Gesture Based Light Design System

Final Report for ECE 445, Senior Design, Spring 2018

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Abstract

Performing artists are limited in their ability to control a venue's lighting in real-time. They rely on light designers to operate complicated and expensive control equipment and are almost never directly involved in the real-time controls. Our gesture based light control system introduces a new medium through which artists can add a new visual component to their performances. With just the movement of their body, a performing artist can directly control industry standard moving head lights in real-time.

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1. Introduction

In today's modern age, many entertainment venues have some variation of a sophisticated lighting system installed to provide great lighting for any kind of theatrical or musical act. Unfortunately, the control systems behind these lights can be very expensive, difficult to learn, and difficult to transport. Mastering the equipment has a steep learning curve and is time consuming in a field where time is of the essence. Most notably, there are few lighting systems that give the on-stage performers the option to be involved in the light show directly and in real-time.

We set out to streamline the process of controlling moving head lights, reduce the burden of travel, and offer a new kind of production to all types of performers. In preparation for our project, we developed three high-level functions that our project must accomplish:

- The user must be able to walk freely with respect to the Control Unit within a distance of 30 feet and, be able to control the Stage Lights with gesture movements.

- The user must be able to select or deselect any single or group of stage lights which they wish to control.

- The system must be able distinguish whether the user is gesturing to control the lights or, if the user is gesturing arbitrarily.

This report will review how we successfully designed, built, and tested our system. We will also share the lessons learned, our conclusions, and thoughts on future revisions.

2. Design

Our system is composed of two control units, the Glove Unit and the Main Control Unit, and individual light units. The Glove Unit is responsible for capturing the physical information on how the user wishes to interact with the system. It then communicates this information to the Main Control Unit. The Main Control Unit is responsible for receiving the data from the Glove Unit and for processing said data. The Main Control Unit processes the Glove Unit's data by converting it into actionable data that light units can understand. The two control units are necessary to minimize bulk on the Glove Unit while also maintaining enough computing power to convert the two data types.

The overall layout of our system on a stage is shown in Figure 1. The Glove Unit is mobile and wirelessly communicates its data to the Main Control Unit. The position of the Main Control Unit allows the Glove Unit to use a small microprocessor and retain full mobility up to thirty feet from the Main Control Unit.

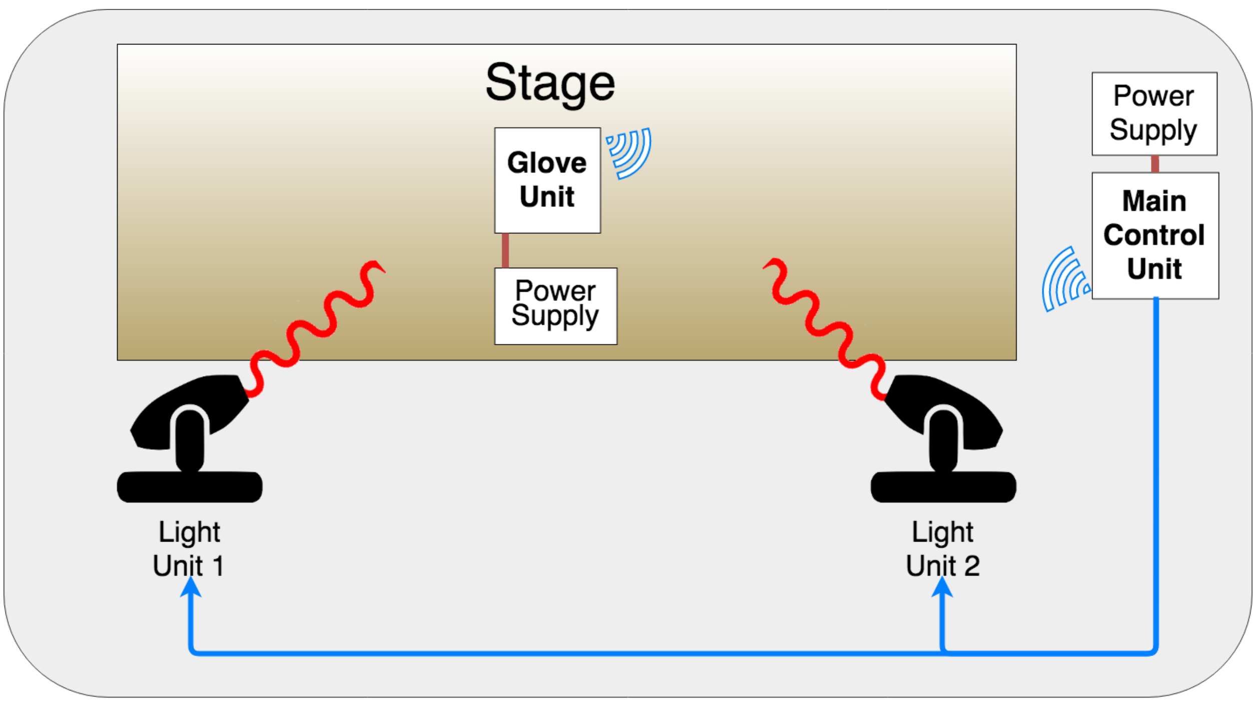

Figure 1: Physical layout of light sources with respect to the stage.
Note: It is important to note that the Glove Unit is free moving while all other units are stationary.

2.1 Block Diagram

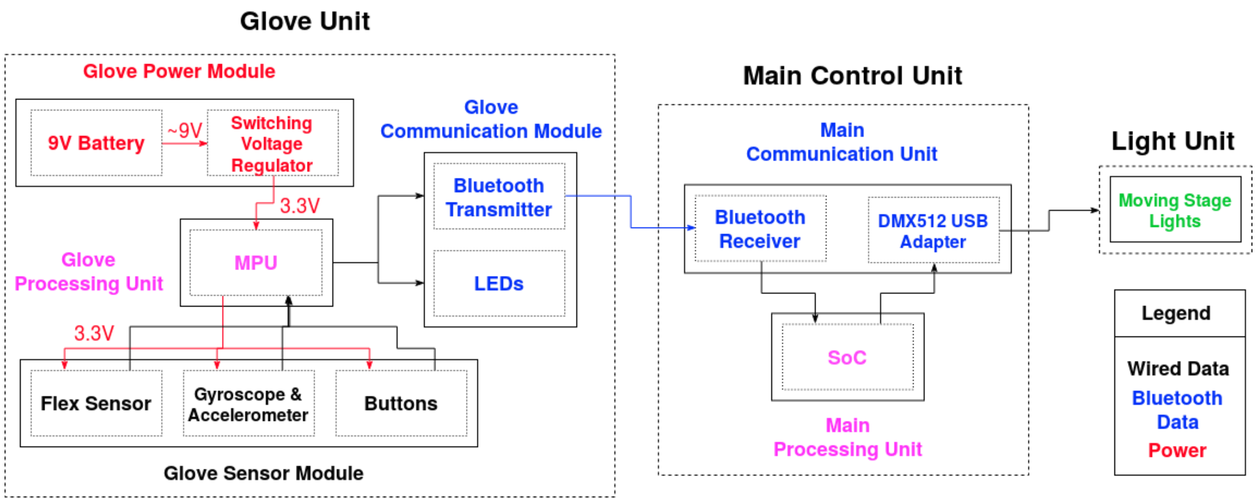

Figure 2: Gesture based light design system block diagram.

The gesture based light design system consists of three total units: the Glove Unit, the Main Control Unit, and the Light Unit. The Glove Unit consists of several modules which work together to inform the Main Control Unit of the user's interactions with the glove. The glove's power module consists of a 9 volt battery which feeds current to the circuit through a switching voltage regulator. The switching voltage regulator brings the voltage down to the 3.3 volts required by the glove components. The glove's sensor module consists of a flex sensor, a gyroscope and accelerometer, and buttons which measure how the user is interacting the glove. The microprocessing unit takes this information and routes it to the glove communication module, which contains LEDs to inform the users of the glove's state and a bluetooth transmitter to send data to the Main Control Unit. The Main Control Unit's Bluetooth receiver picks up the data sent from the Glove Unit and routes it to the main processing unit. The main processing unit uses the data in order to understand how the user wishes to control the moving head lights, and delivers commands to the moving head lights through a DMX512 USB adapter. Finally, the moving head lights take the data coming from the DMX512 USB adapter and follow it in order to bring the user's artistic view to light. The Main Control Unit and Light Unit are both powered through the wall outlet.

