UCF Senior Design I

MITTS

Motion Interface Thermal Touch Sensitive

Department of Electrical Engineering and Computer Science
University of Central Florida Dr. Lei Wei

120 Page Submission

Group 2

David Simoneau	Computer Engineering
Chris Britt	Electrical Engineering
Anthony Hunter Hinnant	Computer Engineering
Francisco Tirado Perez	Computer Engineering

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1: Executive Summary

This product will be a glove controller that has the capabilities of interacting with a virtual 3D object. The design will be focused on taking position inputs from the glove, transmitting data through a processor, and then sending that data through our interface to the computer running the simulation. The project is designed in such a way to allow us to gain experience in PCB design as well as data communication, ARM development, and 3D modeling software API.

The glove will capture motion using multiple accelerometer PCBs located on the center points of each finger bone and one on the back of the hand. Each accelerometer will communicate with the processor board using I2C at a sufficiently high rate to ensure smooth operation. The processor will calculate the relative position of the fingers and hands relative to the '0' accelerometer located on the back of the hand. This will require a reset button to calibrate the system. Once calculated the processor will interpret these positions as commands and then to a Bluetooth module which will send the commands via UART to a receiver which will communicate those commands to the computer and to a 3D modeling software such as Blender. The program will communicate back data that will allow the glove to give sensational feedback to the user. To do this the glove will incorporate Peltier devices for heating and cooling and small vibrational motors for touch feedback. Since the glove will be wireless we will be creating a rechargeable battery board. The choice for a rechargeable board was made because of the need for high quality low weight batteries to supply the high current requirements of the Peltier devices. This provides our project with two main facets. The construction of the glove and the computer Bluetooth interface is the hardware facet, while the incorporation of the 3D modeling software is another facet.

Through this project, we will add to the open-sourced community. The open-sourced community is filled with hobbyists that are always hungry for new challenges and fun project ideas. We look to supply this community with a comprehensive design that people can make use of for their own projects and applications. Specifically, we feel that the ability for hobbyists to interact with their own virtual 3D environments may drive innovation in the field of virtual and augmented reality.

Virtual and augment reality is and has been a hot new topic in technology development for quite some time. With the advent of the HTC Vive, immersive virtual reality gaming became an actual reality. However, a major drawback of current virtual reality is its lack of haptic feedback. When the user touches something in the real world the user can feel its heat and the pressure of my hand on it. This project seeks to bridge that gap in current technology by allowing a control sensitive enough to accurately capture hand motions, while allowing for immersive feedback from the virtual world.

The goals of this project are to work on a fun, technically challenging project that will allow us to learn about real-world circuit design by implementing the knowledge gained from our education thus far. The team will also seek eye-opening conversations with professional industry workers, such as our professors, about industry standards, project design, and engineering concepts. The team is hoping to advance our careers and industry visibility by contributing to an open source community. From this design, the team will have gained industry-level experience to add to our resumes and gain necessary skills required by the field of computer/electrical engineering. The key feature we aim for with our glove input design is for it to have a high frequency rate to get a quick and accurate response rate of our input. The team will implement sensors on the glove that will be able to track the motion of the hand and fingers with a high degree of accuracy and communicate that to 3D modeling software. The software will communicate back to the glove which of the feedback devices should activate and by what degree based on the current position of the virtual hand. The team would also like to establish a base design that future hobbyist might be able to expand from. Since many hobbyist struggle with the more technical aspects of electronic and computer engineering, it is our hope that by designing the more technically challenging aspects of this project we will establish a hardware and code base that can be expanded from easily in the future.

2: Requirement Specifications

Requirement specifications are the technical description of a system to be developed. It is interpreted as an agreement between a customer and developer. Goal of the requirement specifications is the list and quantify the features that the completed system must have to be deemed complete the customer. Requirements of a system adhere to the following principles;

- **Abstract:** The requirement should detail outcome and not implementation
- **Traceable:** The requirement should consist of a single independent element.
- **Verifiable:** The requirement should be testable to determine that it has been met.
- **Unambiguous:** There should be only one way to interpret the requirement.
- **Feasible:** The requirement should be doable/achievable within the required time frame and with the available resources.

Following the above guidelines, the requirement specifications in the following tables outline the quantitative and qualitative goals will determine the success or failure of this project. For example, a quantitative goal would be under Table 1 Spec ID 3: The total time required for all steps in a frame must be less than 33-ms. Meanwhile an example of a qualitative goal would be Table 1 Spec ID 4: The system contains motion capture features.

Spec ID	Detail	Related Value	Unit
1	The integrated package must be able to support designated frames of data per second.	30	fps
2	Each frame will consist of designated number of individual I2C reads	16	reads
3	The total time required for all steps in a frame must be less than given time.	33	ms
4	System contains motion capture features	n/a	n/a
5	System contains processor module	n/a	n/a
6	System contains interface between Blender and processor	n/a	n/a
7	System contains software package for the processor	n/a	n/a
8	System uses open-source 3D modeling software	n/a	n/a
9	System contains battery supply	n/a	n/a
10	System contains Bluetooth communication device	n/a	n/a

Table 1: Integrated Specifications

Spec ID	Detail	Related Value	Unit
11	Must use minimum designated number of accelerometer chips to measure acceleration and track position of fingers and hand.	10	none
12	Glove design with components must not exceed specified weight	2	kg
13	Accelerometers must function within +/- G range	2	G
14	Accelerometers must have specified resolution	10	bits
15	Accelerometers must be I2C compatible	n\a	n\a
16	Must contain minimum number of vibrational motors	6	n\a
17	Must contain minimum number of Peltier devices	6	n\a
18	Must be able to run on batteries	n\a	n\a
19	Must be wireless with respect to 3D environment application	n\a	n\a
20	Must contain limiter on current for Peltier devices	n\a	n\a
21	Accelerometer PCBs should be no bigger than specified dimension	1.5	Cm^2

Table 2: Glove Specifications

Spec ID	Detail	Related Value	Unit
22	The processor must use an ARM architecture chip.	n\a	n\a
23	The any enclosures must not exceed given temperature.	30	C
24	Processor chip must have at given minimum of dedicated I2C lines	1	n\a
25	Processor chip must have sufficient clock rate to support minimum frame rate requirement	n\a	n\a
26	The processor module must have reset option that allows recalibration of system	n\a	n\a
27	System must utilize a power switch	n\a	n\a

Table 3: Processor Model Specifications

Spec ID	Detail	Related Value	Unit
28	The software must be documented as per ANSI/ANS 10.3-1995	n\a	n\a
29	The software must be written in C or C++	n\a	n\a
30	The software must be able to run continuously for given time period without any crashes.	30	minute
31	Software must be able to handle data packet loss.	n\a	n\a

Table 4: Processor Software Specifications

Spec ID	Detail	Related Value	Unit
32	The Utility must operate on Windows 10	n\a	n\a
33	The Utility must have a graphical user interface	n\a	n\a
34	The Utility must interface with Bluetooth device	n\a	n\a
35	The Utility must interface with 3D Software	n\a	n\a
36	The Utility must support one or more concurrently operating gloves.	n\a	n\a

Table 5: Configuration Utility Specifications

Spec ID	Detail	Related Value	Unit
37	The package must be operable for a minimum specified number of time from a full charge standard use.	30	min
38	The device must be able to send and receive data at a minimum frame rate.	30	Frames per second
39	The device must be under a particular weight.	2	kilograms
40	The device must send and receive below a certain latency time.	100	Microseconds

Table 6: Device Specifications

3: House of Quality

The House of Quality allows us to present the goals and technical requirements in a manner that can be easily examined for positive and negative relationships. For example, the Power category and Power Consumption category have a strong positive relationship since without a large power source there cannot be a large amount of power consumption.

