Cubetrix: An instrument-like, portable, cube-shaped device

A Technical Report submitted to the Department of Electrical and Computer Engineering

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Bachelor of Science, School of Engineering

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Fall, 2019

Technical Project Team Members
Talis Basham
Connor Park
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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Signature ______________________________ Date 05/06/2020
Shirley Wang

Approved ______________________________ Date __________
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Cubetrix

Bryan Rombach, Talis Basham, Shirley Wang, Connor Park

12/16/19

Capstone Design ECE 4440 / ECE4991

Signatures

Contents

Figures Shown

Statement of Work

Talis Basham

I wrote the tone playback code and the analog to digital converter interface. The audio code included setup of the TimerA1 hardware for PWM output as well as playback for five simultaneous tone samples. I configured the analog to digital converter to read from all channels sequentially, and I provided a simple interface to query the results. Originally, the ADC was used to receive data from the force sensitive resistors; however, it was changed to read from an analog accelerometer after the FSR's were removed.

Connor Park

I was responsible for gathering the main components of the physical hardware device and integrating those parts into the final product. This included secondary roles such as soldering other parts ordered from Digi-Key and board components onto the main PCB board as well as assembling and disassembling the parts of the device throughout the development process. I also contributed to the initial design schematic of the device using tools such as SolidWorks and collaborated with other team members to modify, develop, and finalize improved supporting platforms to 3D print and incorporate them into the stability and support of the internal structure of the device. I assisted in implementing the layout of the internal structure of the LEDs and force sensors, board and power placement, and exterior painting of the main device. In the context of the whole project, I contributed to the consistent throughput and progress transparency throughout the process with accountability and communication.

Bryan Rombach

I generated the initial idea for the project, designed the circuit, designed the PCB, designed the internal structure in SolidWorks, wrote the LED API, and wrote the algorithm for displaying colors in our final demo.

The circuit was designed in MultiSim after we had determined which sensors we would use. I communicated with each team member responsible for a subsystem to establish what their requirements were, then combined them along with the central components. This design changed multiple times throughout the semester, such as when JTAG debugging was added. Each time, I also made the corresponding design changes to the PCB in UltiBoard. To fit well inside of our cube, the PCB had to be tightly laid out and constrained to a 2x2.8" rectangle. The LEDs presented a specific challenge in their strict timing requirements and our limited memory capacity. To overcome this, I ported open-source arduino code to the MSP to handle our chain of 96 LEDs. I then extended the API to our use-case, adding functions for lighting a specific face. When I wrote the algorithm for determining orientation in our demo, these were invaluable.

Shirley Wang

In the beginning, I mainly helped with ordering parts and creating the block diagram to explain our overall system. Once we began to receive parts, I was responsible for the IMU subsystem. I spent a few weeks figuring out I2C communication with the MSP430 and how to get the desired data from the BNO055. Once I made progress with that, I focused more on the physical design of the device as we received our cube case. With Autodesk Inventor for CAD design and 3D printers, I made an internal structure that would enable the force sensors to reside within the walls of the cube and be able to receive a signal when a force was applied to the walls. I also designed two different platforms that could be attached to the internal structure that would secure the battery pack as well as the PCB board. Ultimately, our final design did not incorporate any of these pieces since the force sensors failed to work, so the internal structure was unnecessary. However, a similar structure would be necessary for any future iteration of the project in order to secure the PCB. Finally, in the integration and debugging of our project I did a lot of soldering, especially the string of LEDs that were placed on each face of the cube. There was also a lot of putting the structure together in order to test the force sensors accurately and taking it apart when certain hardware needed debugging, so I aided in those processes.

Abstract

Cubetrix is an interactive device which reacts to orientation to produce a visual display of lights. The device itself is shaped like a cube with each side panel consisting of a series of LED lights that changes pattern when an internal accelerometer detects certain values. This project focuses on using motion capture and real-time input and output processing to create a functioning and interactive product. The device is completely enclosed and powered by battery and controlled by the MSP430 microcontroller.

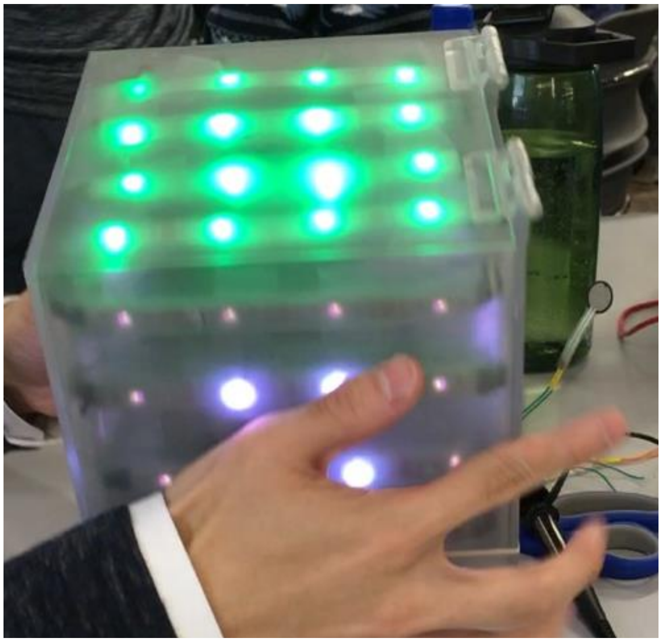

Figure 1. Cubetrix in action

Background

Many people categorize technology solely by its innovation and problem-solving ability, forgetting what makes it unique to humans: creativity. Technology can be used to create nifty toys and devices which don't necessarily fulfill a humanitarian purpose, but enhance peoples' lives in other ways. This project was chosen to use current technology to create a device consisting of various materials that serve to be entertaining and appealing to users but also challenging for the project team members. The project was focused on designing an interactive device that incorporates visual lights to create an artistic product.

There exists many forms of LED lamps that interact via motion or touch. Helios Touch lamps use multiple hexagonal LED panels that can be interchanged by the user to illuminate its surroundings by waving one's hand over the panel [1]. These panels can be installed on any flat surface. Additionally, other light up lamps such as the Cube LED Lamp and Cat Touch Lamp produce lights of various colors via bluetooth and touch respectively [2], [3]. Hasbro's interactive Simon Says toy consists of four different colored buttons that requires the user to mimic and press the light sequence of the four buttons and the sound produced from those buttons serve to assist the user in the pattern recognition [4]. This project aims to incorporate aspects of each of those design mechanisms to produce a new and creative device. These existing devices rely on touch to receive a reaction, but our project will involve orientation as its main input.