2.2 Glove Unit

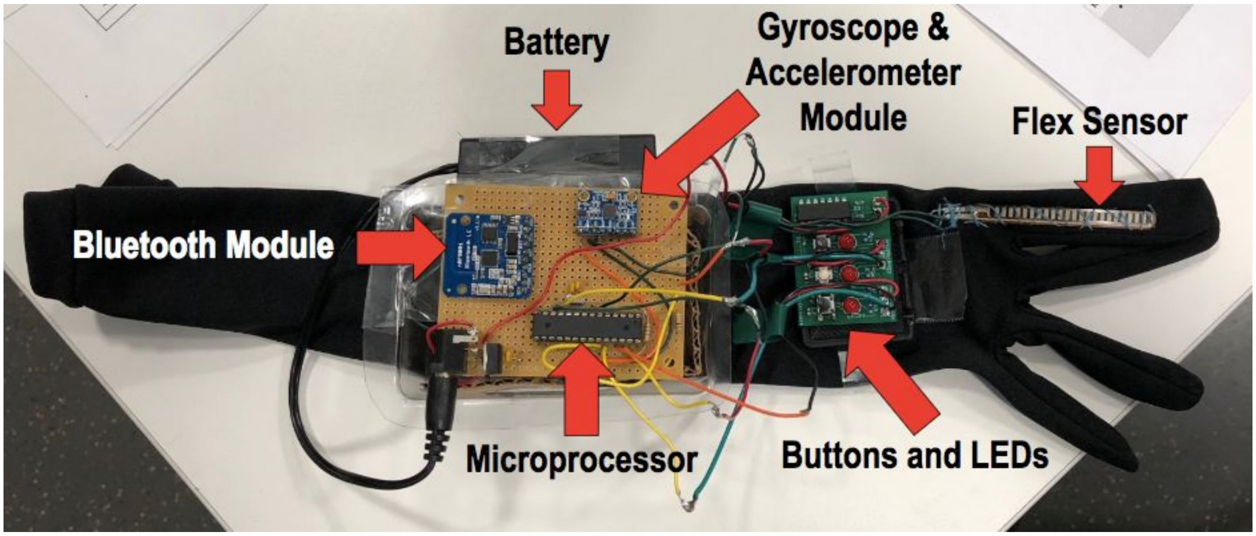

Figure 3: Picture of the Glove Unit.

2.2.1) 9 Volt Battery & Voltage Regulator

The 9 volt battery supplies the power required for the glove circuit. We chose to use a conventional 9 volt alkaline battery to power the circuit due to its portability and simplicity of replacement. This way, the performer does not have to worry about the device not functioning if they forget to charge the battery. An interesting aspect of this battery is that the supply voltage ranges from 9.5 volts to 5 volts over the battery's lifetime [1].

The glove components we wish to work with take in a supply voltage of 3.3 volts. We used the TPS62056DGSR switching voltage regulator in order to convert the supply voltage to the 3.3 volts required by the components. The TPS62056DGSR accepts the range of the voltages supplied by the 9 volt battery and converts them 3.3 volts at an efficiency of 85 percent [2].

$$Battery\ Life = \frac{Capacity(mAh)}{Load\ Current(mA)} * Efficiency = \frac{565\ mAh}{31\ mA} * .85 = 15.49\ hours$$

Equation 1: Expected battery life.

After determining our glove draws 31 mA of current, we were able to determine our battery life to be 15.49 hours using the above equation. This far exceeds our initial estimate of just 3 hours. The reason for this large discrepancy in estimation is because we used a low-power Bluetooth chip in our final design, allowing for a far smaller current draw.

2.2.2) Microprocessor

The microprocessor processes the information received from the sensors and sends its to the Bluetooth transmitter to be delivered to the main control unit. We chose the ATmega328 microcontroller chip because of its high performance, low power consumption, and large community support. Furthermore, the 23 input and output pins allow us to interface with each of the glove components [3]. The connections to the microprocessor's inputs and outputs are shown in Figure 4.

Unfortunately, the microprocessor reached limitations with the on-board memory. By implementing the most basic functionality, we consumed 76 percent of the chip's SRAM. Due to this, the Arduino compiler informed us with a warning that low memory was available and that stability problems may occur. The microprocessor was not able to handle any additional features that we attempted to program on it.

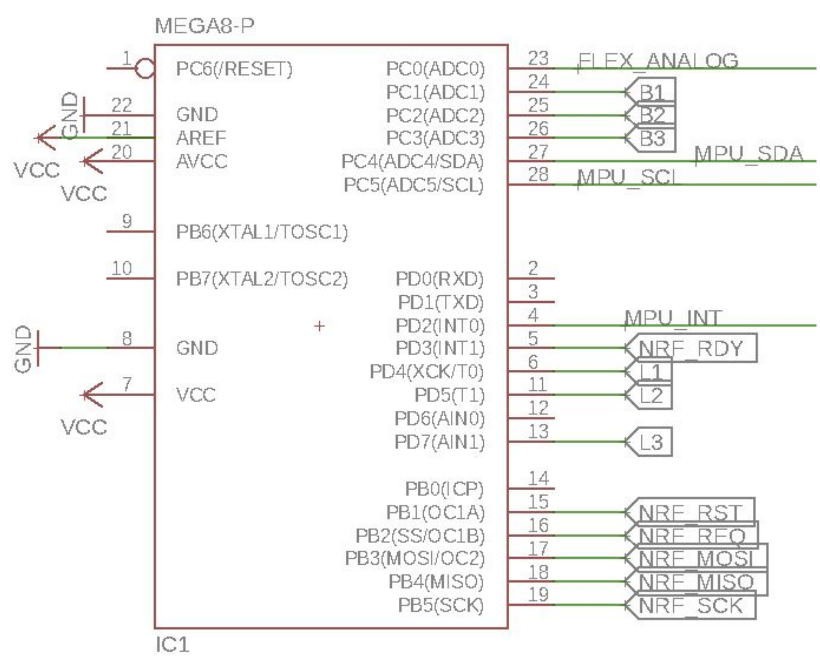

Figure 4: Schematic for the Microcontroller.

2.2.3) Gyroscope and Accelerometer

The gyroscope and accelerometer outputs raw data containing information about the sensor's orientation and acceleration. This information is used in order to determine what gesture a user is performing. The InvenSense MPU-6050 is our accelerometer and gyroscope of choice. The MPU-6050 outputs raw data on on a scale of -180 to 180, while the DMX512 moving stage lights accept a value on the scale of 0 to 255 [4][5]. Due to this, the main processing unit must execute a linear transformation to remap the values. The linear transformation we used is shown in Equation 2. Lastly, gyroscopes and accelerometers are devices prone to error and drift. To combat error and drift, we implemented a calibration feature that allows the user to recalibrate the MPU-6050 at any time.

$$x_{output} = \frac{255}{360} * (180 - x_{input})$$

Equation 2: Equation used to remap raw gyroscope values to values accepted by the lights.

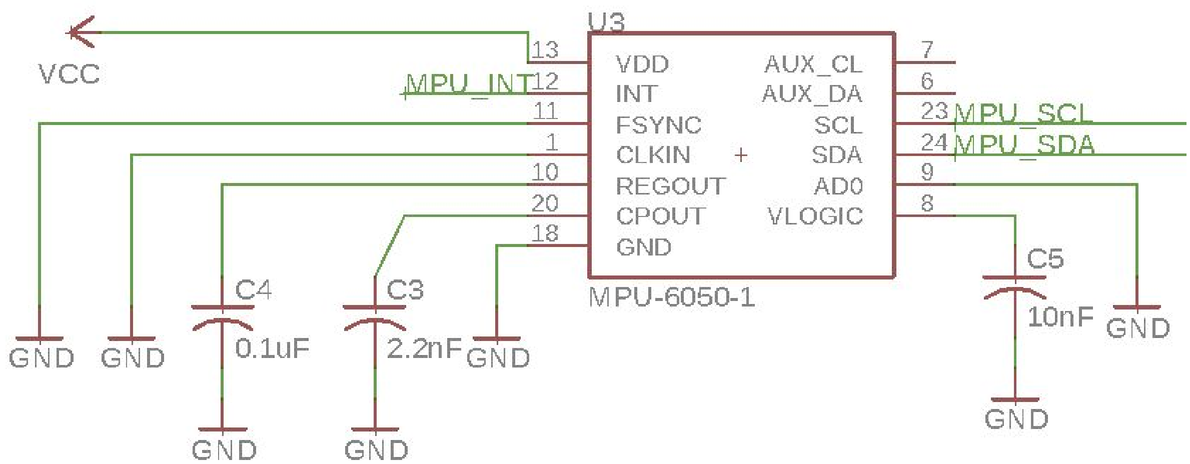

Figure 5: Schematic for the MPU-6050.