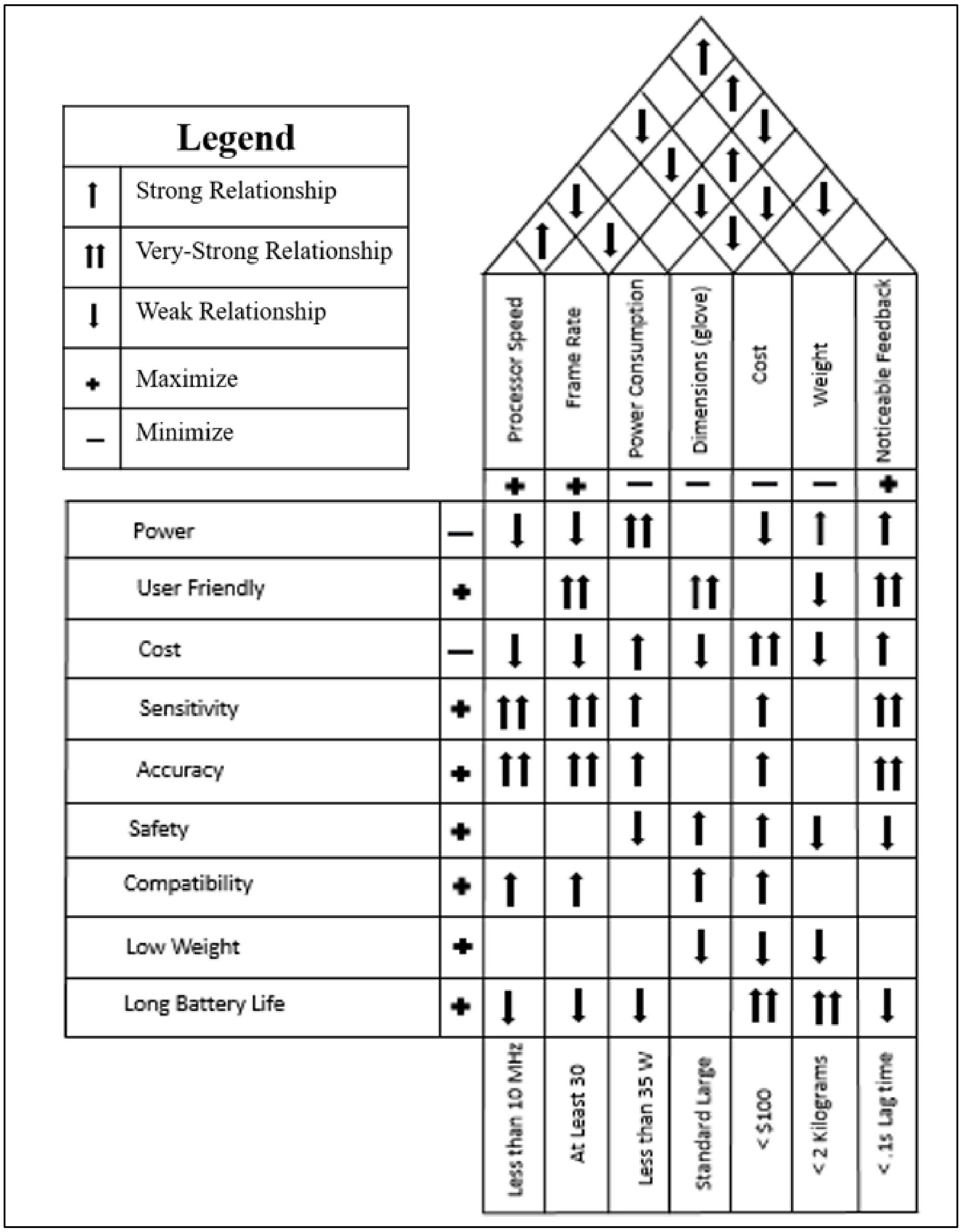
For the left side of the house, it’s important to identify what aspects of the project are important for the consumer. For example: User friendliness is important because we want the project to be easy to pick up and start using for a consumer, and compatibility is important because the consumer will want to use their device with whatever other technology they already own.

The top side of the diagram shows the general product capabilities that we want the device to have. For example: Frame rate is listed with a plus because we want the device to be able to send a fast stream of data to be more “smooth,” while weight is listed with a minus because we want the device to be low weight so that the user can use the device while attached to their hand more easily.

The bottom section of the graph shows specific technical requirements that we need to have for the project. For example: We want the device to be able to update at a rate of at least 30 frames per second, which is a common refresh rate, and we want the device to cost less than 100 dollars to produce.

The arrows at the top and the middle of the graph show the relations between each aspect of the product. For example: Accuracy heavily correlates with processor speed, as a fast processor will help the device react more accurately to movements and is marked with two up arrows. At the top of the graph, processor speed correlates with noticeable feedback, as it will help the haptic feedback respond more accurately when prompted and is marked with a single up arrow. Meanwhile, safety negatively correlates with weight, as the device will generally be safer if it’s lighter while attached to the user’s hand and is marked with a single down arrow.

Overall, the house of quality will help us recognize the needs of the project from both a consumer perspective and an engineering perspective, as well as how they correlate with each other. This will help us recognize the most important goals of our project, and the bigger picture as to what needs to be prioritized and what actions can help many of our goals at once.



Legend	
↑	Strong Relationship
↑↑	Very-Strong Relationship
↓	Weak Relationship
+	Maximize
−	Minimize

		Processor Speed	Frame Rate	Power Consumption	Dimensions (glove)	Cost	Weight	Noticeable Feedback
		+	+	−	−	−	−	+
Power	−	↓	↓	↑↑		↓	↑	↑
User Friendly	+		↑↑		↑↑		↓	↑↑
Cost	−	↓	↓	↑	↓	↑↑	↓	↑
Sensitivity	+	↑↑	↑↑	↑		↑		↑↑
Accuracy	+	↑↑	↑↑	↑		↑		↑↑
Safety	+			↓	↑	↑	↓	↓
Compatibility	+	↑	↑		↑	↑		
Low Weight	+				↓	↓	↓	
Long Battery Life	+	↓	↓	↓		↑↑	↑↑	↓
		Less than 10 MHz	At Least 30	Less than 35 W	Standard Large	< $100	< 2 Kilograms	< .1s Lag time

Figure 1: House of Quality

4: Block Diagrams

A block diagram is a diagram of a system or part of a system in which the primary components are represented by blocks and connected by lines in such a manner the represents the relationship between system components, and the scope of a components influence on the system as a whole. Block diagrams leverage the idea of a black box. The black box shows the basic input and output relationships between the components. The small detail of each component is left to be shown in follow-on more detailed diagrams and schematics.

The figure below represents the high-level architecture, organization, and team responsibilities of the project. There is a clear separation point between the hardware portion of the design, and the software portion where the components are connected only by a wireless interface. This interchange point allows the design to be split into two primary areas of responsibility. The glove team is responsible for and will focus on the design and implementation of the wearable glove device itself. Their responsibilities include selecting of the individual accelerometers, vibrations motors, and thermal devices that drive the feedback experience. The glove team must also handle processor selection and wireless interface selection. The final responsibility of the glove team is to determine the power needs of the hardware glove and design the mobile power component of the system.

The computer team is responsible for selecting the computer platform and operating system that will run the 3D environment software. The blender will be used to create the virtual environment and virtual components such as the controlled hand, and interactive objects will need to be created. Objects in the environment will need logic governing collision as well as properties of hardness and temperature to be feedback to the hardware to provide the feedback experience. To drive and manage the interaction between the glove and the blender software, a custom interface utility will be created. The interface utility will provide a data exchange point inputting, formatting and outputting data from the glove to blender, and inputting, formatting and outputting touch and temperature data from blender to the glove. The computer team will leverage industry standard laptop computers and operating systems to provide a platform that contains a variety of wireless communicating hardware, an operating system for running the interface utility and blender software. And support for major development languages and their associated integrated development environments; such as C, C++, C#, Java, and NetBeans, Eclipse, Codeblocks, and VisualStudio.

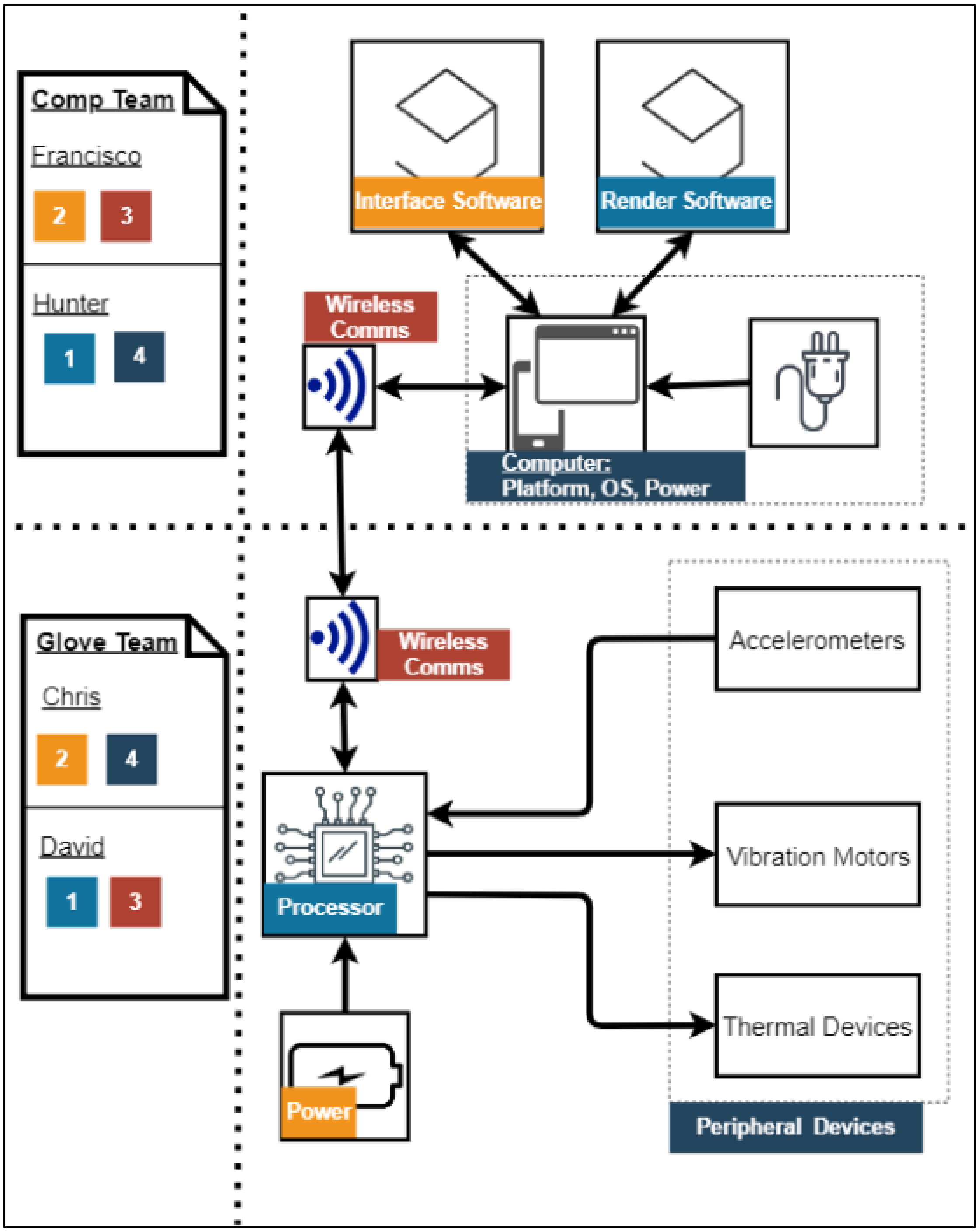


Figure 2: Diagram of Modules and Responsibilities

Figures 3 and 4 show the placement of the accelerometers, Peltier devices, and haptic feedback motors as well as their respective I2C group. The multiple I2C groups are necessary because the selected accelerometers only have 2 possible I2C addresses. This forces the need for an I2C multiplexer with at least 3 selectable bits to address all 16 accelerometers. Due to already having multiple I2C lines the decision was made to place the peripherals (Peltier and vibration motors) on the I2C line that is most closely associated with its position. This is intended to reduce the amount of cabling required to render the glover operational.