The team members share common knowledge from previous coursework in embedded systems, especially the specific lab involving the analog accelerometer. This experience will be helpful in developing the software for the MSP430 microcontroller which controls the input and output. Other previous experience in 3D printing will also aid in the design of the product. Ultimately, there are various pieces of the project that the team members are familiar with, but the integration of all these pieces and the implementation of new aspects will be challenging and a learning experience.

Constraints

Design Constraints

Throughout the design lifecycle, several modifications and additions had to be incorporated into the PCB design while maintaining the same size constraint. The final design reveals many components very packed to fit in the same dimensions given by the size constraint so that the board placement inside the device would be simple and accessible. To get to this point, there were several setbacks due to mismanagement of meeting board send-out deadlines and criterion, however, these did not affect the performance of the board itself. In addition to the board send-out, we were also constrained with parts order submission that were spread out throughout the timeline. This led to idle time while waiting for parts to come in and we were careful to be resourceful with the parts we received as well as the ones currently available.

With regard to the PCB board as a whole, we were pushing the limits of our MSP430 with our design utilizing almost all of the I/O pins on the board. Due to the strict timing requirements of the LEDs, we couldn't operate the MSP at any frequency other than 16MHz. Another time constraint was the time required for 3D models to be printed and integrated and as such printing requires considerable time, we were limited to using models that were constrained to slight offsets in measurements.

Economic and Cost Constraints

There were no significant cost constraints in acquiring parts, however, we were still mindful of gathering low cost parts for the potential of other users aiming to imitate this project. Because most of the parts we had in mind were relatively simple, there was limited tradeoff in getting quality parts because the functionality we required for each part was fundamental. Therefore, we were not constrained to choose price over quality in any parts. For example, we chose to invest in rechargeable batteries so that it would reduce waste and reduce the amount we spend on batteries long-term.

External Standards

The project will utilize WS2813 serial controllable LED's. It must conform to their serial standards to function [9]. We chose this as our visual display because it would limit the number of I/O pins connected to the MSP430. With one clock, and one data pin, we could address all LEDs for each face in order to light them up compared to if we had a separate I/O for each face. The system will be powered by standard AA (IEC R6) batteries[10][11]. This will allow for the use of disposable and rechargeable cells. We chose to use rechargeable batteries for ease of use and to limit parts orders necessary. We decided the device should be powered by battery, so that a user can fully interact with it without the limitation of being attached to a wall. Additionally, using rechargeable batteries offloads the need to deal with AC to the users choice of AA battery charger.

The design implicitly conformed to IPC-2221, the set of standards for PCB layout. These are enforced by our PCB design software, Ultiboard, and verified by FreeDFM. IPC-2221 allows manufacturers to more reliably and more quickly produce PCBs.

Tools Employed

- Code Composer: we used C code in Code Composer to program and test the software for our project. This is where our main algorithms were implemented for controlling our device with the MSP430. Understanding communication with the LEDs and timing requirements was a learning opportunity
- Solidworks: This is a solid modeling tool that was used to design preliminary 3D models for the interior supports of the device.
- Autodesk Inventor: This application was used to design a customized internal structure to our device. In order to secure all the internal devices such as the battery and our PCB, we needed a specific part that fit the dimensions of our cube.
- Ultimaker 2.0: This was the specific 3D printer model that was used to print the 3D parts mentioned above.
- Cura: This was the intermediary application between the CAD application (Inventor) and the 3D printer which set the settings for how the print would go. Some adjustments had to be made after some initial unsuccessful prints, so we had to improve our understanding of what features and settings would be ideal for the specific part we were trying to print. We especially learned about how important the supports were.
- Multisim: This was the schematic software we used to build our hardware circuitry. We improved our skills in developing circuitry for our own purposes and reading datasheet requirements in order to ensure our schematic would work properly.
- Ultiboard: This was the software used to put together our PCB board design. We conducted many iterations of redesigning to accommodate new circuit components as well as more efficiently placing all components to have a more compact board.

Ethical, Social, and Economic Concerns

Environmental Impact

Our device is battery-powered with rechargeable batteries which are slightly more environmentally friendly than non-rechargeable batteries. We may also consider that our device is contributing to light pollution and the desire to entertain with the use of bright lights. Our device is created mainly out of plastic material, which does not contribute well to the environment especially if it is disposed in any way.

Sustainability

Although the product is designed for entertainment, the efficiency of energy usage should be documented even if it is not made a major concern. Greater energy efficiency correlates to longer lasting use. The largest draws on the battery will come from the LED lights. The amount of time the batteries are able to last in operable range was not calculated, but a rotating set of batteries can always be available if they are charged. The physical sustainability of the product is also a concern if the lid always opened in order to change the batteries. The LED connections may get worn, or the physical hinge.

Health and Safety

The manufacturing process must leave the cube free of dangerous edges because it will be roughly handled. Jagged edges on the frame, side panels, or fasteners could cause minor injury within the normal use parameters. Additionally, the product will contain a Lithium-Polymer battery which can pose a fire hazard if improperly charged or damaged. Overall, all pieces should remain contained within the device, so no external parts will cause harm when handled normally. The only case of touching internal parts is when the batteries are being changed, which may pose as a safety risk so future iterations of the design should consider how to better isolate the battery pack.

Manufacturability

The mountings for interior components must be sturdy and balanced for the sake of usability. The center of mass is important to human perception of how to handle the cube, and components must not be shaken loose in the course of normal use. We may be constrained on the type of material we can use, or the ability to find parts that fit our design. For future manufacturing, we intend to 3D print our parts and recognize that such a design may be costly to mass produce if our product is on the market. If mass produced, there might be significant design adjustments made in order to speed up the process of integration. Three main components of our project would be solidified: the PCB board with all hardware circuit parts, the battery which should be accessible, and the physical device. The PCB is designed so it can be mass produced if the parts were automatically soldered on. The battery pack and internal architecture would have to be changed in order to be more accessible. The physical structure would mainly see a change in the LEDs since they were manually added to our plastic cube, but in mass production we could have the LEDs customized and packaged onto the device already.

Ethical Issues

There is a risk of triggering a seizure in a viewer with epilepsy because of the flashing patterns of light. To mitigate this, patterns could be designed to be less likely to trigger such a seizure by avoiding certain frequencies of light pulsing [8]. Additionally, a warning could be placed on packaging for the production product, as is required in some districts.