2.2.4) Bluetooth Transmitter

To wirelessly communicate to the Main Control Unit, we chose to use the Bluetooth communication protocol. We did so because Bluetooth is fast enough for our data needs and is low-power enough where we could use a standard 9V alkaline battery. The Glove Unit's microprocessor controls the Bluetooth Transmitter. It does so by first reading the data from the buttons, flex sensor, and the gyroscope and then communicates to the Bluetooth Transmitter what data to send to the Main Control Unit. We chose the nRF8001 Bluetooth 4.0 chip due to its very low power consumption with peak currents as low as 12.5 mA [6].

2.2.5) Flex Sensor

The flex sensor is used to distinguish if the user is flexing their index finger or not. The resistance of the flex sensor changes as a function of bend angle. Thus, we can obtain a voltage that varies as a function of the bend angle by creating a voltage divider circuit between the flex sensor and a resistor. The varying voltage level is analyzed by the glove's microprocessing unit in order to determine if the user's index finger is being flexed. The ADA1070 flex sensor was chosen for the task.

2.2.6) Buttons & LEDs

Our glove features three buttons and three LEDs. Two of the three buttons are used to select which of the two lights the user wishes to control. The two corresponding LEDs shine when a light is selected for movement, or remain off if they are not. The third button may be pushed to change the color of the lights, or held for longer than 1 second to calibrate the lights. If the third button is momentarily pressed to change the color of the lights, the corresponding LED flashes to inform the user that the action has been recorded. A second PCB was designed for the button and LED circuit to make mounting onto the glove easier. Due to the fact that the microprocessor is operating at 3.3 volts, the SSL-LX5093IT LEDs from Lumex were selected due to their low turn on voltage of 2 volts [7]. Furthermore, we decided to include a Schmitt trigger hex-inverter between each of the buttons and the microprocessor in order to shield the capacitors from dissipating charge into the microprocessor.

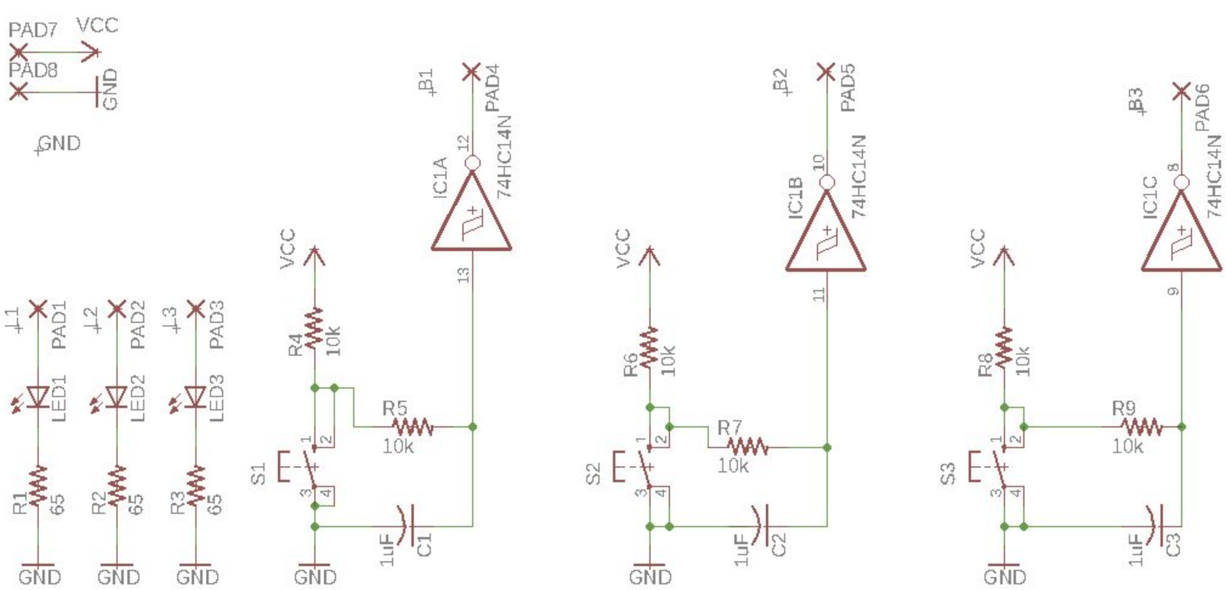

Figure 6: Schematic for the Button & LED PCB

2.3 Main Control Unit

2.3.1) Power Supply

The Raspberry Pi 2 is the only component of the Main Control Unit that we must power. Luckily, the Raspberry Pi 2 accepts power through a standard adapter that plugs into the wall. The adapter accepts AC at 100-240V and 60Hz and converts it to DC at 5V and 2.5A.

2.3.2) System on Chip (SoC)

The main concern with the processing unit is its integration with the DMX512 adapter and the Bluetooth receiver. We chose to use the Raspberry Pi 2 development board with Linux installed on it. By running Linux, we were able to utilize Python and its existing libraries to interface with the plug-and-play DMX512 adapter and Bluetooth receiver with the SoC. This decision saved a large amount of time because we did not have to write our own libraries for interfacing with the light units.

2.3.3) DMX512 Adapter

The industry standard for professional grade lighting communication is the DMX512 protocol. The DMX512 adapter is used to deliver the data required for the moving-head stage lights. This one adapter can communicate up to 512 channels [8]. With a standard moving-head stage light occupying 9 channels, up to 56 moving-head lights can receive data from this one adapter.

2.3.3) Bluetooth Receiver

The Bluetooth receiver is connected to the Main Control Unit and receives the signals broadcasted by the Glove Unit’s Bluetooth Transmitter. The Bluetooth receiver is a standard Bluetooth 4.0 plug-and-play USB adapter that we used out of the box. The range that the Glove Unit’s Bluetooth Transmitter and the Main Control Unit’s Bluetooth receiver have is detailed on page __ and in figure __.

2.4) Light Unit

The moving-head stage light fixture that we used for this project is the American DJ Accu Spot 250 II. We used two of these lights and daisy-chained them in series. This allowed us to use one USB to DMX512 adapter from the Main Control Unit. Then the first light connects to the second light in series with a standard DMX512 male-to-female cable.

The Accu Spot 250 II receives 9 channels of data, with each channel being an integer value of 0 to 255 [9]. As discussed in section 2.2.3, the data from the gyroscope is on a range of -180 to +180. In order to communicate with the light units, we needed to create a remap function that would remap the data from the range of -180 to +180 to the range of 0 to 255.

In order to ensure that the Light Units and the Gyroscope are in-sync and calibrated together we first found the mid-point values for the pan and tilt channels of the light units. The mid-point values are when the light unit is point dead center. Dead center is when the pan is at 180 degrees to the light's starting position, and when the tilt of the light is perpendicular to the light's base. The corresponding median values on the DMX512 range is 130 for pan and 36 for tilt.

$$\Delta_{pan} = p_{actual} - p_{median}$$
$$\Delta_{tilt} = t_{actual} - t_{median}$$

Equation 3: Delta offsets used in calibration function.

Using the current pan and tilt values of the lights and the median values, we calculate the difference in these two as seen in Equation 3. The offset is different for both the pan and tilt, depending on the orientation of the Glove Unit at time of calibration. This is not the final calculation for the Light Units. Rather, once the system is fully calibrated and the delta offsets obtained, we now take the newly calculated values from Equation 2, and subtract the delta offsets from these newly calculated values.

3. Design Verification

3.1) Glove Unit PCB

With the PCB for the Glove Unit fabricated, we set out to solder all the components onto the board and verify its functionality. While soldering the board we noticed that some components seemed to be completely missing their connections on the PCB. We inspected the schematic that we designed and it was seemingly perfect. After inspected the schematic we designed, we took a closer look at the actual board that we designed only to realize that there were 8 connections missing on the board itself. This was a human error caused by not inspecting the board file close enough.