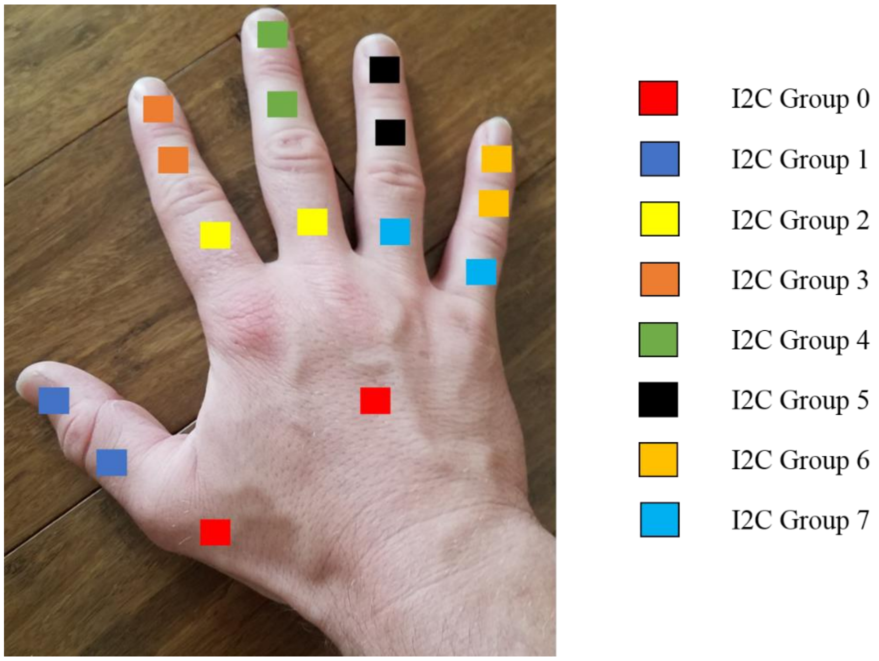


Figure 3: Diagram of Accelerometer Placements

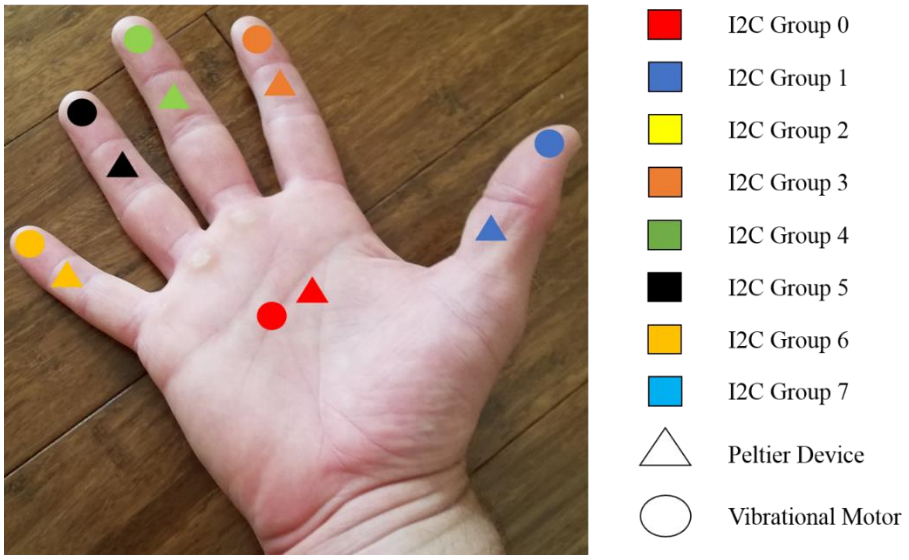


Figure 4: Diagram of Placements of Peltier Devices and Vibrational Motors

5: Milestones

The milestone table is a guide for the project to stay on schedule. Without a milestone table to keep the project organized and on track to be completed on time, the possibility of falling behind and becoming unorganized is greatly increased. For someone to know what they need to do and by what date, then they're more inclined and aware. The following tables show the details on how the tasks are dated and tasked to, starting with Senior Design I tasks and followed by Senior Design II tasks.

#	Senior Design I ~ Tasks	Due By	Admin	Pages Done
1	Have divide and conquer with rough outline of what needs to be researched	June 8th	Group 2	10
2	Have complete standards and have picked out all components for glove	June 15th	Chris	10
3	Have complete standards and components picked out for processor interfacing with glove	June 22nd	David	35
4	Have full understanding how data will be entering/exiting processor and have pseudocode for 5 necessary functions	June 29th	Group 2	60
5	Have power figured out and full understanding of how we will interface with 3D software	July 6th	Francisco	78
6	Order components. Research more into how to code ARM processor and interface with components. Build a breadboard or microcontroller interfacing with controller to ensure data will transmit correctly from outside input.	July 13th	Group 2 Hunter	98
7	Have photo of all components. Start making 3D components in Blender and have more understanding of how interacting with them will work. Then start constructing/designing glove for rough component placement.	July 20th	Group 2	115
8	Have report finished. Finalize any details. Proofread. Add/Subtract necessary information. Ensure citations present. Proofread again.	July 27th	Group 2	120+
9	Full Report Due ~ if time, make prototype and reorder and broken parts	July 30th	Group 2	120+

Table 7: Project Milestones

#	Senior Design II ~ Tasks	Due By	Admin
10	Prototype glove	Aug 24th	Group 2
11	Prototype processor, redesign glove, and start fully coding	Aug 31st	Group 2
12	Prototype interface with 3D software and redesign processor	Sept 7th	Group 2
13	Get accurate input into Blender and some type of output from Blender.	Sept 14th	Group 2
14	More implementing of all three components (glove, 3D software, haptic feedback)	Sept 21st	Group 2
15	More implementing of all three components	Sept 28th	Group 2
16	Troubleshooting / Redesign	Oct 5th	Group 2
17	Troubleshooting / Redesign	Oct 12th	Group 2
18	Fix individual issues with any of the three main components	Oct 19th	Group 2
19	Fixes to individual issues with any of the three main components	Oct 26th	Group 2
20	Put all together. Try to have all coding functionality complete.	Nov 2nd	Group 2
21	More testing.	Nov 9th	Group 2
22	Troubleshooting. Have design/prototype complete if possible	Nov 16th	Group 2
	Thanksgiving 21st-26th		
23	Long weekend. Probably away for family. Ordered extra necessary components in case of hot fixes or things break. Test boundaries. Ensure standards and requirements are met.	Nov 23rd	Group 2
24	Hopefully an extra processor and glove made that both work. Hours of more testing needs to be done. Test boundaries more. Overheat, Cool, Drop, Vibration, Drastic hand movements	Nov 30th	Group 2
25	Present and get A.	Dec ?	Group 2

Table 8: Project Milestones -continued-

6: Cost
This project is not trying to set a record for low-cost but would like to implement a design that's cost-effective for potential hobbyists or enthusiasts to utilize or build our design. The total price we are looking to spend for all used, wasted, or extra components and items is $1000, but having a total build cost of under $100 for a "packaged" PCB design, enclosure, power adapter(s), 3D software interface with transmitter/receiver PCB, and glove. The purpose of having such a high price range for this design is to have the freedom to try out different components, fail a couple of times, learn from our mistakes, and not worry about trying to keep to a specific budget.

The project will most likely not have any funding due to lack of need in the market. However, when we seek funding, we will request from companies in the fields of gaming, for VR or AR needs, and of the movie industry for animation.

Item	Quantity	Price (rough estimate)
Glove	2	$20
PCB Design ~ Processor Board	4	$150
PCB Design ~ Glove	4	$150
Electrical Components on PCBs	?	$200
Bluetooth modules	2	$40
Peltier Devices	10	$50
Power Supply	2	$20
Vibrational Motors	10	$50
Gyroscope Sensor	2	$50
Room for Error	?	$270

Table 9: Expense Estimates

7: Project Management
Project management can be a big issue during a project. Whether it be an individual not completing a task on time, people not knowing what they should be doing, and everyone staying on the same page about what the project is supposed to look like. These topics are all covered in the idea of project management. The *CIO* website [1] defined project management as" the application of specific processes, knowledge and skills, techniques and tools, as well as inputs and outputs that project managers and teams utilize to successfully meet project goals and deliverables." In the next few sections, we will talk about different methods for project management that we will be using to aid us in a more organized and efficient design project.

