino™includes a programming language to control the microcontroller, as well as an easy-to-use Integrated Development Environment (IDE). There are many versions of the Arduino™, which fit a wide range of applications. Many similar products exist, but the Arduino™was chosen for the following reasons:

- Low cost.
- Easy to setup and use.
- Provided libraries and examples that simplify the use of many electronic components.
- Many online open source projects for reference.
- Its programming language is a simplified version of C/C++ [17]. This is advantageous because it is easier to work with

than assembly language, and has more capability than other languages, such as PBASIC [12].

- Compatible with Windows^{TM}, Mac^{TM}, and Linux^{TM}operating systems.

For these reasons, the Arduino^{TM}has revolutionized electronic prototyping by significantly simplifying the process. In the book "Practical Arduino^{TM}: Cool Projects for Open Source Hardware", it is stated that the Arduino^{TM}is "an endeavor that has caught the attention of an astonishingly wide range of people and provided opportunities for those who might otherwise have never picked up a soldering iron or written a single line of code" [18]. An article in Make magazine went as far as to predict that "within the next 5 to 10 years, the Arduino^{TM}will be used in every school to teach electronics and physical computing" [19].

Tablet for remote control

Augmented reality (AR) is a fast-rising paradigm in human-computer interactions. While the concept was conceived of in the 1960s, only now is it becoming a truly ubiquitous technology [20]. Some of the main reasons for the recent rise in AR applications are the development of natural user interfaces (NUIs) and their integration with hand-held computing devices like smartphones and tablets [21]. Van Krevelen and Poelman [22] review the state-of-the-art in augmented reality and discuss the requirements of todays augmented reality systems, which include tangible UIs, gesture-based interactions, gaze tracking, context awareness, computational framework, wireless networking, and data storage and access technology, to name a few. Todays tablet-based computing systems like the iPad and various tablets using the Android system are equipped with front and rear-facing cameras, accelerometers, multi-touch displays, wireless and mobile networking systems, and GPS tracking systems, which make them ideal for augmented reality applications.

In addition, tablet computing devices are rapidly becoming popular in education framework. Part of the reason is the natural intuitiveness that is afforded by these devices. In addition, it provides an integration of multiple sources of visual information, which reduces the "split-attention" effect, based on the Cognitive Load Theory [23].

The rising popularity of electro-mechanical toys controlled by tablet and mobile devices is a strong indication of the future of the tablet-based paradigm in AR systems [24], [25]. In the past, many students in ME444 have desired wireless control of their toys. As a result, we decided it would be key for future ME444 students to have the option of utilizing a tablet for wireless control.

Since we wanted a tablet to be a control option in the future, we informed the groups that their toy designs must interface with a tablet, specifically the iPad, so as to gain feedback on its integration. Consequently, iPads were supplied to each group. The iPad tablet was chosen because it can easily interface with the

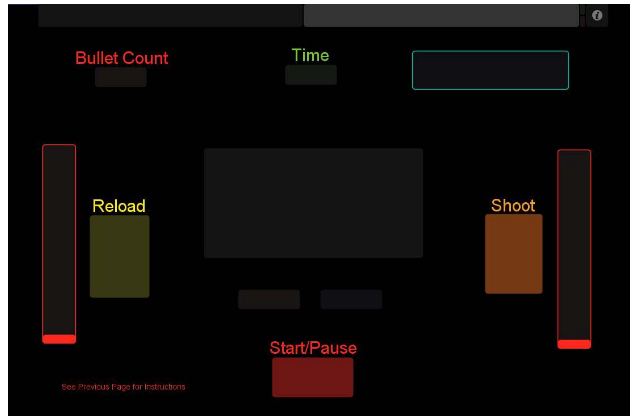

FIGURE 1. Example of a layout in the TouchOSC application.

Arduino^{TM}using an existing app called "TouchOSC" [26]. This app is editable, allowing the user to add various touch buttons and labels, which can then be used to control electronics connected to the Arduino^{TM}. The TouchOSC app can also utilize the accelerometers of the iPad. An example of a TouchOSC app layout is shown in figure 1.