After realizing our mistake, we intended to fix the missing connections by soldering jumper wires onto the PCB. Unfortunately, these attempts were unsuccessful. The missing connections around the MPU-6050 Gyroscope and Accelerometer chip were too small to solder jumper wires onto. To solve this issue, we quickly adjusted to using a perforated board instead.

We soldered all of our components for the Glove Unit onto the perf board and set out to verify it was working. To verify it was working, we first tested the voltage regulator to ensure that we would not burn any of the chips. At input voltage of 6-12V, the voltage regulator successfully outputted 3.3V. Further, we then programmed the microprocessor to attempt to connect to the MPU-6050 and the nRF8001, and if successful, to start advertising the signal "BSTPALz" on the Bluetooth Module. After powering on the device, we used and iPhone running Nordic Semiconductor's nRF Toolbox App to search for the "BSTPALz" signal. The signal appeared on the iPhone just as expected.

3.2) Glove Unit Microprocessor

A concern with the ATmega328 microprocessor chip is that it must be tested for programmability. There are some versions of the chip that come with the ability to be programmed, while others do not. In order to verify that our chip was programmable, we programmed it to loop between turning an LED on and off through one of its outputs. The chip functioned as programmed, so we knew it was programmable.

3.3) Flex Sensor

To verify the flex sensor, we gathered data points using a multimeter. We tested what the resistance levels are at a particular bend angle. As you can see in the graph below, the flex sensor produces a relatively linear resistance with an increasing bend angle.

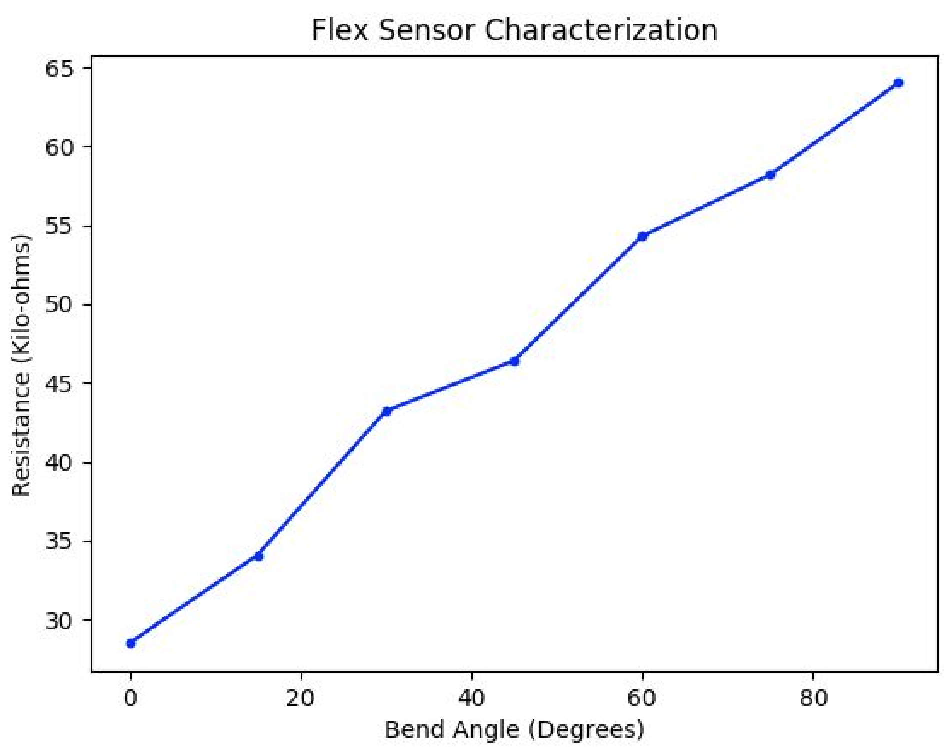

Figure 7: ADA1070 flex sensor resistance vs. bend angle.

3.4) Button and LED PCB

The button and LED PCB was verified by ensuring the LED circuits lit up when supplied a 3.3V signal, and ensuring the button circuit output an active high signal when pressed. A power supply was used to supply any inputs. The PCB functioned correctly.

3.5) Bluetooth Transmitter and Receiver

We tested the Bluetooth range with the strategy of simulating the noise and interference expected in an average small-size entertainment venue's environment. There were at least 20 other Bluetooth devices advertising within range of the Main Control Unit, at least 10 WiFi routers, and 6-inch wall at 20 feet. We also did our best to point the Bluetooth transmitter's antenna away from the Main Control Unit. In this environment, we found the reliable range of the Bluetooth to be 32 feet. This was nearly an exact match of our predicted range of 30 feet. The graph below shows the data points collected during this test.

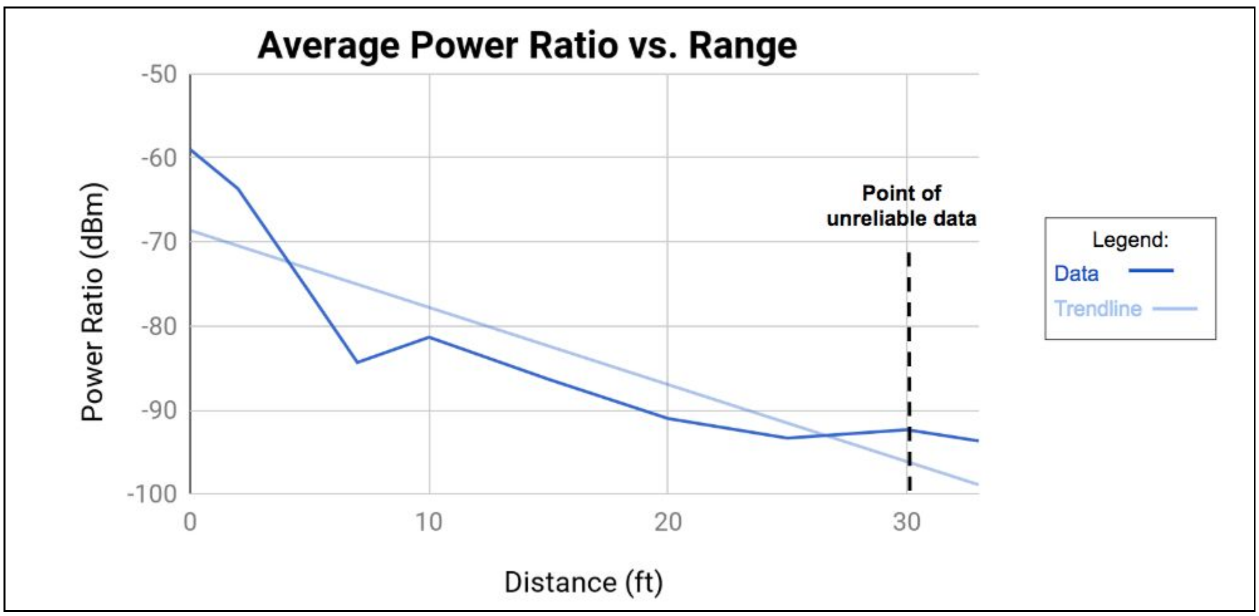

Figure 8: nRF8001 power ratio vs. range.

3.6) DMX512 Adapter and Light Units

The USB to DMX-512 Adapter must accept data via the USB protocol and convert it to the DMX-512 protocol. We verified this by connecting the adapter to the Main Control Unit and to the Light Units. Then we sent single packets of data to the adapter and watched to see if the Light Units responded accordingly. The most difficult part for this verification test was communicating to the adapter via USB. We were able to first send individual packets by writing a short program and executing it directly on a command line prompt. The Light Units successfully responded to this test. To test that the adapter could accept many packets of data in a quick succession, we wrote another program to send 9600 bits of data per second, as this would be the maximum possible under the chose baud rate of 9600. The adapter was unphased in this stress test and the Light Units were successfully interpreting the converted data.