7.1: Project Management Staff
Essentially what the project plans to do is we have project management for the project, whom is Chris, and we have people responsible for different parts of the design. Then, we have course staff, which are people designated for project development, or rather, helping with project decisions since they have the most experience. Chris is the project lead because he is the team member who has had the most experience with hardware design. With him

being project lead, informed decisions can be made. The diagram for this concept can be seen below:

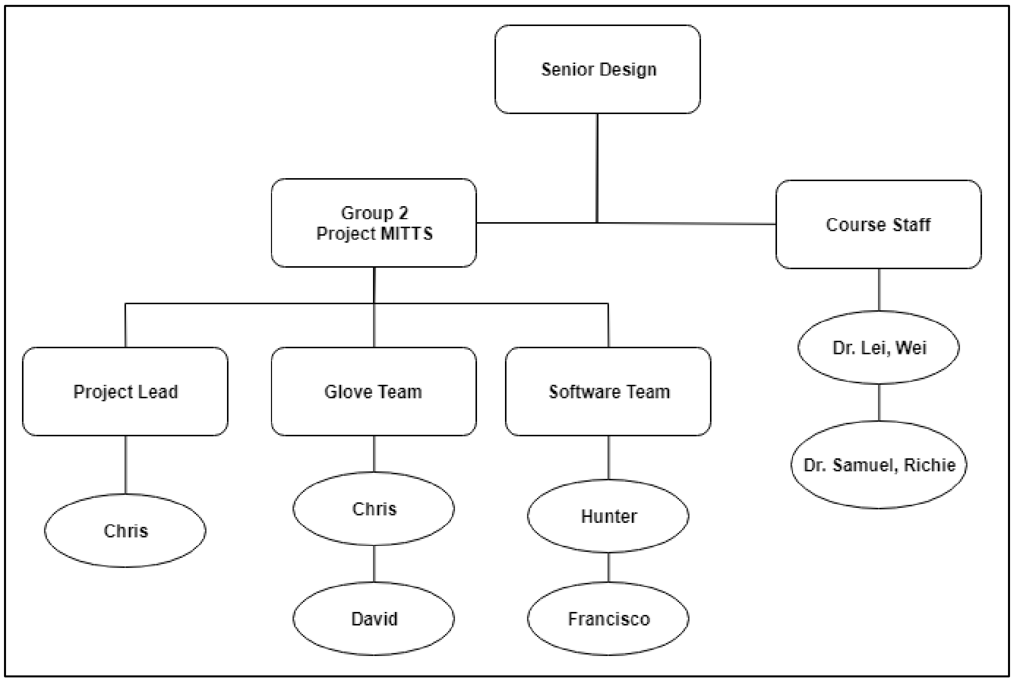


Figure 5: Project Organizational Chart

7.2: Why Projects Fail

According to the *CIO* website on why projects fail, one of the top reasons for project failure is misalignment between project goals and business strategy. There is evidence that shows if a project has a specific group dedicated to project alignment, then they have a much higher chance of success on a project. Just getting organized can make a world of difference. The article goes on to list other reasons for project failure, which include:

- a lack of executive sponsorship and support
- vague business goals or requirements
- unrealistic project scope or scope that is not closely controlled
- insufficient time dedicated to planning
- an inability to bridge the gap between strategy formulation and implementation
- insufficient or misallocated resources, including talent
- unforeseen unmitigated risks
- misaligned project management methodologies
- a haphazard approach to project management
- talent that is spread too thin (not dedicated)
- project managers or team members that lack the necessary training and knowledge

Things we might be worried about from this list include vague requirements because there isn't a set requirement for this design, rather we are making it up as we go. Also, since we are all working separately and only meet once a week, we might forget if we've set an arbitrary requirement and forget also to inform the others. We could suffer from lack of necessary training and knowledge due to the fact that we haven't worked on a senior design project or anything related to our design, so we are learning as we go. This may affect us in time that we've dedicated to the project. Overall, the project is rather small, and we have teachers to guide us, a whole two semesters to work on the project and we don't have a budget, so the odds are with us.

7.3: Project Management Goals

Continuing with the CIO article, they go on to say that "project management professionals first and foremost help drive, guide, and execute company-identified value-added goals." Since we are such a small team, we all are here to help with this methodology. We have one clearly defined goal, and that's to develop our senior design project in a manner that gets us an 'A'. From there, we have sub-goals of completing each delegated task in a timely manner: the glove design, the processor design, the interface design, and the Blender product design. With all of these goals completed, it should be rather easy to piece them together to fulfill the one true goal.

7.4: Project Management – Team Building

For a team to be successful, they must be comfortable in the environment that they are working in. Aristotle is quoted to say, "Pleasure in the job puts perfection in the work." Essentially, the gist of what he means, is that the more you enjoy the job, the better the outcome of the product will be. Enjoyment can be obtained from a job in a plethora of ways. To name a few, clean air, friendly workspace, comfortability, inspirational work, passion for the work required, travel time to work, and even more.

For our group to successfully go about our project, we found it to be important that we have a time where we hangout outside of working on the project. In this sense, we will find a camaraderie between us and enjoy meeting up, rather than relish the fact that we need to do work that is rather tedious. Mentally, this can be draining. In order to remedy this, we scheduled a hangout and spent a whole day playing board games, eating, and spending time outside of work. This has improved the feeling of joy in our meetings and increased productivity overall.

8: Glove Design

The glove portion of the project will house the input sensors and output devices. Specifically, it will house 16 accelerometers which will provide the input sensor data. It will also house 6 Peltier devices and 6 vibrational motors which will provide the output sensory feedback to the user. Included in the overall glove design are the batteries, the main processor board, the regulators, the digital to analog converters that will drive the Peltier devices and the vibrational motors, and the housing of the electronics. The final item that will need to be designed is a charger which can provide current limited power to the rechargeable batteries. Though the charger may be a stretch goal since the batteries can be recharged simply with a desktop power supply. An important item that will need to be selected but will not need to be designed is the glove itself. We will discuss in length the options and constraints for each design choice and part selection.

8.1: Glove Construction
The glove will not be a glove in the traditional sense. Instead of being a full sheath of fabric or some other material surrounding the hand, the ‘glove’ will consist of strips of Velcro with the various electronic components attached to it. The PCB board will be attached to the Velcro by a consumer grade bonding agent. While the Peltier devices will be attached using a thermally conductive bonding agent to a flexible foil which will be wrapped around the Velcro strip. This is to ensure that the Peltier device can reference the ambient temperature while still being soundly mechanically attached.

8.2: Power
The specification for power consumption of the glove is less than 35 W. This must be balanced with the highest power consuming device. The thermoelectric cooler/heaters otherwise known as Peltier devices. The assumption was made that power consumption will be driven by the highest power consuming devices, in this case the Peltier devices. By finding the power specification for running the Peltier devices for the specified amount of time we can put an upward limit on our power consumption. Since we will never run the Peltier devices at the maximum rating, for safety reason, there will be more than enough power left to run the microprocessor and all peripherals.

8.3: Heating and Cooling
To simulate the feel of temperature from a virtual environment an electronically controlled heating and cooling element is required. For weight considerations this device should be solid state as it would be impractical to have a radiator or a mechanical heat pump on each finger. Fortunately, a solid-state thermoelectric heating and cooling device does exist. It is called a Peltier device, after Jean Charles Athanase Peltier who discovered the effect in 1834. The Peltier effect is what occurs when a current is made to flow through a junction of two disparate conductors. Heat can be generated or removed from that junction. In effect this means that by varying the polarity and magnitude of the current though the Peltier device we can control the temperature in each finger by creating a heating or cooling affect.

8.4: Peltier Selection
Originally the TES1-03102 [2] was chosen as it is only 15mm by 15mm by 3.8mm and was the cheapest Peltier device at its size at a price point of approximately $4 per unit. It has a maximum current of 2 amps and a max voltage of 3.75 volts. It also has a max power rating of 4.3 watts and can vary the temperature by about 69°C. The order was placed with kedrgoods.top, but unfortunately after several weeks of waiting the order has not materialized. It can only be assumed that either the order will eventually arrive or that it will not. Either way a usable Peltier device was needed for testing and design refinement. The decision was made to reorder the Peltier devices needed from a more reputable supplier. In this case Digi-Key was chosen as the supplier. The device chosen was the CM23-1.9 manufactured by Marlow Industries [3]. This device is superior for this project to the TES1-03102, however the CM23-1.9 is over twice as expensive as the TES1-03102 at a price point of approximately $11 per device. It was chosen because like the TES1-03102 it was the cheapest available at the size required to fit on the fingertip. This main consideration of size and price is possible because the project does not require high or exact changes in temperature. This means that the efficiency of the device is not as important as

its size and price point. Table 9 shows a comparison of the properties of the Peltier devices at room temperature or 27 °C. Figure 6 shows the voltage and current load relationships for the CM23-1.9. While Figure 7 shows the efficiency curves of several generalized Peltier devices.