Intellectual Property Issues

It is unlikely that our device is patentable. US Patent 4801141A covers a toy which lights up and plays tones based on orientation. Our device nearly meets the descriptions of independent claims 1 and 3 which cover an enclosed system producing light and sound based on orientation. Furthermore, dependent claims 2 and 4 specify the use of LEDs as the lighting elements. However, the claim specifies the use of switches for orientation and introduces a controlling element intermediating the switches and the microcontroller.

US patent 4936780A describes a block that generates speech based on input from touch sensors. Independent claim 1 explicitly states that the audio produced is synthesized speech, so it is irrelevant to our project. Dependent claims 2 and 3 claimed the device with capacitive and pressure sensitive switches respectively. If we had set out to patent our device it is likely that we would have made similar claims for the side interfaces.

US5066011A details a flashing bouncy ball. Independent claim 1 describes a contained system that lights up in response to force, but it explicitly denotes the use of a flash tube for illumination.

Detailed Technical Description of Project

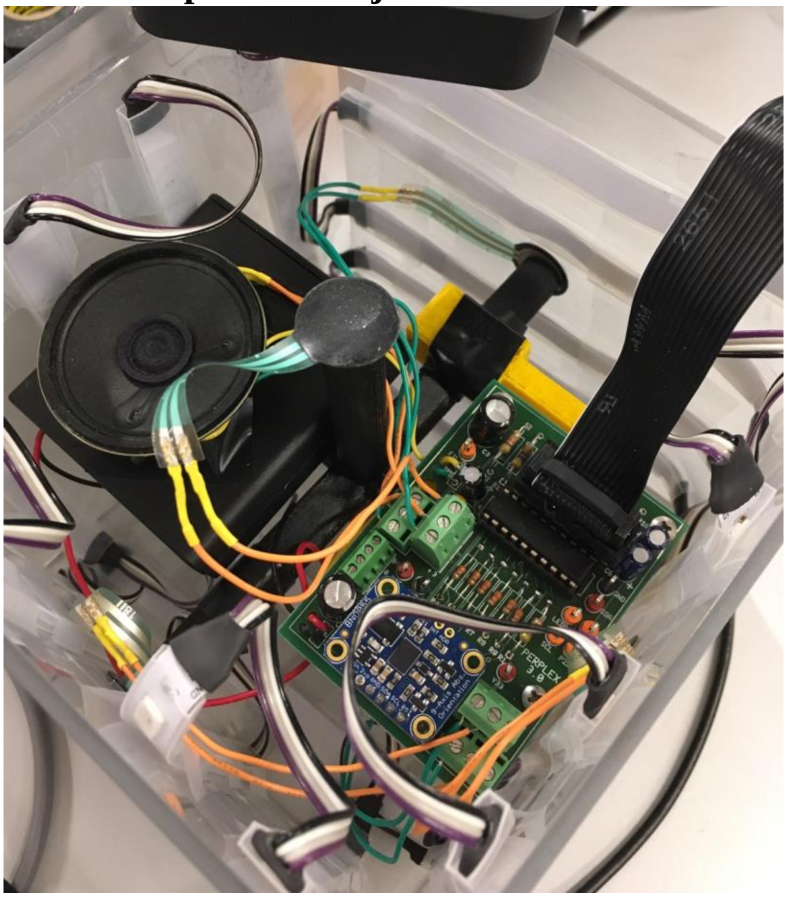

Figure 2. Cubetrix internals

Cubetrix is a device in the shape of a cube that changes light pattern based on human input. The cube is a portable size as it is meant to be touched and moved and rotated. Similar to a die, each face of the cube will have a different meaning— a different colored light illuminating it when that face is on top. The response time of the cube must be fast, so the user can meaningfully interact with it.

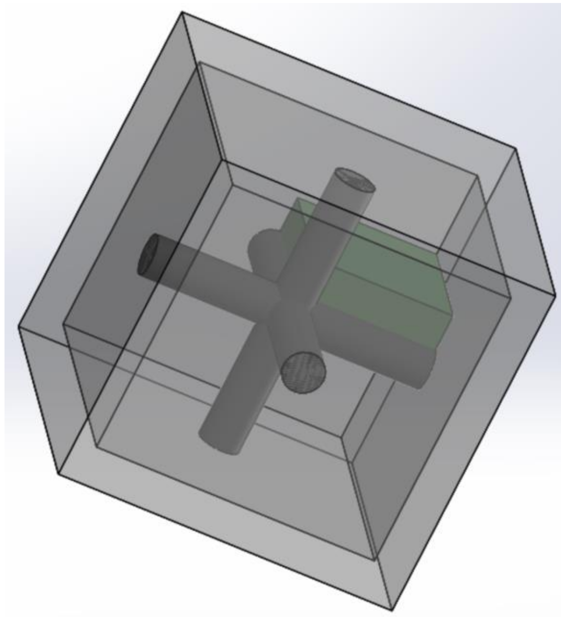

Figure 3. Structural Overview

Figure 3 shows the high level physical design. The outer casing of the cube is a 6”x6”x6” clear cube of ¼” acrylic with one face able to rotate out on an attached hinge [15]. Inside, a six-point frame with radius ¾” provides structural integrity and resistance against pressure applied to the sides. The PCB, MSP430 Launchpad, and battery pack are attached to the frame inside the cube, and the rotating face is held in place with a rubber band.

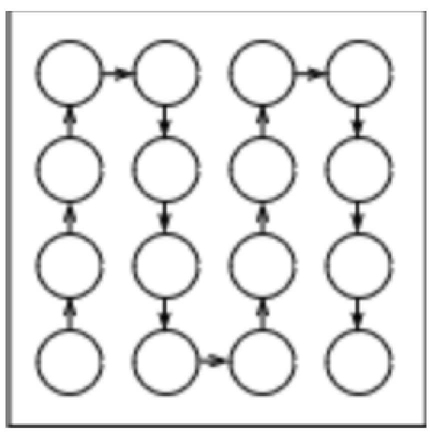

Figure 4. LED configuration on each side

Inside each face of the transparent cube, the LED strip is lined in a fashion resembled by the figure above. This creates a 4x4 array of LEDs and enables different patterns to be displayed on one side of the cube. It also covers the surface of the cube perfectly so that no part of a side looks empty when the LEDs are lit. Each side was also spray painted with a semi-translucent paint in order to create a more dispersed light effect and reduce the visibility of the internal parts in the cube.