4. Costs

4.1 Parts

Part	Model	Manufacturer	Retail Cost	Bulk Purchase Cost	Actual Cost
Gyroscope & Accelerometer	MPU-6050	TDK InvenSense	$7.27	$4.07	$7.27
Microprocessor	ATmega328P	Atmel	$2.28	$1.68	$2.28
Bluetooth Module Transceiver	nRF8001 Breakout Board	Adafruit	$19.95	$15.96	$19.95
Battery	9V Alkaline Battery	Amazon	$1.19	$1.19	$1.19
Buttons (x3)	B3F-1000	Omron Electronics	$0.75	$0.47	$0.75
LEDs (x3)	SSL-LX5093IT	Lumex	$1.20	$0.24	$1.20
Capacitors	Various	Various	$9.42	$2.97	$9.42
Resistors (x18)	Various	Various	$7.54	$2.21	$7.54
Inductors	B82432T1103K	TDK / EPCOS	$0.91	$0.37	$0.91
Voltage Regulator	TPS62056DGSR	Texas Instruments	$1.95	$0.83	$1.95
TTL Chips (x2)	Various	Various	$1.05	$0.23	$1.05
Flex Sensor	ADA1070	Adafruit	$7.95	$6.36	$7.95
Glove	Long Dress Glove	ZaZa	$4.35	$4.35	$4.35
Raspberry Pi 2	Raspberry Pi 2	Adafruit	$39.95	$39.95	$39.95
Bluetooth Module Receiver	USB Bluetooth 4.0 Low Energy	Pluggable	$12.95	$12.95	$12.95

USB to DMX-512 Adapter	ultraDMX Micro	DMXKing	$72.00	$72.00	$72.00
Head Light (x2)	Accu Spot 250 II	American DJ	$499.98	$499.98	Free
PCB 1	2 Layer PCB	PCBWay	$30.00 (445 Budget)	$30.00 (445 Budget)	$30.00 (445 Budget)
PCB 2	2 Layer PCB	AllPCB	$15.33	$15.33	$15.33
Totals			$736.02	$711.14	$236.04

Table 1: Component costs.

4.2 Labor and Schedule

Week	Mat	Debjit	Ian
2/5/2018	Researched DMX-512 communication protocol and designed Power Supply for both Control Units.	Researched and designed high-level Main Control Unit	Researched and designed high-level Glove Control Unit
2/12/2018	Design Document	Design Document	Design Document
2/19/2018	Created schematic for the Power Supply for both Control Units	Created schematic for the Main Control Unit	Created schematic for the Glove Control Unit
2/26/2018	Programed Glove Control Unit sensors and Bluetooth communication	Programed Main Control Unit for Bluetooth and DMX-512 communications	Ordered all supplies, began design for Glove Control Unit PCB
3/5/2018	Physically prototyped Power Supply and voltage regulator	Connected the Main Control Unit to Light Units and tested DMX-512 Communication	Physically prototyped the Glove Unit with sensors
3/12/2018	Verified both Control Units' programs	Glove Control Unit Schematic/PCB order	Glove Control Unit Schematic/PCB order
3/19/2018	Spring Break	Spring Break	Spring Break
3/26/2018	Continued physical prototype	Continued physical prototype	Continued physical prototype
4/2/2018	3D Design and Printed the Housing Unit for Glove	Fixed any bugs with the program and actual prototype	Resolved consistency issues between programs and the prototypes
4/9/2018	Finished case and work with PCB to ensure seamless integration with the Glove Unit	Replaced Glove Control Unit prototype with PCB	Solder the PCB Board sensors and replace the prototype on the Glove Unit

4/16/2018	Completed all verification tests. Completed and resolve any last minute issues. Work on demo.	Completed all verification tests. Completed and resolve any last minute issues. Work on demo.	Completed all verification tests. Completed and resolve any last minute issues.
4/23/2018	Presentation/Demo	Presentation/Demo	Presentation/Demo
4/30/2018	Final Paper	Final Paper	Final Paper

Table 2: Project Schedule

Our fixed development cost included 3 people at wages of $40/hr. Each person worked an average of 5 hours per week over the course of the 12 weeks on this project:

$$3 * \$40/hr * 5\ hr/week * 12\ weeks = \$7200$$

With our component costs and labor, our total development cost is $7436.04. We are not ordering anything in bulk, however if we were a company looking to build our system on a large scale, we would see a price decrease of $24.88.

5. Conclusion

5.1 Accomplishments

For the first time, performers with zero light design experience are able to take control of the lights themselves in a physically appealing way, adding to the showmanship of their performance. We successfully implemented our entire system: motion controlled lights which follow the user's hand, allowing real-time control. With our calibration function, the user is able to minimize drift and noise, on top of providing the option to recenter the lights. We took our design one step further by providing a color selection option that can switch between four commonly used colors in lighting design: red, purple, blue and white. The code and ability to introduce further colors and gestures such as light intensity and strobe also exist, though are not currently implemented.

5.2 Uncertainties

One issue that we would like to tackle next is the drift from the gyroscope sensor. The gyroscope functions flawlessly during movement, but when it is held stationary the gyroscope reports values that slowly drift away from the true location. This is a design flaw with the gyroscope that could be solved by using a more expensive gyroscope chip. However, to keep costs low, we would like to implement a more advanced movement detection algorithm. We believe that it is possible to use the accelerometer data in order to detect if a user is keeping their hand stationary or not. If our movement detection algorithm would detect that the user is not moving, the gyroscope data corresponding to the drift would be thrown away.

As was previously discussed, we would also like to reprint the main logic PCB for the Glove Unit. As we caught our mistakes in the board design, we could easily shrink the Glove Unit to a smaller size if we were to reprint our board.

5.3 Ethical Considerations

Our project does not have any major ethical concerns as it simply adds entertainment value to something that has already existed. The only ethical consideration of concern is that our batteries are currently not rechargeable, inviting environmental pressures. While we plan to introduce a rechargeable battery into our product, it is important that the user still has the ability to use a disposable 9V battery in case they come to a performance without their equipment fully charged.

Although there are minimal ethical considerations there are some possible safety concerns to be addressed. Foremost, rechargeable batteries and even alkaline batteries have the potential to explode under improper use [10]. To minimize this risk, we will always recommend to follow standard storage and usage procedures for disposable alkaline batteries. To elaborate, there is essentially a nonexistent chance of electrocution from the glove device at such small voltages. However, to take full precautions, we took the additional step to isolate all electrical components from the users skin. No electrical components makes direct contact with the user.

Next, users of our system may be exposed to high voltages when using standard professional DMX512 moving head lights. These lights consume large amounts of electrical power, and are powered directly by the wall outlet. We communicate this potential electrical hazard to all users of our system through the use of warning labels.

In most cases, the DMX 512 protocol does not include a parity check or an error check [11], [12]. This means that when using a DMX-512 hardwired system, such as our current approach, there is a potential risk that the wires used to communicate to the lights pick up interference and cause an undesired operation. In the worst case, this means that the moving head lights move uncontrollably and at incorrect colors/brightness levels until it receives a new correct signal. We fully disclose this risk to the users of our system and include warning labels. The requirement to use our system will be that all moving lights be in a physical area that gives a full range of movement to the moving-head light with zero possibility of collision or human contact.

We do not suspect interference, electrocution, and battery explosions to be large problems, but according to IEEE Code of Ethics #1, we must “hold paramount the safety of the public... and disclose promptly the factors that might endanger the public or environment” [13]. We believe we have fully followed this code and all other standards laid forth by the IEEE Code of Ethics.

5.4 Future Work

In the future there are two areas we are going to address foremost: the glove's appearance and functionality. Currently, our design resembles a prototype more than it does a finished product. We would like to improve our glove's wiring by concealing the wires in the fabric of the glove. Furthermore, we believe that replacing the two PCB boards with a smartwatch-esque touch display would improve the aesthetic and would add an interface that is much easier to customize. Furthermore, we would like to implement a stronger microprocessor that would have enough power to process this extra data. Although these changes would cause the glove to consume more power, we can afford these costs due to the glove lasting 12 extra hours than we anticipated it to. Lastly, implementing a movement tracking algorithm would allow us to eliminate the drift of the gyroscope.

5.5 Acknowledgments

We would like to thank Zach Ware for the inspiration behind the project and for allowing us to borrow his moving head lights. Without his inspiration and equipment, this project would not have been possible. We would also like to thank Anthony Canton for his assistance and mentorship throughout the semester. Thank you to the entire ECE 445 Course Staff for a great semester.