	TES1-03102	CM23-1.9
Dimensions (mm)	15x15x3.8	8.18x6.02x1.65
Price per Unit ($)	$4	11.08
Δ Tmax (°C)	69	71
Qmax (watts)	4.3	3.4
Imax (amps)	2	1.9
Vmax (DC)	3.75	2.8

Table 10

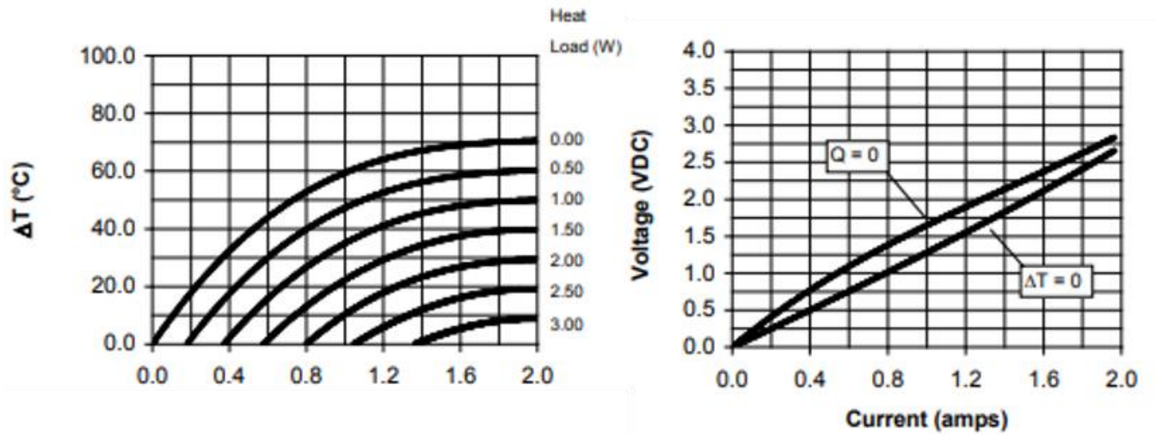


Figure 6: CM23-1.9 Voltage and Current Loads at 27°C

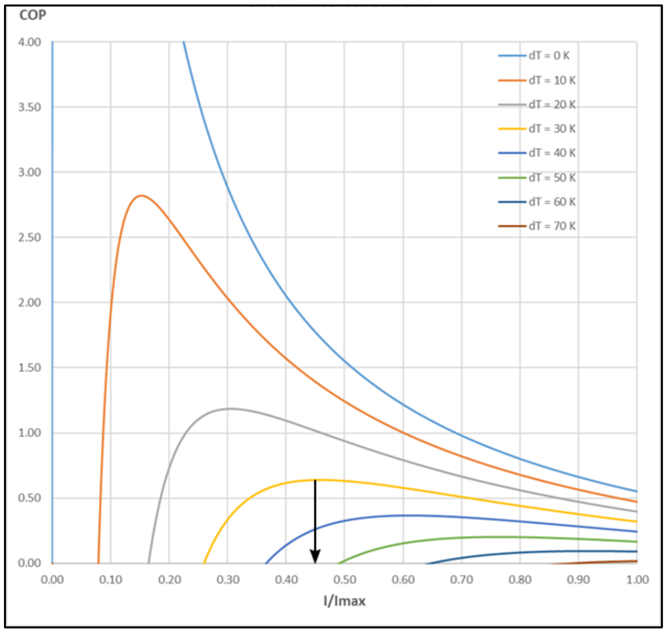


Figure 7: Performance vs Current for Various Temperature Differentials in a Generalized Peltier Device

What Figure 7 shows is that for temperature differences between the hot and cold sides of the device below 40°C there is a steady drop in efficacy above 45% of Imax. While temperature differences above 40°C are not very efficient at all. This means that since the project will not have temperature differences exceeding approximately 20°C the Peltier device will not need current more than 40% of its Imax value. This means that a high watt resistor can be affixed in series with the Peltier device to make regulation of current quite simple [4].

8.5: Switching Direction Using N-FETs

Figure 8 shows the tentative schematic for controlling the direction of current in the Peltier device since the direction of the current will control if it heats or cools. Figure 8 shows that a possible plan to vary the directionality of the current by using power switching N-FETs to open channels between however we may decide to use solid state relays depending on the limitations of the N-FETs that we can easily and cheaply obtain. The use of so many N-FETs carries the risk of too high heat dissipation, however most of the N-FETs will not be active at the same time or if they are it will be briefly. Unfortunately, this design will not be applied in the project since it has proved to be very difficult to find FETs that can handle both low voltage and high current at a reasonable price point and small footprint. If this circuit was not going to be duplicated then this design might be practical, but it must be replicated 6 times on a limited amount of space. As a result, it was decided that an H-bridge will have to serve this purpose.

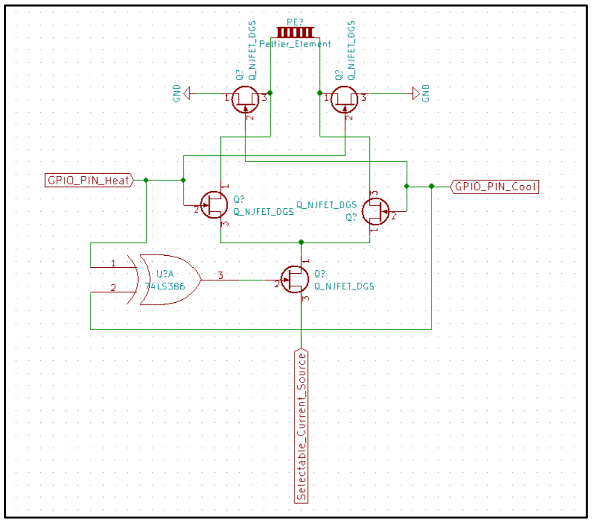


Figure 8: Tentative Schematic of the Directionality Controller

8.6: Switching Direction Using an H-Bridge

H-Bridges are essentially packaged N-FET switching schemes as previously described. They allow for voltage to be applied across a load in opposite directions and can have many unique properties.

The design considerations used in selecting an H-bridge are as follows. It must be able to supply a relatively high current at relatively low voltage (approximately 1.5 amps at 3.7 volts). It must have a relatively small footprint since it will have to control 6 Peltier devices. Finally, it must be relatively cheap, less than approximately $3 per unit. One of the main issues with using the FET solution was that the FETs that could meet all the criteria were so expansive as to be ruinous to this project.

Fortunately, a low voltage high current H-bridge was found that fit all of the required specifications. The DRV8836 Dual Low-Voltage H-Bridge by Texas Instruments is able to output a maximum current of 1.5 amps with an operating supply voltage of 2 to 7 volts. It has a selectable phase/enable or in/out interface that allows for changes in the polarity of the current by changing the phase or changing the high low pins respectively. Most importantly it has a small package size at 2 x 3 mm. Finally, it is cheap at approximately $1.5 per unit. The only drawback is that the Enable of the H-Bridge must be at least half of the supply voltage. This is not a huge concern since it will just change how the in-series resistor on the Peltier line is selected. It is more advantageous to have a lower temperature range than a higher one in this application. The DRV8836 has a sleep mode that will be continuously on to save power but will deactivate as soon as any of the GPIO pins that control voltage to its two channels activate. Figure 9 shows the application schematic of the DRV8836 when driving a device at up to 3 amps. Note the dual channels, which in this application will be used to drive two separate Peltier devices [5].

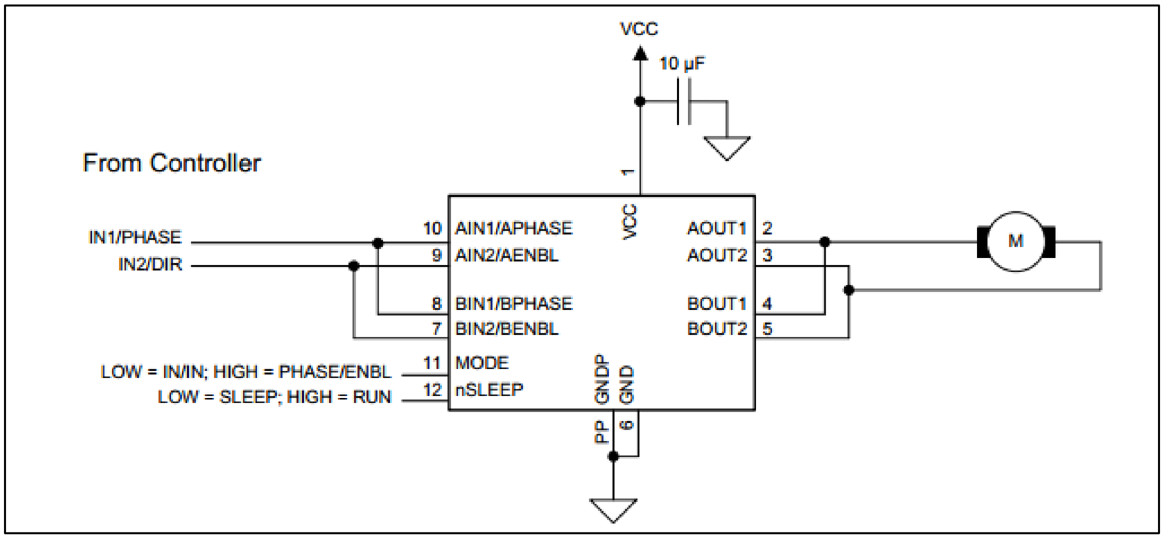


Figure 9: Application Schematic of the DRV8836

8.7: Controlling Magnitude with a Digital to Analog Converter

The magnitude of the current may be driven by the input voltage and the inherent resistance of the Peltier device ~2 ohms including the resistance of each FET switch which would be about 0.1 ohms each. To be able to control that voltage digitally we must implement a digital to analog converter circuit. In this case we chose to implement a Summing Amplifier type digital to analog converter. Using 4 GPIO pins to control 3 N-FETs allows us to pull from a 2-volt rail it will allow us to control the magnitude of the Peltier device with enough granularity to provide realistic feedback. Figure 3 shows the tentative schematic for the digital to analog converter that will drive the Peltier device. Note that it takes advantage of a summing circuit design allowing granular selection of exactly what voltage we would like it to produce according to the Equation 1. Where voltages 0 through 3 are all equal to 2 volts. Table 1 shows the binary states and the voltages they will produce when each line is attached to a 2-volt rail.

$$V_{out} = -\frac{1}{8}(8V_0+4V_1+2V_2+V_3)$$

Equation 1: Digital to Analog Converter

v0	v1	v2	v3	Total	V = 2 Volts
0	0	0	0	0	0
0	0	0	1	-0.125	-0.25
0	0	1	0	-0.25	-0.5
0	0	1	1	-0.375	-0.75
0	1	0	0	-0.5	-1
0	1	0	1	-0.625	-1.25
0	1	1	0	-0.75	-1.5
0	1	1	1	-0.875	-1.75
1	0	0	0	-1	-2
1	0	0	1	-1.125	-2.25
1	0	1	0	-1.25	-2.5
1	0	1	1	-1.375	-2.75
1	1	0	0	-1.5	-3
1	1	0	1	-1.625	-3.25
1	1	1	0	-1.75	-3.5
1	1	1	1	-1.875	-3.75