Results

Both groups developed their toys using the i8^{TM}framwork, which is described by Taborda et al. [27, 28] as involving "concepts representing the design process. Inspiration and insight are the starting point. Ideation and imagination support the design concept creation and exploration. Iteration and implementation are present in every design process at every stage and keep the previous four is present all around the process. Finally every design is intended to have impact, by solving the initial problem, satisfying needs or at least originating more ideas. These concepts together form the solid basis for innovation through design." An abstract representation of the i8^{TM}framework is provided in figure 2.

The first pilot study group developed a "zombie graveyard" game. The basis of this game was to target and shoot small rapid prototyped figurines (painted to look like zombies) with a laser gun that was controlled by the iPad (see figure 3). The figurines and gun were mounted on a game board at fixed locations. The gun used two servo motors to provide two degrees of freedom, which were controlled using the accelerometers of the iPad. A laser pointer mounted on the gun was used to target the figurines. Each figurine had a light sensor to detect the laser and an LED to indicate if it had been killed. When the player had aimed the laser at the figurine, a "shoot" button was pressed on the iPad. If the laser was hitting the light sensor on the figurine

FIGURE 2. The i8™ framework representation.

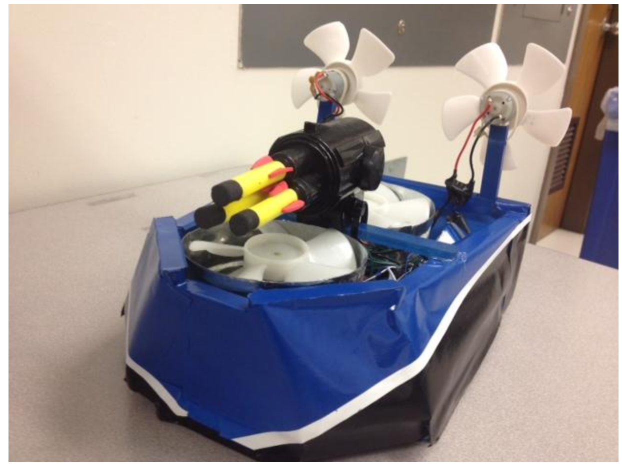

FIGURE 4. iPad controlled Hovercraft.

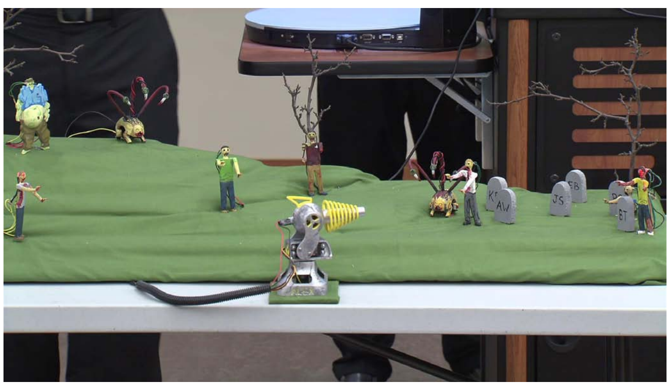

FIGURE 3. Electro-mechanical zombie graveyard game which uses the iPad.

when this button was pressed, it was registered as a hit and the figurines LED was turned off. The goal of the game was to shoot all the figurines on the game board in a specific amount of time.

This group's game worked very well. One of the main reasons for their success was that they frequently requested the help of the TA with programming and circuit issues. In addition, they started programming the code and assembling the circuit a few weeks before the due date. This allowed time to fix problems and debug the code. While the circuit to control the laser gun, light sensors, and LEDs was very simple, the programming required was much more in-depth. This group had very little to no experience creating circuits and programming, but they were able to finish both tasks by spending a significant amount of time developing their game, and by utilizing TA support.

The second pilot study group built a hovercraft (see figure 4) that was controlled by the iPad. Fan blades attached to two high RPM DC motors were used for lift. In addition, two more fan blades were attached to lower RPM DC motors for steering. A gun was also mounted on the hovercraft, which shot foam bullets. Buttons on the TouchOSC app were used to adjust the speed of the steering motors, as well as shoot the gun.