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Appendix

A) Decision Diagram for the Glove Unit

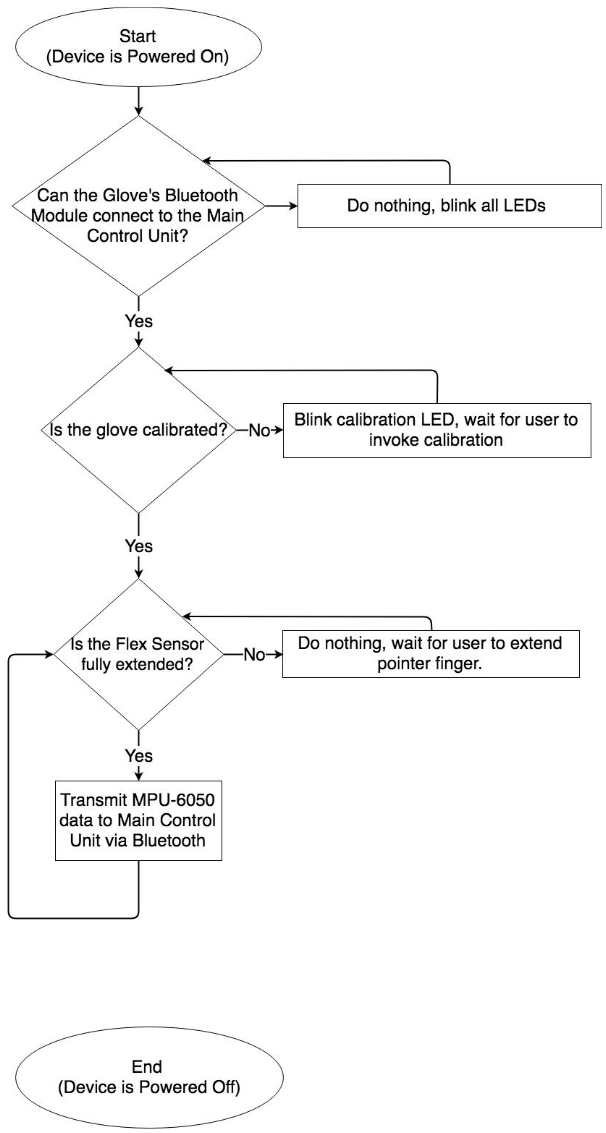

Figure 9: Glove Control Unit decision diagram.

B) Decision Diagram for the Main Control Unit

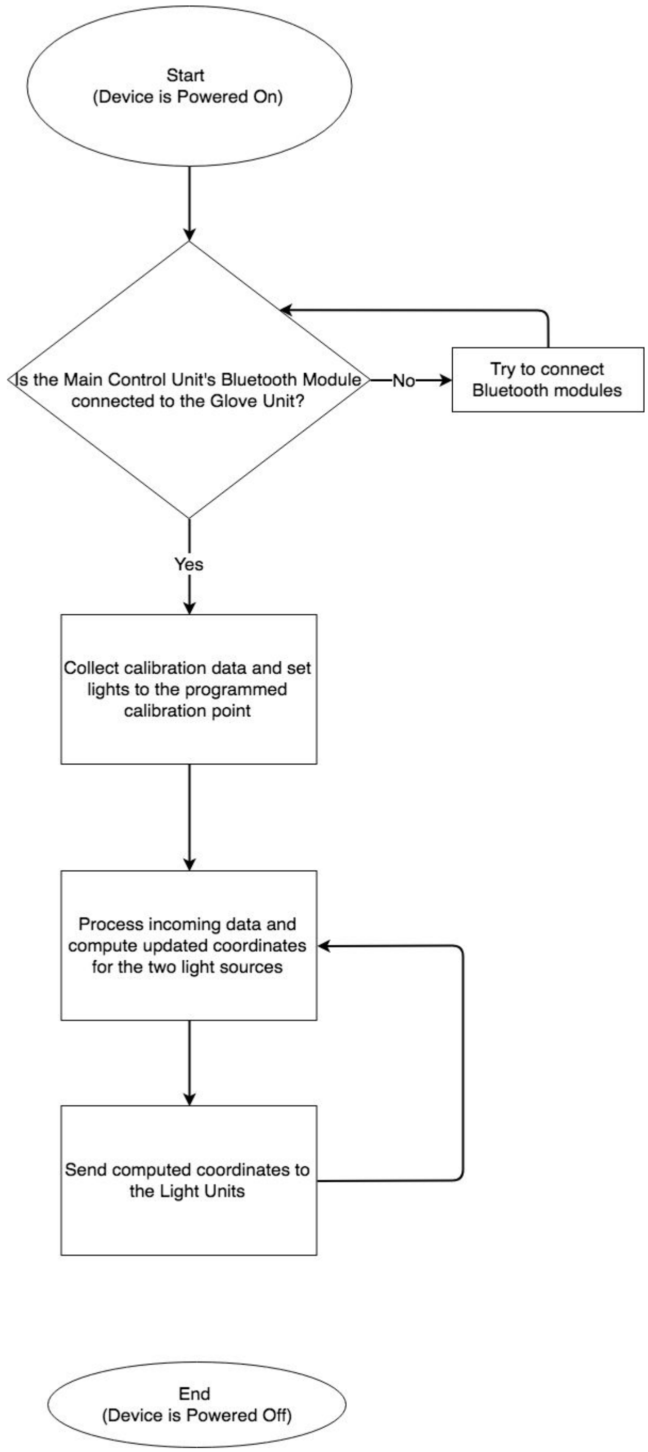

Figure 10: Main Control Unit decision diagram.

C) Requirements and Verification Table

Requirement	Verification	Verification Status (Y/N)
1. Battery supplies 600 mA-hours of current at a voltage of 3.5 V.	1. Connect a fully charged 9 Volt battery to a power drawing test circuit. 2. Discharge the battery at 150 mA for at least three hours. 3. Utilize a voltmeter to ensure the supply voltage stays above 3.5V throughout the procedure.	1. Y 2. Y 3. Y
1. Voltage regulator supplies ~3.5 V for an input voltage of 6-9 V. 2. Operates in the current regime of 0-200mA. 3. Maintains a thermal stability below 100℃.	1. Confirm the output voltage operates within 10% of 3.5V over the input voltage range of 6-9V and current range of 0-200mA through the use of an oscilloscope. 2. Ensure the component maintains a temperature under 100℃ through the use of an IR thermometer.	1. Y 2. Y
1. The gyroscope and accelerometer must not consume more than 5 mA of current to ensure low power consumption. 2. The gyroscope and accelerometer should have enough accuracy to track the location differential of the glove without introducing a 5 degree error between the calculated finger pointing vector and actual finger pointing vector.	1. An oscilloscope will be used to measure the chip's current consumption at a 3.5 V supply input. 2. The gyroscope and accelerometer will be tested with gesture motions and movement to ensure the error between the estimated and actual finger pointing vector stays within five percent through a three hour usage.	1. Y 2. Y
1. The bluetooth chip must not consume more than 110mA of current to ensure low power consumption. 2. The range of the bluetooth signal must exceed 30 feet.	1. An oscilloscope will be used to measure the bluetooth chip's current consumption at a 3.3 V supply input. 2. The chip will be used to broadcast a test signal which will be received over a range of 20 to 40 feet and tested by matching with the original test signal to determine signal integrity.	1. Y 2. Y
1. The flex sensor must change it's resistance if a user is pointing their index finger versus when they are not pointing their finger.	1. The flex sensor will be sown into the glove and wired up to the microprocessor. An ohmmeter will be used to detect if there is a change in resistance when the finger is resting versus when the finger is pointed. 2. A pointed finger corresponds to a resistance level of less than 35K Ohms. 3. An unpointed finger corresponds to a resistance level of more than 35K Ohms.	1. Y 2. Y 3. Y
1. The DMX adapter must output signals using the proper DMX-512	1. The DMX adapter will be tested by pairing it with the main control unit microprocessor and communicating known control signals to the	1. Y

communication protocol.	lights to see if they align with the actions executed by the lights.	
1. The microprocessor must be compatible with the bluetooth receiver and DMX adapter.	1. The microprocessor will be tested with the components to ensure the microprocessor receives and stores meaningful values.	1. Y
1. Verify the button circuit delivers a high signal when pressed, and a low signal when not pressed.	1. Use an oscilloscope to confirm the output of the button circuit is ~3.5V when pressed and 0V when not pressed.	1. Y
1. The microprocessor must be compatible with the sensors and bluetooth chips. 2. The microprocessor must not consume more than 15mA of current to ensure low power consumption. 3. The microprocessor must turn on the LEDs when its corresponding button has been pressed.	1. The microprocessor will be tested with the sensors to ensure the microprocessor receives and stores meaningful values. 2. An oscilloscope will be used to measure the microprocessor's current consumption at a 3.3 V supply input. 3. Confirm the LED turns on to the corresponding button when the button is pressed.	1. Y 2. Y 3. Y
1. The receiver must receive the bluetooth signals at a strength above -70 RSSI value at a range of 30 feet.	1. The RSSI value of a bluetooth test signal 30 feet away will be tested over the course of an hour to determine it remains above -70 at all times.	1. Y

Table 3: Requirements and verifications.