Table 11: Peltier Device DAC Voltage

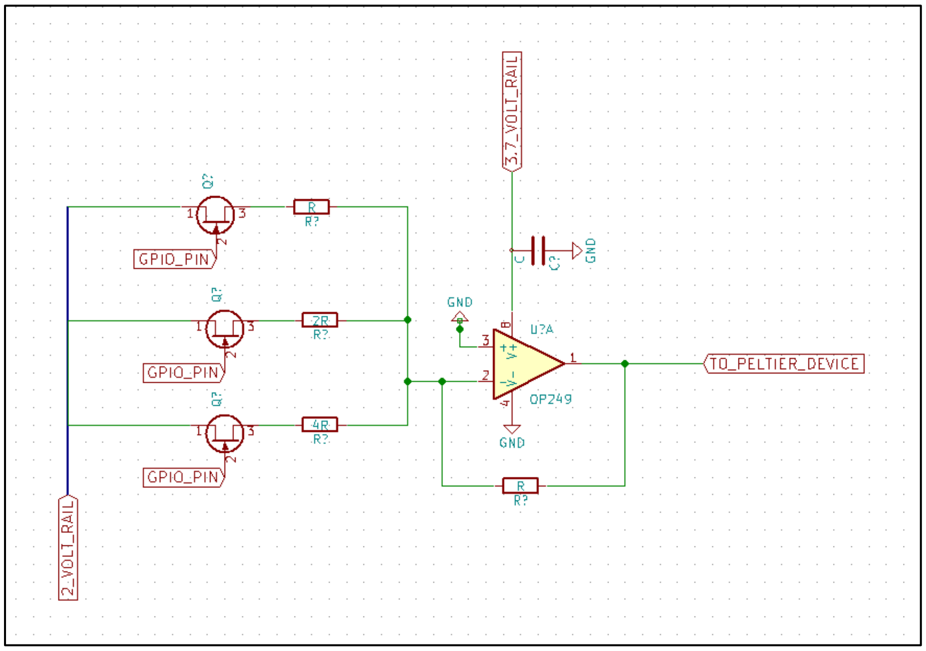


Figure 10: DAC Schematic

8.8: Controlling Magnitude with a Digital Potentiometer

A digital potentiometer could also control the Peltier device. Digital potentiometers work similarly to an analog potentiometer except the digital versions we have examined use I2C registers to control the resistance of the device. It should be noted that I2C is not the only control method but is the one we will be using since we already plan on using I2C extensively in the device. For example, a digital potentiometer may be sold with a resistance of 2.5kΩ and 256 steps. This would mean that resistance can be controlled to a resolution of approximately 10Ω. In this case resistance would be rounded to the nearest integer resistance value in software. Figure 11 shows the tentative schematic for the magnitude control scheme. The circuit in Figure 11 has 4 parts which are the switching circuitry, the voltage divider, a unity gain buffer, and an inverting amplifier.

A GPIO controlled switched that takes advantage of the properties of both P-FETs and N-FETs to avoid a third logic state. The third logic state in this case is if the main switching FETs gate voltage is not sufficient to place it in the saturation region. In this case the FET would not act wholly like a switch but have some other logic which is quite undesirable. To avoid this a PFET is held high by tying it to the rail (PFETs are closed when the gate is in the saturation region). Then when the GPIO pin is brought high it opens an NFET that connects the PFET and ground. This ensures that even if the GPIO voltage isn't enough to fully open the NFET gate the voltage at the PFET gate will fall to ground or close enough and ensure that the whole circuit acts like a switch.

The voltage divider is the heart of this circuit. It uses a digital potentiometer (shown as a regular potentiometer in the tentative schematic) to vary voltage division and select what voltage is fed to the unity gain buffer. If the digital potentiometer is a 100kΩ with 8 bits of control, then it will have 256 steps or about 390Ω of resistance per step. At the lowest setting and having 3.7 volts fed to it the unity gain buffer will receive approximately 14 millivolts while the highest setting will see the unity gain buffer receiving 1.85 volts. The digital potentiometer will be controlled with I2C since we are already extensively using that communication protocol to control accelerometers. As long as the devices we choose don't have address conflicts then they can be easily added to the same I2C lines as the accelerometers.

The unity gain buffer is simply there to act as a high impedance buffer between the fluctuating switch and rail circuitry and the amplifier and Peltier device. The amplifier is simply an inverting amplifier with a gain of 2 to offset the division by the voltage divider. This means that at the lowest setting the Peltier device will receive 28 millivolts and at the highest setting it will receive 3.7 volts.

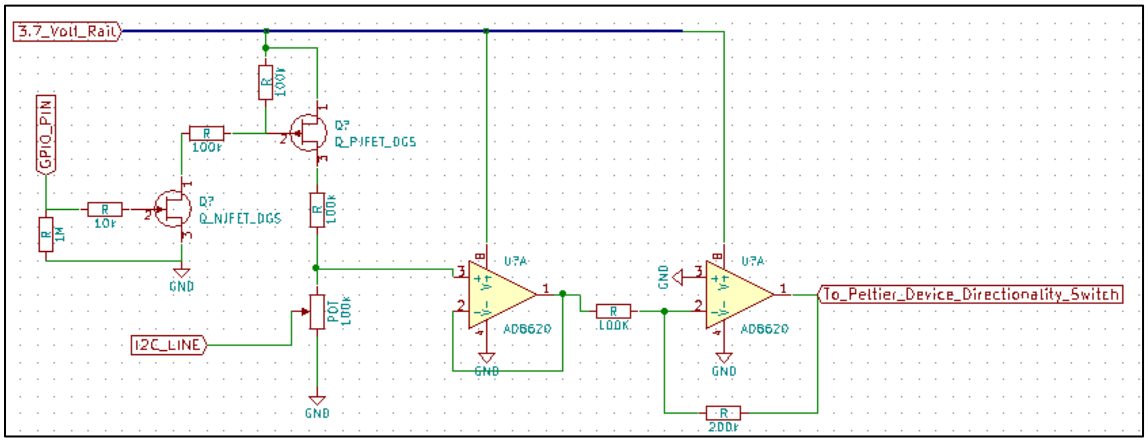


Figure 11: Potential Peltier Device Schematic

8.9: Digital Potentiometer Part Selection

There are three main parts that must be selected for the digital potentiometer control scheme to properly function. The digital potentiometer, the operational amplifiers, and the switching FETs. The resistors are considered trivial since only their footprints will matter and that will most likely be 0805s since they are small enough to maximize space but large enough to easily place by hand if necessary.

The digital potentiometer was selected by the following criteria: resistance, footprint, I2C control, and price. The part that was decided upon was the AD5248 by Analog Devices. The AD5248 is a dual, 256 position, I2C compatible digital potentiometer. It has a small footprint of 3mm x 4.9mm and can is I2C controlled. It has a resistance of 100kΩ and can be powered by a 3.3-volt rail. At $2.81 per unit it is rather expensive for a component however since it can support two separate, controllable 100kΩ wipers per unit it is more realistically for this project calculated as $1.4 per unit since half as many are needed to fulfill the project requirements. Figure 12 shows an internal block diagram of the AD5248. The internal block diagram shows how this part can be used as two separate potentiometers for this projects purpose [6].

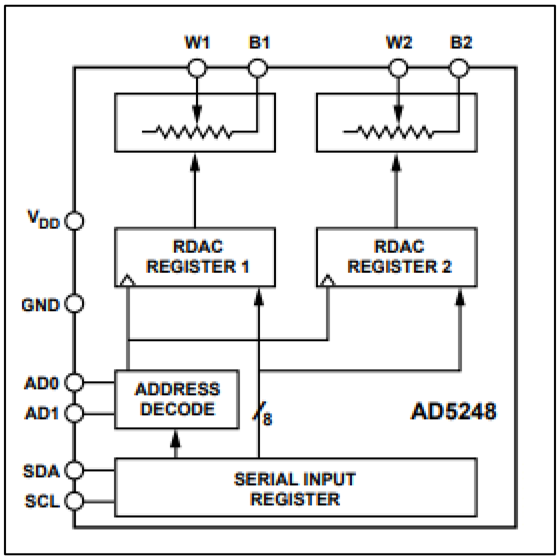


Figure 12: Internal Block Diagram of the AD5248

8.10: Operational Amplifier Part Selection

The need for the operational amplifier as shown in Figure 13 is twofold. It is needed as a high impedance buffer and as an amplifier. The amplifier is to correct the voltage division to its proper voltage while still allowing the divider to control the voltage while the high impedance buffer is used to prevent any unexpected interplay between the amplifier and the voltage divider. For this reason, the parts selection was not rigorous since the application is not particularly rigorous. A general-purpose rail to rail low power operational amplifier was selected. Specifically, the TSV321 was selected, though for implementation the TSV324IDT will be used since it has 4 operational amplifiers in each package. The driving qualities that led to this selection were low power and price. The TSV321 produces an output current of approximately 80mA which will allow it to be used in both the Peltier controller but the vibrational motor controller as well. At a price of $0.58 per unit in the 4-unit package it is quite cheap. It can also be operated on a single rail 3.3-volt supply. Since it will used for buffering and amplifying small discrete voltage changes over a relatively long period of time the slew rate should not impact the design. Figure 13 shows the internal structure of the 4-part package that will be implemented in the design [7].