This group was unable to get their toy to function properly. This was mainly due to a poor design and a poorly built circuit. There was a high level of difficulty involved in designing the hovercraft. Not only was the circuit more complicated than the previous group, but there were additional factors that needed to be determined. Ensuring the hovercraft would lift was dependent on the motors selected and the weight of the toy. The battery selection was also intricate, needing to be as light weight as possible while supplying the motors the necessary current. In addition, the battery had to have enough capacity so the toy could function for a minimum of a few minutes. Even though there was this high level of difficulty, little assistance was requested of the TA. As a result, there were errors in the final circuit, which caused multiple motors to burn out. In addition, the design of the hovercraft was too heavy, requiring an excessive amount of motors for lift, which caused a very high current draw of the system. This group also started their final circuit assembly and code generation too late, leaving only a few days to solve any unexpected problems. If this group had allotted more time to create their final circuit, they may have been able to fix the errors. However, with the high current draw of the motors, the toy would have exhausted its power supply too quickly.

In regards to coding, both groups utilized the resource of the TA. However, since the zombie graveyard game required much more programming, more assistance was given to this group. Overall, the code for both groups worked well.

Discussion

The pilot study proved that electronics can be successfully integrated into our class. A key difficulty of this integration was the small amount of time available. In order to design and build the electro-mechanical toys within the given timeframe, the groups relied heavily on the TA. Specifically, the groups needed a significant amount of help with designing and building their circuits, as well as selecting their components. This was expected, as mechanical engineers typically have very little experience with these tasks. Even though the groups seemed to pick up on the Arduino™code quickly, considerable help was still needed from the TA. Their difficulties informed us on how we can design a tree structure and content of the platform to make the process easier, and thus reduce the required support of the TA.

The pilot study demonstrated the Arduino™as a great tool in simplifying the development of the electro-mechanical toys. It eased the burden of programming, and allowed the students to handily read in sensors and control motors via a microcontroller.

Using the TouchOSC app to interface between the iPad and the Arduino™proved to be very efficient. The groups were able to easily tailor the app to their needs. One drawback of this app is that it is limited in its functionality. The groups had shown interest in features such as video feedback, sound generation, and altering the aesthetic design of the app, all of which were not possible using TouchOSC. However, creating a custom app for each group was not feasible within the timeframe of the class. The amount of programming would be vast for a custom app. In addition, the programming language for Apple applications is Objective C, which has a steeper learning curve compared to Arduino's programming language.

PROPOSED PLATFORM

Using the information garnerned from the pilot study, we have designed a platform that simplifies the integration of electronics, while at the same time providing a substantial educational benefit. At the heart of this platform will be the Arduino™, due to the pilot study confirming that it greatly simplifies electro-mechanical development.

Circuit Modules

While the Arduino™significantly reduces the difficulty in integrating electronics, the pilot study showed that the hurdle of designing and building circuits still remains. Most mechanical engineering students have little to no experience in this area. Consequently, learning these skills can be a lengthy process. To alleviate this problem, and expedite this electronic integration process even further, we will either create or buy circuit modules. Many components, such as motors and power supplies, require circuitry to control and/or drive them. These modules will contain this needed circuitry, eliminating the need to design and build a circuit, and requiring the students to only connect the components. Screw terminals will be used, which will allow for quick and secure connections to the modules. Initially, there will be a module for each of the components listed below:

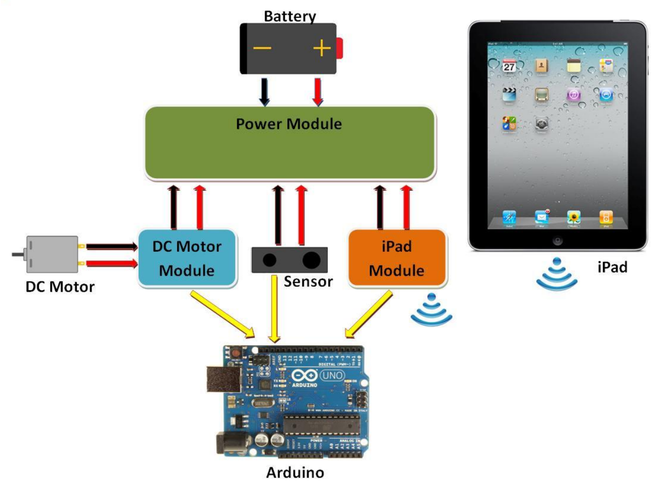

FIGURE 5. Example of a basic modular setup

- Power supply
- DC Motor (encoder optional)
- Stepper Motor
- Brushless Motor
- Solenoid
- LED
- Electrical Switch (transistor)
- iPad™

More modules will be added in the future as students require the use of additional components which require circuitry. A diagram of a basic setup using some of these modules is shown in Figure 5.