D) Additional Photos

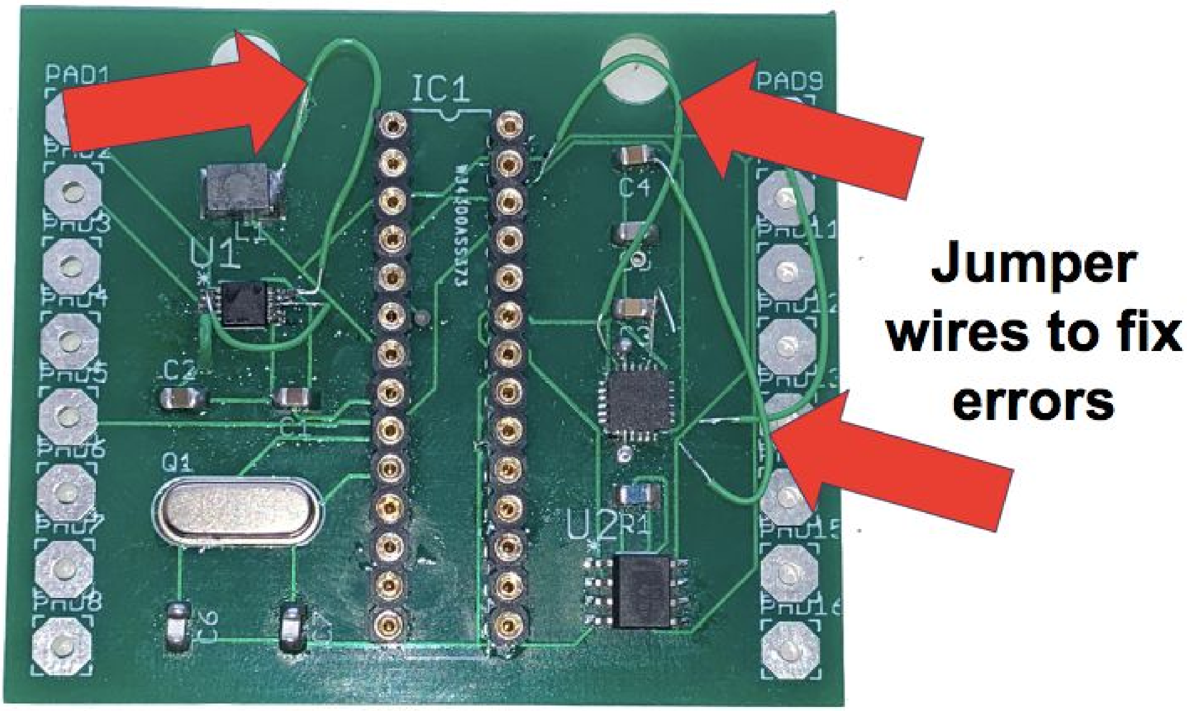

Figure 11: Glove Unit PCB.

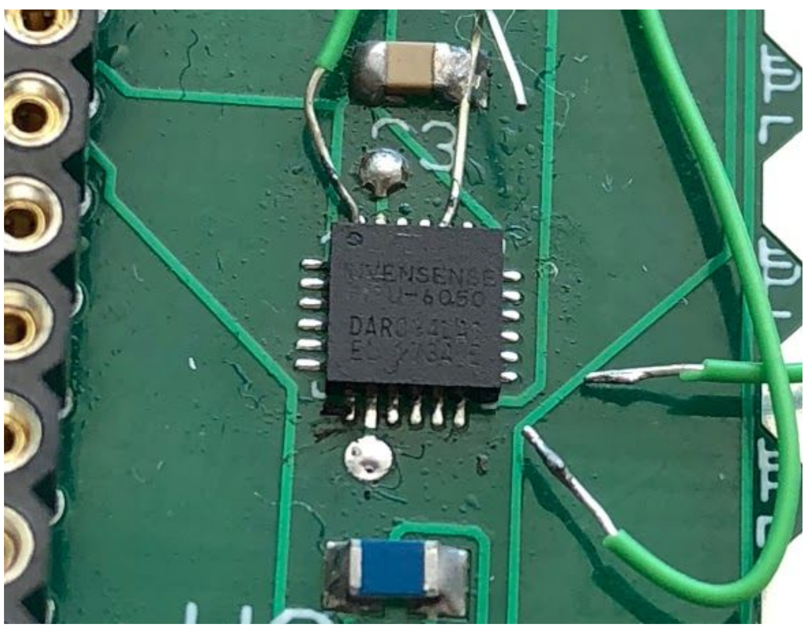

Figure 12: Glove Unit PCB zoomed in on MPU-6050.

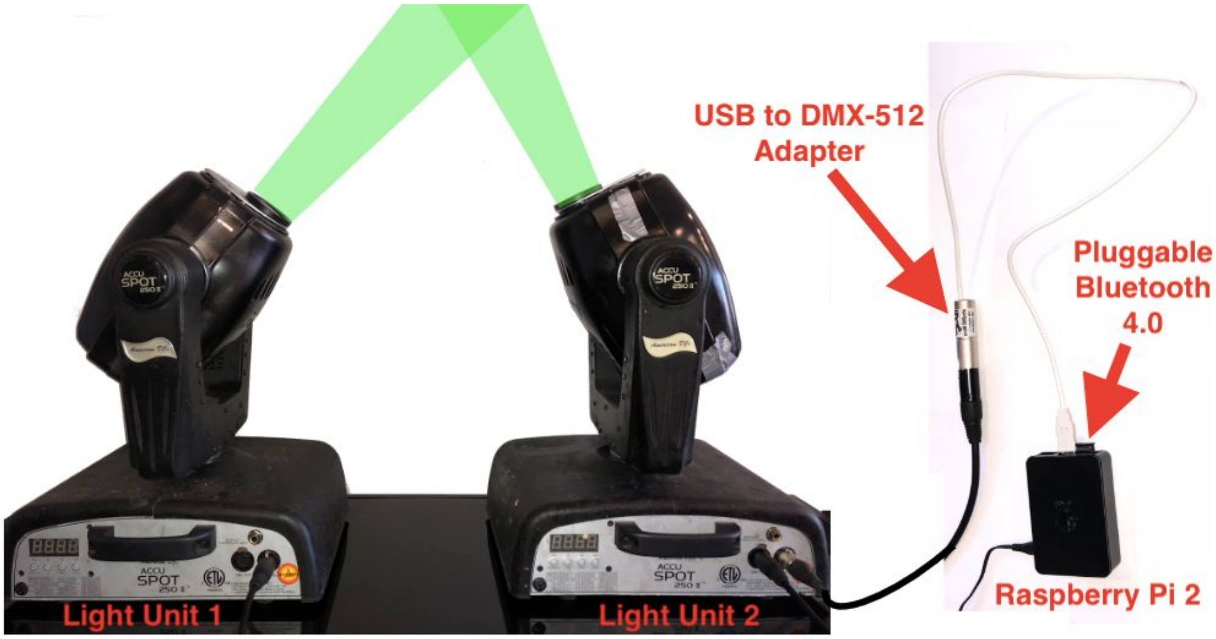

Figure 13: Picture of the Main Control Unit attached to the Light Units.

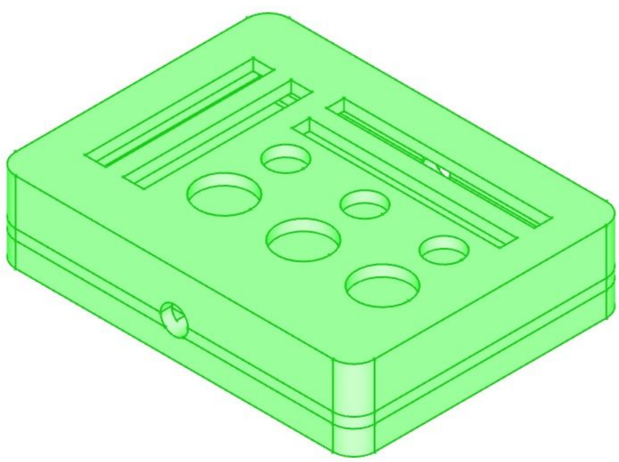

Figure 14: Custom Button and LED PCB 3D printed casing.