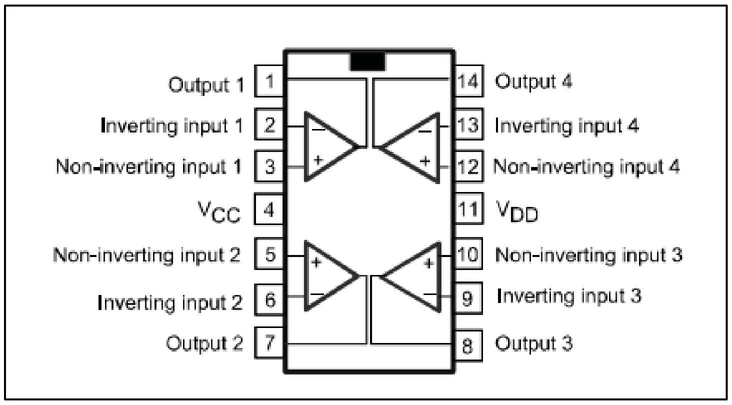


Figure 13: Implementation Diagram of the TSV324IDT

8.11: Switching FET Circuit and Part Selection

To properly act as a switch any FET solution must only have 2 states, on and off. To ensure this the circuit shown in Figure 14 was developed. It uses both a PFET and an NFET to ensure that the PFET which is the ‘switch’ opens fully and stays in the FET’s saturation region. It does this be holding the PFET high until a the NFET’s gate is brought high. When this happens the NFET opens and pulls the gate of the PFET to ground. This opens the PFET and allows current to travel through the semiconductor.

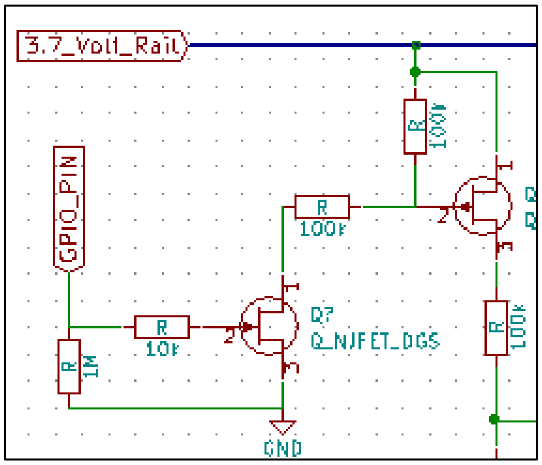


Figure 14: FET Switching Circuit Schematic

The part selected for this task was a dual channel NPFET. Specifically, the NX3008CBKS was selected. It was selected since the design team had worked with them in the past and was confident that the switching circuitry would work reliably for almost all conditions within the glove project. Figures 15 and 16 show the current characteristics for both the

NFET and PFET portions of the NX3008CBKS. Since almost all of the switched potions of this design go to high impedance devices large amounts of current do not need to be switched [8].

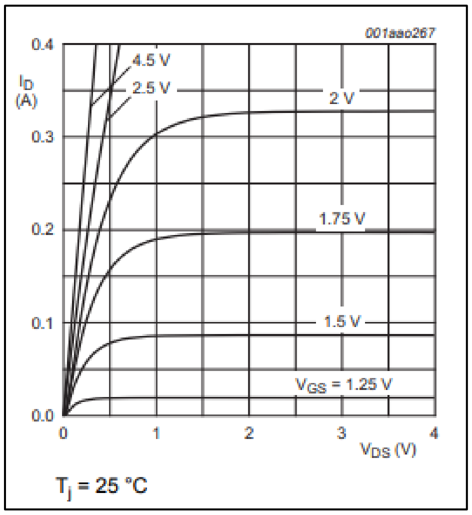


Figure 15: Drain Current vs Drain Source Voltage as a function of Gate Source Voltage for the NFET

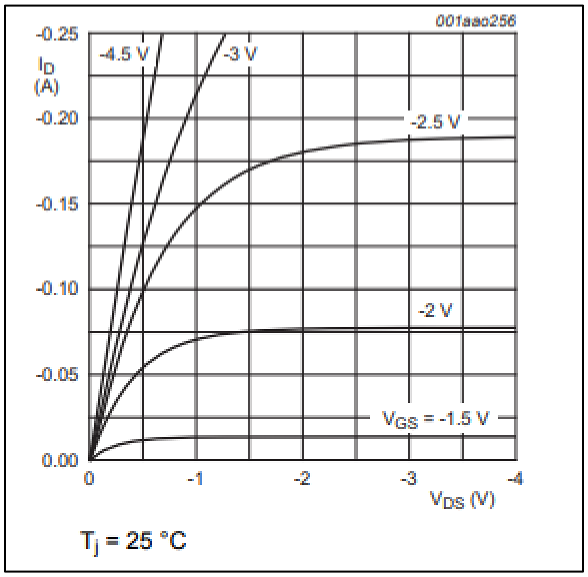


Figure 16: Drain Current vs Drain Source Voltage as a function of Gate Source Voltage for the PFET

8.12: Controlling Temperature of the Peltier

To properly control the temperature of the Peltier device a proportional integral derivative controller should be implement (PID), but as can be seen from the following discussion a full PID controller is not necessary.

A PID controller is a loop feedback controller that calculates the error value between the current state of the device and the desired state. It does this by applying adjustments based on proportional, integral, and derivative error terms. The overall function can be viewed in Equation 2. Which shows the output change in the device u(t) is a function of the sum of proportional, derivative and integral errors [9].

$$\boxed{u(t) = K_{\mathrm{p}} e(t) + K_{\mathrm{i}} \int_0^t e(t')\,dt' + K_{\mathrm{d}} \frac{de(t)}{dt}}$$

Equation 2: PID Controller Equation

This equation is not wildly useful in and of itself, graphs that show the impact of each term are more useful. Figures 17 through 19 show the impact of the proportional, integral, and derivative terms on the response of a generic device.

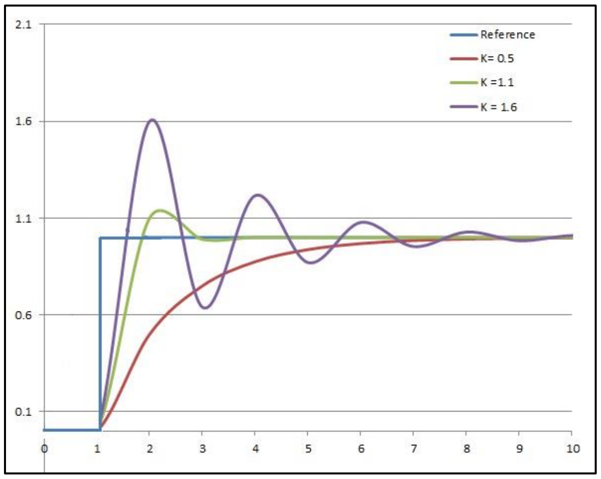


Figure 17: Impact of the Proportional Term on a Generic Device

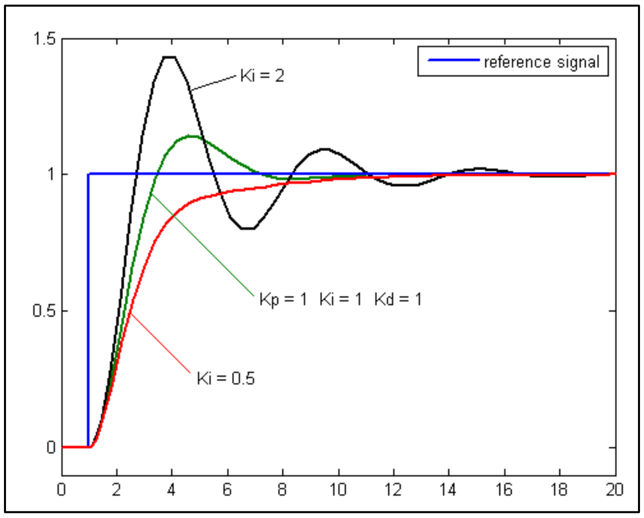


Figure 18: Impact of the Integral Term on a Generic Device

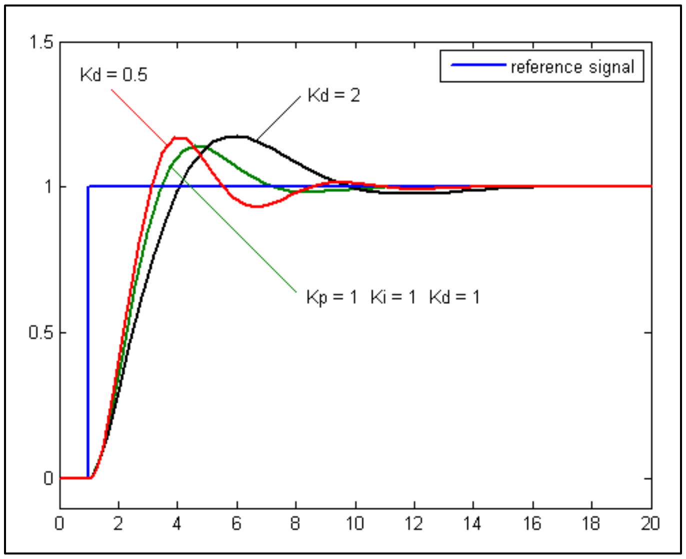


Figure 19: Impact of the Derivative Term on a Generic Device

From examining these graphs, the proportional term is what generally drives the response however it is either very vulnerable to overshoot or reacts very slowly. The integral term impacts the oscillations by damping them down quickly. The derivative term greatly decreases the response time of the system in reaching its desired value and greatly reduces overshoot. Combined these terms result in a system with a low response time, low overshoot, and heavily damped oscillations.