This device is controlled by an MSP430G2553 [5], which processes the inputs and controls the outputs. An analog accelerometer, ADXL325 [14], is used to determine the orientation of the cube. Each side is equipped with an array of 4x4 WS2813 [9] LEDs which are each individually addressable through a GPIO pin on the MSP. The LEDs on each face are connected serially according to the pattern in Figure 4, which allows the same addressing for center-four and outer-twelve LEDs to be used regardless of orientation. The faces are similarly connected in a sequence: Top, Back, Right, Bottom, Left, Front as seen with the hinges on the opposite side of the top face from the viewer's perspective. The accelerometer data is read into an ADC on the MSP430 through three analog inputs, one each for X, Y and Z acceleration. Through testing, the set of accelerations which correspond to each side facing up was determined. Using these hard-coded values and the accelerometer readings, the top side is determined and a corresponding color scheme is sent to the LEDs.

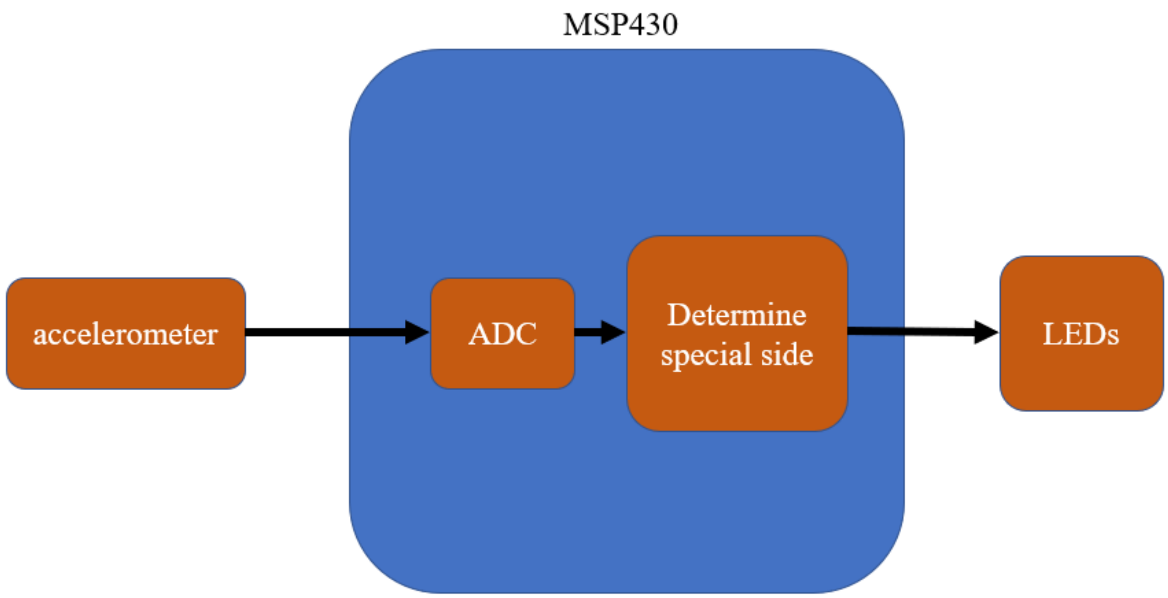

Figure 5. Block Diagram of our system

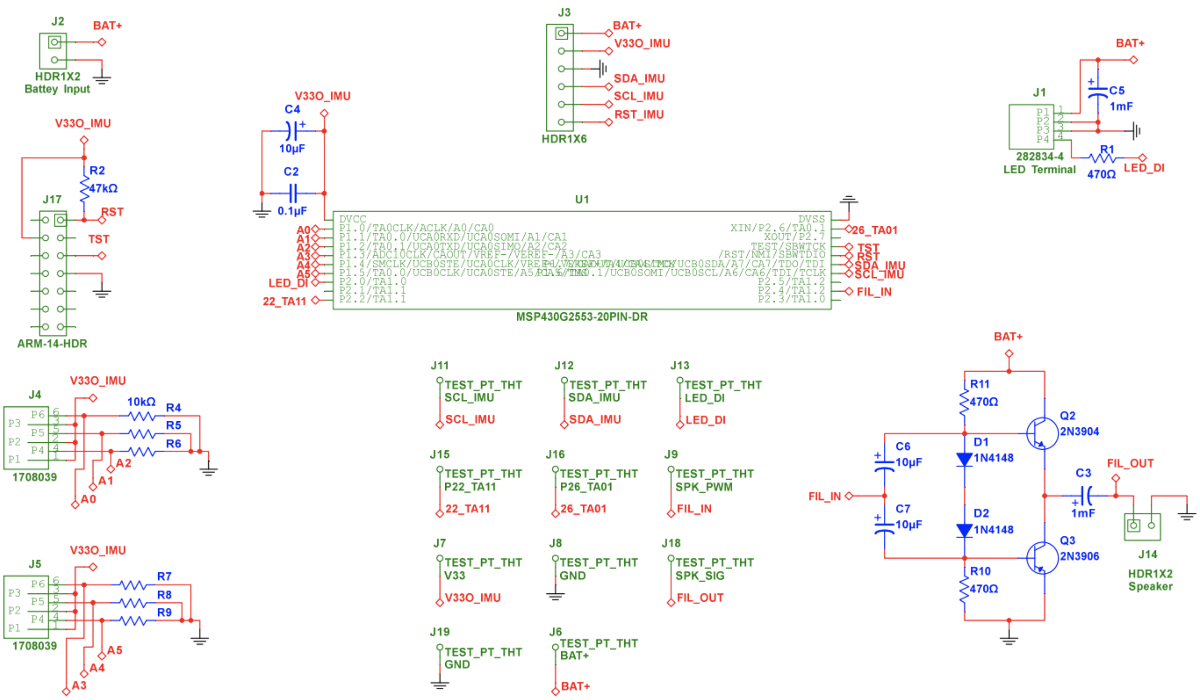

Figure 6. Multisim schematic

There are 4 essential subcircuits in this design: the IMU connection, the ADC inputs, the LED connection, and the speaker circuit.

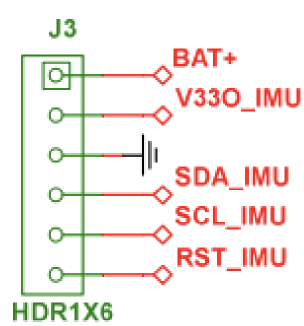

Figure 6.1. IMU connection

The IMU used was a BNO055 on an Adafruit breakout board [7]. We chose to use a breakout board for compactness; because only 6 pin connections were needed, the breakout floated over a portion of the PCB and allowed interconnects beneath it. Additionally, the filtering and power circuitry was already on the board with SMD components. This allowed the rest of the design to utilize the breakout board’s regulator to have a consistent 3.3V supply from our batteries. The MSP communicates with the IMU using I2C.