The power module is a key element of this platform, as it will take the power from a student chosen battery and break it out into the standard voltages required by the various components. In addition, the power module will have a bus line for the unregulated voltage from the battery. A more detailed diagram of this proposed power module can be seen in Figure 6. Most components and/or modules will also have to be connected to the Arduino™. However, this will still be a quick connection as stripped wires can easily be plugged into the female headers of the Arduino™. As shown with the "Sensor"in Figure 5, some components require only power to function properly, and thus will not need a dedicated module.

A significant benefit of this platform is that the modules allow for a broad selection of components, providing the students

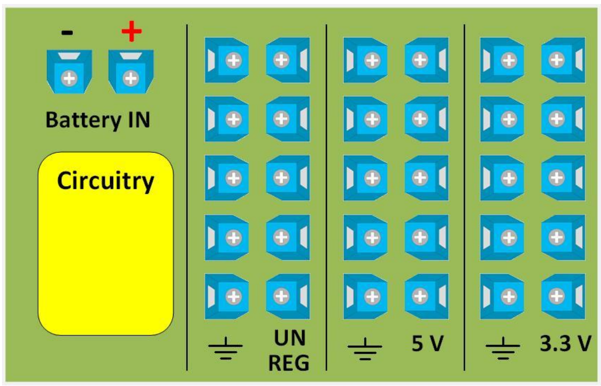

FIGURE 6. Proposed power module

a wide range of batteries, motors, sensors, and other electronic components to select from. For example, many different DC motors will be compatible with the DC motor module. This will allow for flexibility in the students designs, as they will not be constrained to a specific set of components.

Program Segments

Although the Arduino™simplifies programming a micro-controller, we found in the pilot study that it can still present a challenge for mechanical engineering students. Even with programming experience in C/C++, the semantics of Arduino's language must still be learned, as well as what libraries and code structure are needed to control or read the electronic component to be used. To accelerate this learning process, we will provide the students program segments for each electronic component they use. These segments will be well commented, explaining how the code works, and what to edit to alter functionality. If more than one electronic component utilizes the Arduino™, then the program segments must be combined. Each segment will have comments explaining how to accomplish this.

Even though there is a wide variety of each type of electronic component, the code to control or read it is the same. This allows for the program segments to satisfy our desire for flexibility in the students selection of components. In addition, we will continually expand the number of program segments, allowing for more and more types of electronic components to be incorporated.

Comparison to Lego®Mindstorms®

Lego®Mindstorms®is a platform for developing customizable and programmable robots [29], utilizing a modular architecture similar to that of our proposed platform. It consists of a set of sensors and motors which can be quickly connected to and controlled with the NXT Lego®brick micro-computer. The NXT can be programmed a variety of ways, one being a drag-and-drop programming language. The framework of the robot can be built using the included Lego®Technic building elements, which also allow for the sensors and motors to be easily mounted.

The Lego®Mindstorms®platform is a great way to introduce robotics, allowing for quick fabrication and easy programming. However, we found that the limited set of motors and sensors would put too tight of a bound on the scope of possible electro-mechanical toys. This lack of flexibility would not only limit potential functionality, but it would restrict the size and shape of the designs as well. This is the key difference from our proposed platform, which allows for a wide selection of components. In addition, going through this selection process will yield more valuable knowledge about the components in regards to availability and functionality.

While Lego®Mindstorms®provides an easy way to quickly build the framework for an electro-mechanical toy, it is not a benefit for our class since students are required to design and rapid prototype the framework of their toys.

Even though the drag-and-drop programming of Lego®Mindstorms®can expedite the implementation of simple programs for people with minimal programming experience, we feel utilizing our program segments will still allow the students to complete their toys within the timeframe of the course. In addition, the drag-and-drop programming structure is limited to simple programs [30], [31], [32]. To alleviate this problem, Lego®Mindstorms®allows for many programming languages to be used for control their NXT micro-computer, however, utilizing this option provides no simplification when compared to programming the Arduino™.

Lastly, Lego®Mindstorms®currently has no way to easily incorporate a tablet for wireless control. Since this type of control is desired for our platform, Lego®Mindstorms®is not a viable option.