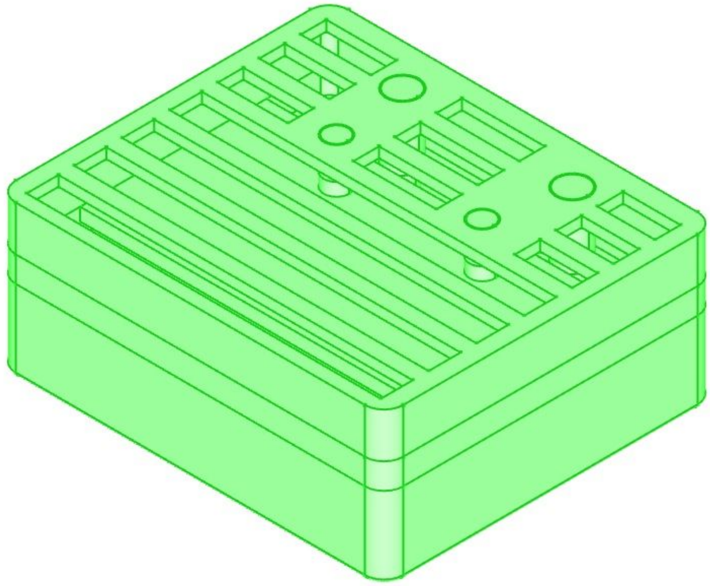

Figure 15: Custom main PCB 3D printed casing.

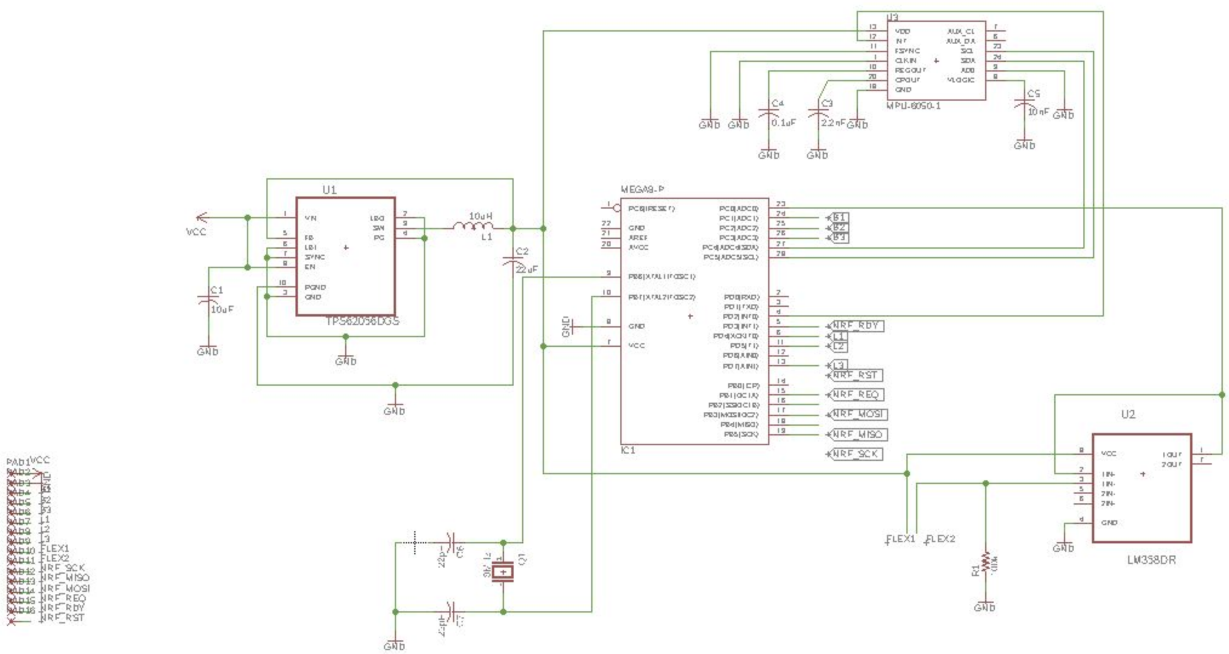

Figure 16. Entire Glove Unit's schematic.

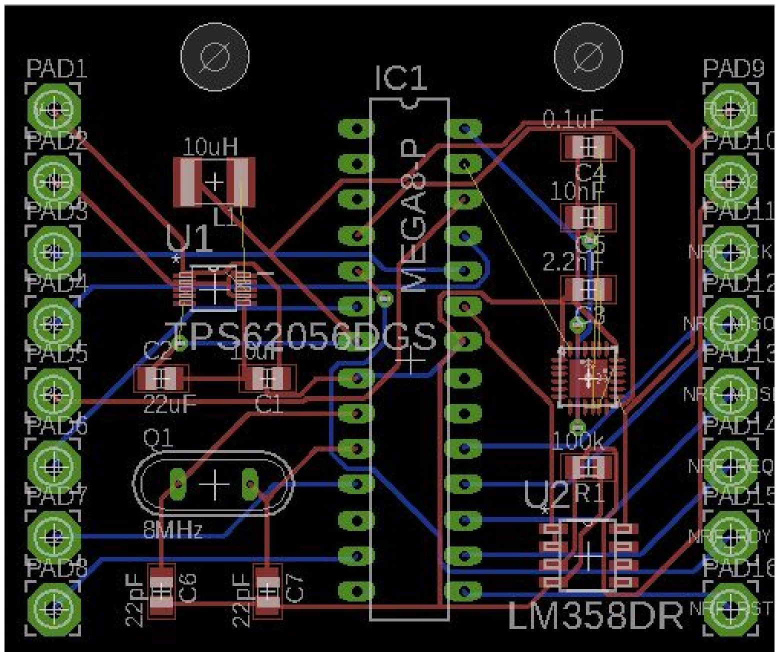

Figure 17. Glove Unit's board design.

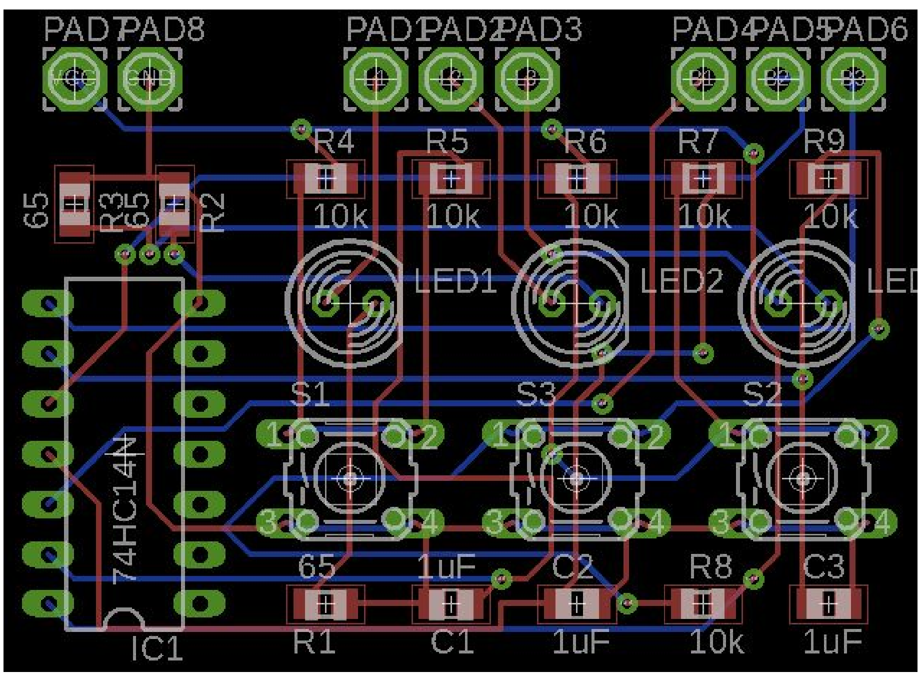

Figure 16. Button & LED board design.