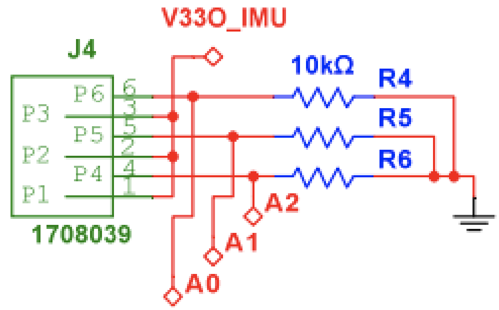

Figure 6.2. ADC input

In our target design, 3 force sensitive resistors [6] were connected across vertical pairs of pins in this double high 2x3 screw terminal. They formed a voltage divider on V33 with the 10k resistors. The middle of the divider was read to the ADC to detect force. In our revised design, the resistor were removed and the screw terminals were used to connect the voltage based accelerometer.

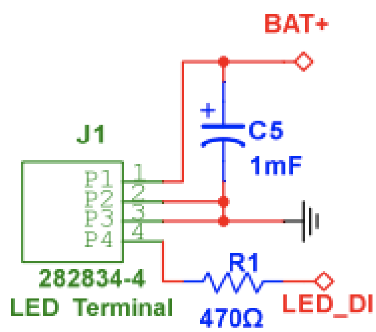

Figure 6.3. LED connection

The LEDs required a data input connected to a GPIO pin (LED_DI), an input voltage 3.7-5.3V (BAT+), and two ground inputs. The bypass capacitor and series resistor are voltage and current protection respectively.

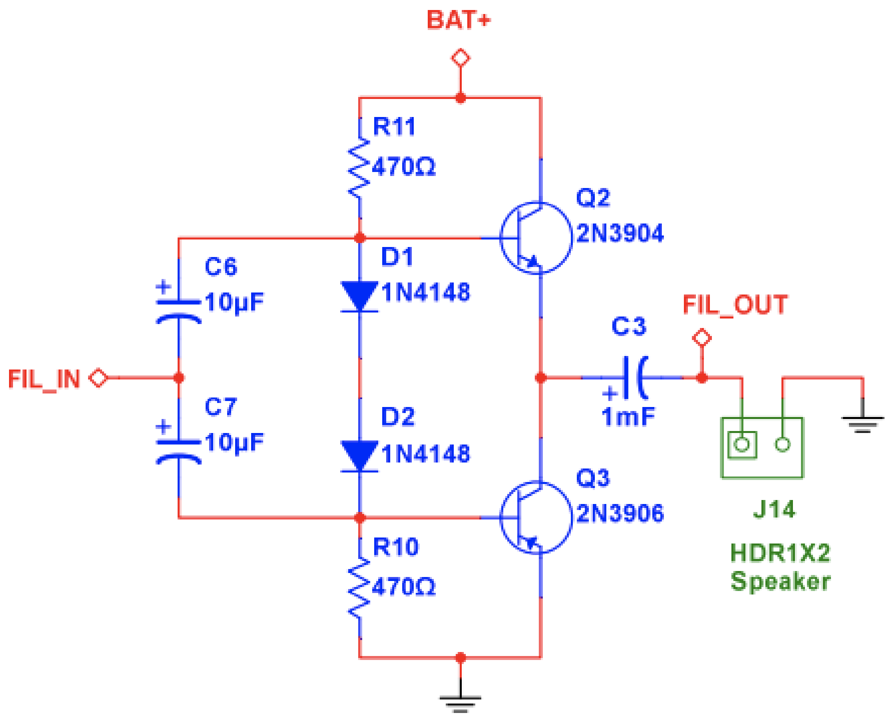

Figure 6.4. Speaker circuit

The input to this sub-circuit, FIL_IN, is the PWM signal generated on a GPIO pin of the MSP. That signal simulates a variety of periodic signals, but only in the positive range. of 0-3.3V. For a traditional speaker to be effective, its input must be centered at zero and vary above and below that. This circuit shifts the effective output of the PWM circuit down while simultaneously amplifying and driving it.

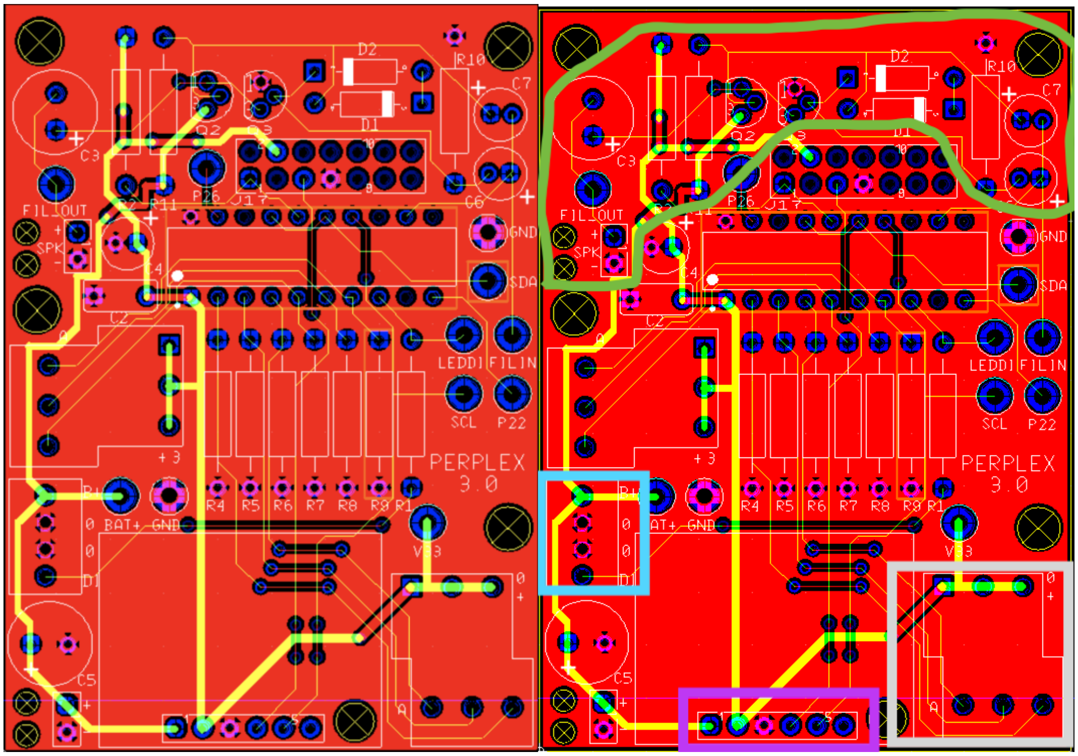

Figure 7. PCB Layout
IMU:Purple, ADC:Gray, LED:Blue, Speaker:Green

The primary goal of the board layout was to cluster like components. This was especially necessary for the speaker circuit, which had a number of larger components and connections between them. A secondary goal was to make the screw terminals for the ADCs and LEDs easily accessible. Instead the two ADC terminals being placed together, they were placed on different edges of the board to prevent a rats nest of incoming wires.