Platform Content

To correctly incorporate electronics, and thus implement the Arduino™, circuit modules, and program segments, the students will follow a structured format. The following steps should be completed in order, and none should be skipped unless a student is already knowledgeable in that area:

1. **Overview of the platform:** We will present a description of the key components of the platform (Arduino™, circuit modules, and program segments) and how they will function together. This step needs to be completed before the ideation stage of design, as it will allow for a broader scope of ideas to be generated. We are thus aiming towards a greater design space, but also bounding it by making the knowledge to design electro-mechanical toys accessible.

2. **Overview of electronic components:** A list of electro-mechanical components will be provided to the students. This will inform them of the components at their disposal, and what they can do with them. The components to be included are listed below:
   - DC motors (ungeared, geared, servo, stepper, and brushless)
   - Encoders
   - Solenoids
   - Proximity and range sensors (infrared and ultrasonic)
   - Other sensors (sound, force, vibration, accelerometers, and gyros)
   - Force sensors
   - Vibration sensors
   - Piezoelectric buzzers
   - Electrical switches (transistors)
   - iPad

   It will be emphasized that these are not the only components available, and to let us know if additional functionality is desired. For the same reasons as in the previous step, this overview of components must be completed before the ideation of toy designs. This provides students with a greater affordance in creating concepts, but also letting them know TA assistance will be available.
3. **Selection of electronic components, Arduino™, and power supply:** Once the students know which type of electronic components they want to use, then they will utilize a provided selection guide for each desired component, which will explain how to choose the specific component from the variety of options and configurations. These guides will describe the key specifications for each component, and what they mean.
   Next, the students will be provided a selection guide for choosing their power supply. This will first describe how to determine the voltage and current needed, as well as key points about the different kinds of batteries, such as current output, size, weight, and other important information. In addition, selection of corded wall socket power adapters will be explained.
   Lastly, there will be a selection guide for choosing the version of Arduino™to use. This will first describe how to determine the number and type of input/output pins needed, which will be dependent on the quantity and type of electronic components selected. Since the number and type of input/output pins can vary for different Arduinos™, this information will determine which versions are compatible. Other key differences between the different versions will also be described.
   All of the guides will also list any additional parts that need to be purchased for the component to function. Lastly, a list of recommended vendors will also be included in all of the guides.
4. **Implementation tutorials** An implementation tutorial will be provided for the power supply and each type of electronic component. These will instruct students on how to incorporate said components into their toys by explaining the following:
   - Which module is needed, if any.
   - How to connect the component to the modules, power supply, and Arduino™(if applicable).
   - Any other pertinent information.

   For example, if the iPad is used, a tutorial will describe how to download and use the TouchOSC app.
5. **Make connections and test:** To make and test connections between the electronic components, modules, Arduino™, and power supply, the students will be provided with tutorials which explain the following:
   - How to select and strip wires.
   - How to solder.
   - How to test connections with a multimeter.
6. **Arduino™overview:** To successfully program the Arduino™, basic information on the semantics of the programming language and how to use the IDE will be presented to the students.
7. **Compile program segments and generate final program:** Using commented instructions in the programs segments, students will need to compile all of the segments into one program. While these compiled program segments will provide the code to control or read many electronic components, students will still need to use logic functions to determine how and/or when to do so. Once this is done, the students can debug their code until it is functioning properly using the Arduino's IDE.

CONCLUSION

The results from the pilot study informed us of the major hurdles in incorporating electronics into our course: limited time, circuit design and fabrication, and programming the Arduino™. This led to the design of the proposed platform, which includes circuit modules and program segments to solve the aforementioned problems.

These tools also allow for the use of a wide range of electronic components, differentiating our proposed platform from Lego Mindstorms, and allowing more flexibility in selection and a broader design scope. In addition, we believe that requiring the students to select their components from a wide pool will provide more of an educational benefit, in terms of garnering knowledge about the functionality and availability of said components. To aid and expedite this selection process, first the students will be provided with an overview describing the electronic components available, and what they do, allowing for the students to determine which components they would like to use. Following this, the students will be supplied tutorials for each type of component, informing them on how to select and buy the components. Other tutorials will also be provided with regards to making and testing connections.

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