Throughout the process of this project, many initial ideas and design requirements were not met and the final product turned out significantly different from our proposed project. Many of the major problems arose during integration shortly before demo and thus, drastic measures had to be taken in order to accommodate them. If these issues were found earlier, the outcomes might have been different. Our initial design aimed to incorporate two inputs and two outputs, which changed to one input and one output. We designed our system to utilize nearly every I/O pin on the MSP430 with force sensors, IMU breakout board, speaker output and LEDs. We intended our product to be unique in having both touch and orientation combined to create a musical and visual output. Not many past products involve such extensive interaction. We also hoped that the project would be scalable and including many subsystems would enable more flexibility for future design. This is still true of our product, but with less subsystems to work with. There were many problems throughout the different stages of our project that culminated to changing our final project requirements.

In the beginning stages of the project, we spent a lot of time designing and envisioning the project. Some setbacks we faced were mainly due to parts order mishaps or PCB board print mistakes. This delayed our timeline and limited the ability for us to begin testing the different subsystems of our device. The PCB board prints proved to be a significant hindrance as well because some send outs returned with faulty boards. For example, the first board we sent out returned with the different layers mixed up, so it was rendered useless. We also endured many schematic changes like adding the spy-bi-wire and updating the speaker circuit. Each of these changes eliminated the ability for us to truly test our PCB until the integration phase.

The integration of all our subsystems was the part that brought the most problems as expected. One issue was that we had to learn I2C protocol with the MSP430 in order to get data from the IMU (BNO055). Once we figured out how to do that on its own, it didn't seem to work when integrated with the code, especially with all the interrupts from other code as well. Going back and forth from integrated and isolated testing, it seemed to become inconsistent so in the end we decided to go with an analog accelerometer. Another issue that took away a lot of time was when we needed to test the force sensors, they needed to be assembled in order to get an accurate reading and set the thresholds from there. The assembly process of the internal structure was tedious and extensive as it required precision of placement as well as individually placing six force sensors into the screw terminals. Whenever a hardware issue was found - loose solder or changing resistor values on the PCB - the whole assembly had to be taken apart. With the force sensors, we struggled to find the balance between securing the force sensors to the wall with tap but not having too much tension to max out the ADC. When we found that the force sensors were maxing out, we tried to calculate a different resistor value to place in the voltage divider with the force sensitive resistor (FSR). This desoldering process was long and potentially detrimental to the board because after that, we began to have issues with the JTAG debugger attached to the spy-bi-wire. Speaking of that, some manual adjustments had to be made with our header because some of the pins were connected incorrectly on the PCB. Having issues with the debugger significantly set us back from being able to work on the software efficiently because it limited our ability to flash the MSP430. Ultimately, this was the reason we had to change to using the MSP430 launchpad and utilizing only certain parts of our PCB circuit. If given more iterations of printing the PCB board, we might have been able to catch our mistake with the spy-bi-wire or use a backup board in case we burned out some part of the board while desoldering.

Other issues that were found throughout the process, somewhat unrelated to integration, include an issue with too much voltage in the battery. We anticipated our fully-charged batteries to be 1.2V each, so 4 batteries in series would produce 4.8V which was in range for the LEDs. However, we discovered that when fully charged, the batteries could hold up to 1.4V which would result in an overall voltage source of 5.6V which was beyond range for the LEDs. Because of this, we adjusted our design to include 3 batteries in series instead of 4 so that when fully charged, we would have a power voltage of 4.2V which is acceptable for the LEDs and other subsystem requirements. We also encountered a short circuit problem in the connections that came with the LED strip. This short circuit caused our battery pack to begin smoking, damaged several LEDs throughout the strips, and may have damaged other PCB components. It was certainly a big setback considering it was not a result of our own work. Much time was spent soldering sets of 4 LED strips together to make a usable strip for our desired pattern on each wall of the cube.

Finally, we continued to have problems with the force sensors, so testing with an ohmmeter revealed that they were no longer functional which means we might have placed too much tension on them for too long. Here, we learned that ordering more FSRs would have been a better idea. From this point we were forced to remove this subsystem from our project and move forward with other subsystems like the IMU. However, as mentioned above we were getting inconsistent functionality with I2C protocol with the BNO055, so we transitioned to an analog accelerometer header board to the launchpad because we no longer needed the ADC pins for the force sensors, and we could use the header board because we chose to use the launchpad. With the LEDs we faced initial difficulties, but were glad to have the subsystem consistently working in the end. We ran into timing conflicts between the LED displays and the audio playback that could not be resolved in the remaining time. Although both worked independently, the audio was chosen to be cut because we decided it was the more important output. Our overall goal of creating a cube that a user can interact with and see an understandable output was still met. We also were able to create an enclosed device with a simple outer appearance.

Project Timeline

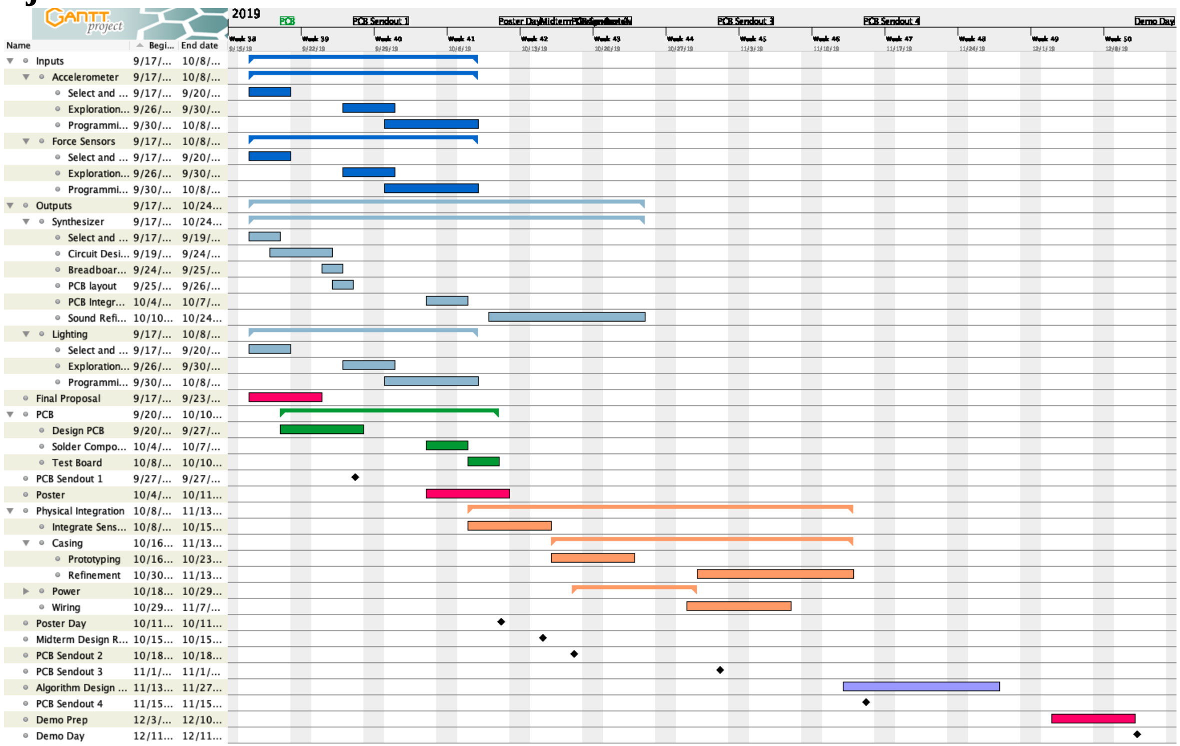

Figure 8. MDR Gantt

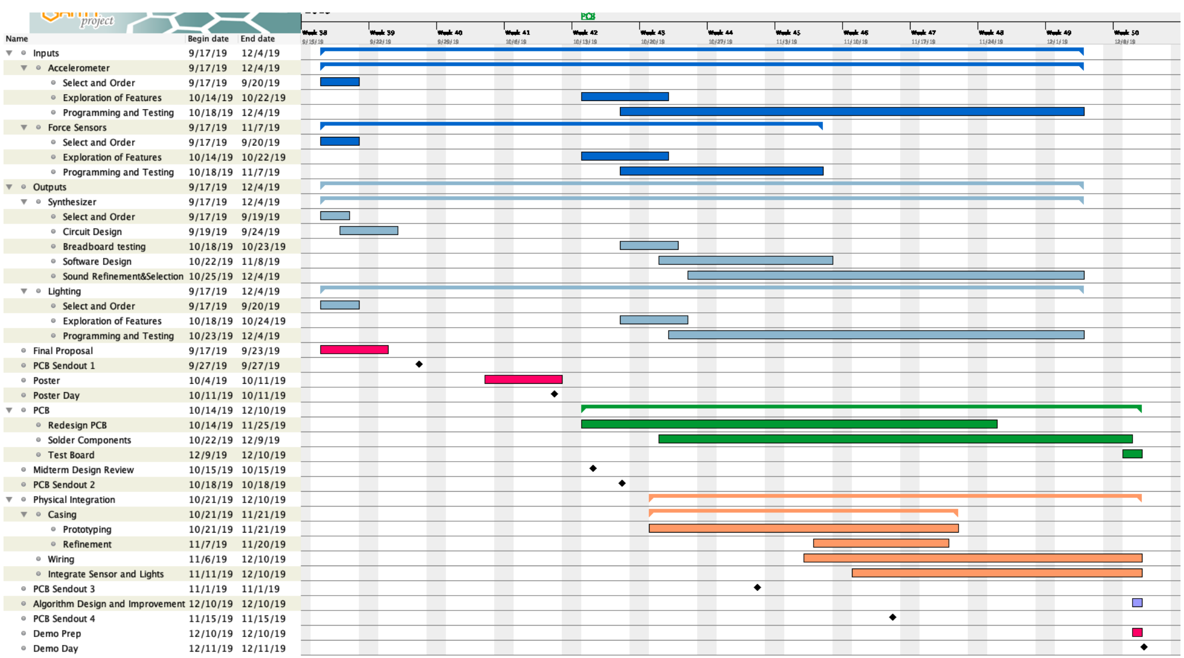

Figure 9. Retrospective Gantt

The serial tasks of our project were mainly overarching phases like the design phase, the ordering phase, the subsystem phase, and the integration phase. In the design phase, we mainly worked together to make decisions on what the design should be like and work in parallel on separate parts like block diagrams, test plans, and circuit design. The ordering phase is where we began to send in parts orders and finished PCB designs. We continued to make design decisions while working on the PCB design as a main task. The subsystem phase came after we received our parts and worked in parallel with redesigning the PCB and discovering new circuitry that needed to be fixed. In the subsystem phase there were more parallel tasks being done, where each member took on a subsystem to test. For example, Talis was able to verify the FSR circuit and read values from the ADC. He also worked with the speaker to create software-defined signals to play tones. Bryan worked on the LED subsystem, Shirley worked on I2C protocol with the BNO055, and Connor worked on physical design layouts and soldering the PCB for testing. After each subsystem was successfully tested, we worked on integration, especially in the code. Bryan and Talis worked more on the software integration while Shirley and Connor worked more on the hardware side. We printed 3D parts to secure the internal structures and more accurately test the FSRs in our system rather than just a proof of functionality. During the integration phase, there are not many parallel tasks since there is one device and one debugger. Some parallel tasks included resoldering parts that were insecure while other team members brushed up the code.

Test Plan

Our proposed test plan mainly identified five different subsystems of the whole system: power source, FSR, BNO055, speaker, and IMU. Each subsystem was tested separately by first writing software to get data or communicate with the input / output with the desired circuit. Then, each subsystem was slowly integrated into each other. First, the FSR was tested for functionality by attaching it to an ohmmeter and measuring the resistance when being pressed. Then we wrote code to receive the analog value of the FSR when attached to a voltage divider circuit. We tested the speaker by writing a software-generated tone and playing it. We saw a limitation in the maximum volume of the speaker output, so we constructed a more complex circuit to improve the quality. We integrated both of these subsystems together as a preliminary design by taking in the ADC value and producing a subsequent signal with varying amplitude to the speaker. The BNO055 was tested for functionality with an Arduino. Then, we explored I2C communication and tested it through the debugger in Code Composer and the Launchpad to verify we could get the desired orientation values. Finally, the LED subsystem was first tested by writing code to light up a small strip of LEDs. Then limitations were further tested by trying to light up the whole strip with specific colors. The oscilloscope was used extensively to verify the data being written to the LEDs. With the power source, our main testing option was a multimeter to verify the voltage left in the battery and also the connections in the battery pack to the PCB.

The PCB was also a major device that needed testing. We mainly conducted connectivity tests with the multimeter to verify all our expected connections existed. After soldering all our parts, we had test points designed into our board in order to conduct further tests with each subsystem. For example, when integrating the LED subsystem we used the LED data test point to verify that the data was actually being sent to the hardware. Through this testing, we identified a possible disconnection within the screw terminal that held the LED connections. More integration testing with the software was done through the debugger on Code Composer with the JTAG connection to our PCB. When this stopped working, we resorted to using the MSP430 Launchpad. Many of the problems we encountered were described in the previous section, but we arrived at those decisions because of testing results. The main tools for testing were the oscilloscope for the data signals and voltage measurement, we used virtual bench for voltage measurement and ohmmeter, we used a multimeter for voltage measurement and connectivity, and the code composer debugger to verify values in the MSP430.

Final Results

Our final device is a cube that is fully enclosed and battery-powered. It is always lit by LEDs covered on all sides of the cube. Whatever side is "up" or opposite to the direction of gravity shows a color other than white. Each side has a different designated color: red, green, blue, teal, purple, or yellow. The rest of the sides will show white. The reaction time shows no significant lag in a way that is obvious to the human eye. Our final device was successful in producing an interactive device that provides some sort of output based on the human input. It successfully utilized LEDs as a visual output, and orientation as an input. We also met the requirements of an enclosed device that is battery powered.

Costs

See the appendix for a full table of costs for this project. The parts that cost the most were the acrylic box which encompassed the whole device, the LEDs and the BNO055. For our final device, we did not use the BNO055 but the analog accelerometer header instead, but we included the BNO055 cost since it is most likely higher than a typical accelerometer. In the case of mass production, the PCB would probably include the analog accelerometer directly connected to the MSP instead of the header to the launchpad in our design. Other design considerations would be to customize the acrylic box to include LEDs manufactured onto a box that is translucent so that the unnecessary amount of tape we used would not be relevant. Then, the main connection would just be the LEDs to the PCB. All of the electronic components are mostly taken at unit price (if we were to order one), but the price of each of these significantly drops if they are ordered in mass, so that would reduce the cost of manufacturing several of these devices. The plastic material for the internal structure is relatively cheap and easy to produce, so there is no cost concern there as well.

Future Work

This project is very versatile and simple in terms of understanding the architecture of inputs and outputs, but difficult in terms of integration and functionality. For students who wish to expand upon our project, some advice would be to ensure a fully functional project much earlier on and continue to scale that device to a more full potential. We faced many pitfalls and difficulties in the last stage of integration and most definitely should have allocated more time for it. The issues we faced were unforeseen and also very consequential. First consideration would be to order more parts and keep track of where they are. We had bad communication and organization of our parts, so when we thought we had ordered more force sensors we actually didn't and ended up having to remove the subsystem completely when they lost functionality. Second would be to consider the Spy-bi-wire from the beginning. We still are not sure what caused the issues with the connection in the end, but the process would have been smoother if we had known and considered the spy-bi-wire as a necessary component to the board much earlier on. Furthermore, designing and testing the PCB is a central part to the project, so testing earlier iterations of the board would have been helpful so that limited soldering and desoldering would happen on our only functional board. Ultimately, it comes down to having more time to test and integrate the system. We did not give priority to the physical internal structure until later on, which was necessary to test the force sensors accurately and we took that subsystem for granted because we assumed it would work. We did not foresee that its basic functionality could be ruined from physical pressure. If a single piece of advice was given to a future team looking to design a similar project, it would be to allocate more time for integration and debugging.

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Appendix

Part	Manufacturer	MFG Part Number	Vendor	Vendor Part Number	Unit Price	Quantity	Price
MSP placeholder	Adam Tech	ICS-320-T	Digikey	2057-ICS-320-T-ND	$0.23	4	$0.92
LED screw terminal	TE Connectivity AMP Connectors	282834-4	Digikey	98335-ND	$2.68	2	$5.36
6 pin female header	Sullins Connector Solutions	PPTC061LFBN-RC	Digikey	S7004-ND	$0.52	2	$1.04
force sensor screw terminal	Phoenix Contact	1708039	Digikey	277-1357-ND	$5.66	4	$22.64
black test point	Keystone Electronics	5011	Digikey	36-5011-ND	$0.35	5	$1.75
orange test point	Keystone Electronics	5010	Digikey	36-5010-ND	$0.35	5	$1.75
red test point	Keystone Electronics	5013	Digikey	36-5013-ND	$0.35	5	$1.75
male pins	3M	961136-6404-AR	Digikey	3M9457-36-ND	$2.27	1	$2.27
1000 uF capacitor	Nichicon	UHE1E102MHD6	Digikey	493-1558-ND	$0.84	5	$4.20
10uF capacitor	KEMET	ESK106M035AC3AA	Digikey	399-6598-ND	$0.17	6	$1.02

1000uF capacitor	Panasonic Electronic Components	ECA-0JHG102	Digikey	P5509-ND	$0.10	4	$0.40
JTAG interconnection 2x7	3M	2514-6002UB	Digikey	MHB14K-ND	$2.76	3	$8.28
batteries	FDK America, Inc., a member of Fujitsu Group	HR-3U-2500	Digikey	SY134-ND	$5.90	6	$35.40
battery charger	Energizer Battery Company	CHPROWB4	Digikey	N734-ND	$19.92	1	$19.92
battery pack	MPD (Memory Protection Devices)	BH3AAW	Digikey	BH3AA-W-ND	$4.25	1	$4.25
BNO055	Adafruit Industries LLC	2472	Digikey	1528-1426-ND	$34.95	1	$34.95
FSR	Interlink Electronics	30-81794	Digikey	1027-1001-ND	$8.64	8	$69.12
backup speaker	CUI Devices	CVS-1508	Digikey	Y134-ND	$2.91	1	$2.91
MSP430 dev kit	Texas Instruments	MSP-EXP430G2ET	Digikey	296-50264-ND	$10.37	1	$10.37
LED strip	ALITOVE	AL-WS2813-150WH-WP	Amazon	B07B62KZ1J	$20.99	1	$20.99
Acrylic 5-Sided Box w/ Hinged Lid					$42.64	1	$42.64

Krylon Sea Glass Spray Paint	Krylon		Amazon		$10.47	1	$10.47
					total	**cost**	**$302.40**