In most applications that use a Peltier device a low response time, low overshoot, and heavily damped oscillations are ideal and often necessary. For example, precision is needed in an application where Peltier devices are used as to cool computer processors. Specifically, the microchip's temperature will vary wildly depending on its computational load. To respond to this and keep the chip cooled to its very exacting temperature requirements means that the Peltier control system must respond quickly to perturbations, the responses must be quick, the responses cannot overshoot, and the responses cannot oscillate. Failure to meet any of these conditions could lead to permanent damage to the processor, and in these applications a PID controller is needed.

Applying Peltier devices to temperature in a haptic feedback system is not a precise system with large temperature perturbations. The human hand cannot tell the difference between 55°C and 59°C. Neither can the human hand tell the difference between a 10°C temperature change over 10 ms or 100 ms. Imprecision of that magnitude would be ruinous in the processor application but is not even noticed in the application of haptic feedback. This means that the system can have a relatively low response speed and that oscillations of several degrees are acceptable. From this information it seems that a full PID controller is unnecessary and that a simple low gain proportion controller will suffice. The controller must be low gain ($k < 1$) to prevent large overshoot. This will result in a very slow response time but since the human body operates on a very slow time scale relative to electronic components and mathematical feedback systems it will not be a concern.

8.13: Thermistor Selection and Implementation

To implement this feedback system the team will take advantage of the built-in analog to digital converter on the STM32F030C8. Figure 20 shows the schematic that will be used to measure the temperature. This schematic shows a basic voltage divider with a 100 kΩ resistor in series with a 10 kΩ thermistor. As the temperature increase the resistance of the thermistor will decrease and less voltage will be read by the ADC. The thermistor will be a NXRT15XH103FA1B040 [10] which is a thermistor with 10 kΩ of resistance at 25°C and a max power of 7.5 mW. It has a B value tolerance of 1% and a B25/50 of 3380K. The B value is the temperature change coefficient as shown in Equation 3. In Equation 3 the R_R value refers to the resistance at room temperature (25°C) which in this case is 10 kΩ. The STM32F030C8 has a 12-bit ADC which will allow for high milli-degree accuracy in reading the temperature from the thermistor. Figure 21 shows a block diagram of the control scheme that will be implemented to control the Peltier Device. The actual adjustments and gain of the system will be implemented in the software of the processor.

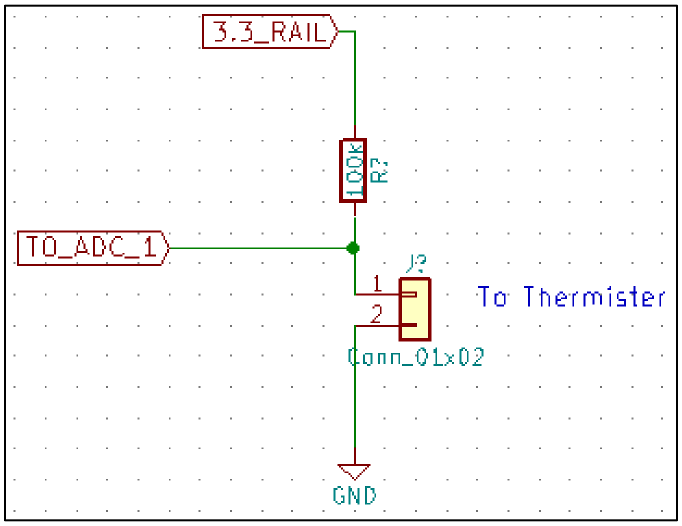


Figure 20: Schematic of the Thermistor Temperature Voltage Divider

$$\boxed{B = \frac{T \cdot T_R}{T - T_R} \cdot \ln \frac{R_R}{R_T}}$$

Equation 3: Equation Relating Temperature Variation and Thermistor Resistance

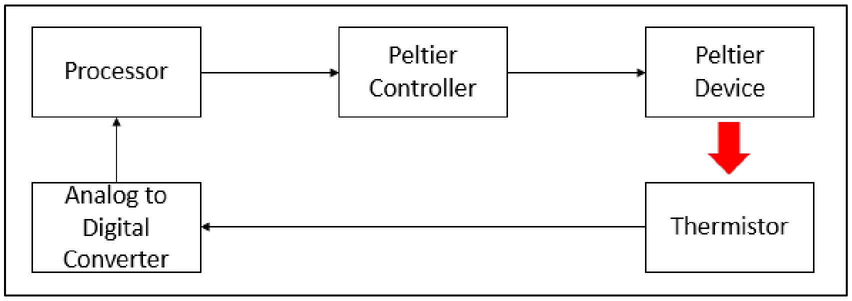


Figure 21: Block Diagram of the Peltier Feedback and Control Mechanism

8.14: Final Peltier Controller with Enable and Phase

The Peltier device will be controlled by the schematic in Figure 22 All previous schematics were tentative and have contributed to the design of this final layout. Note that this schematic can control two Peltier devices, but the second device has not been added in for clarity's sake. This schematic consists of five distinct parts. The P/N dual channel switch is the first part that will be discussed. It is as described in the Switching FET Circuit and Part Selection. Essentially as the NFET's gate is brought high it opens a channel to ground from the gate of the PFET and forces a full opening of the PFET. This in turn opens voltage to the I2C controlled digital potentiometer which creates a voltage divider based on the set resistance. This voltage feeds into a high impedance buffer to ensure that there is no interplay with the next steps. Following the buffer is a non-inverting operational amplifier with a gain of 2. Since the maximum voltage the voltage divider can produce will be half of the 3.3 rail, this amplifier is there to rectify that since the Peltier device should be able to take up to 3.3 volts. Finally, this voltage feeds into a high impedance H-bridge. The H-bridge has a low power sleep mode from which it is awakened when either FET switch for the two Peltier's it controls are activated. The phase shift that will change the polarity of the current is controlled by another FET switch which is controlled by a separate GPIO pin. This makes the assumption that Peltier's on two adjoining fingers will have the same current polarity which though logical may not be the case.

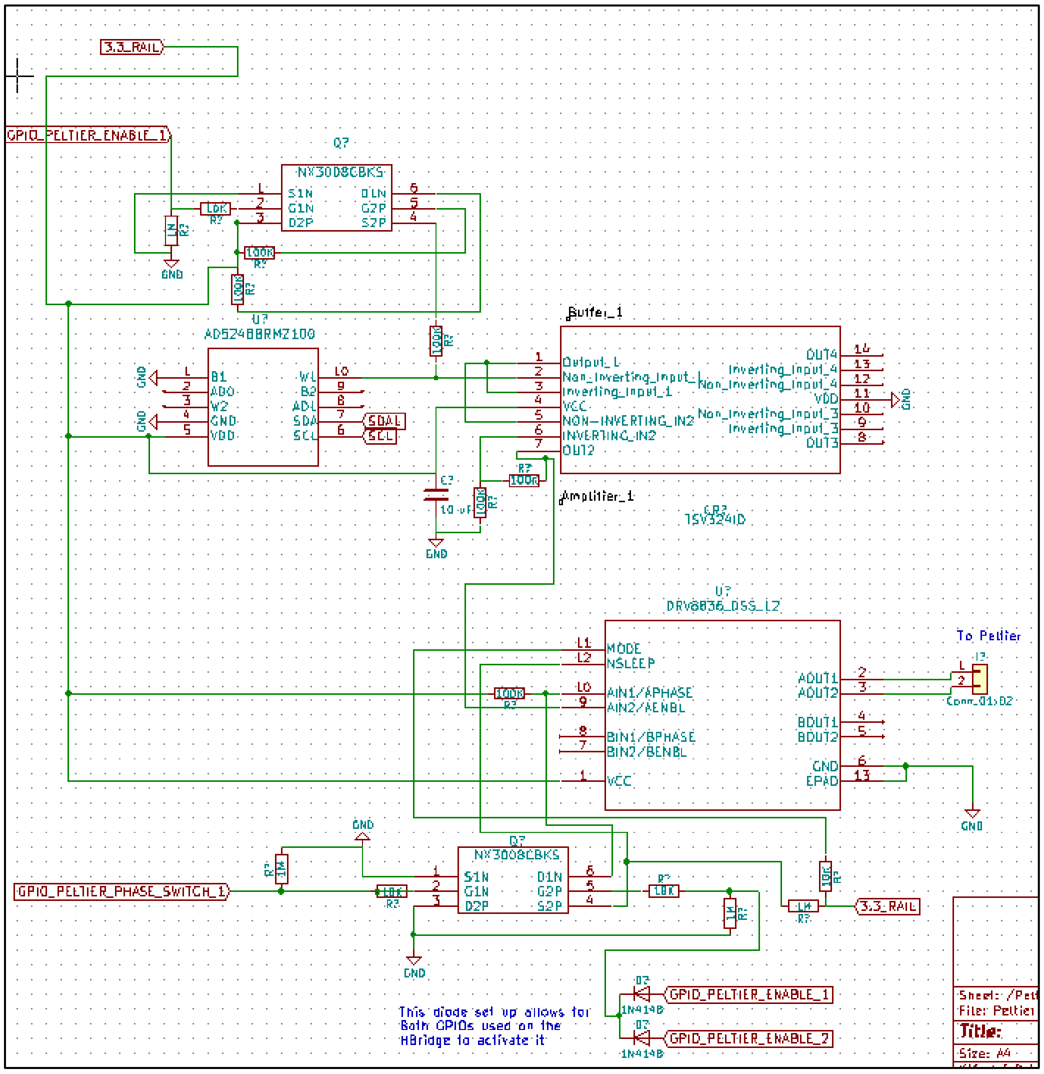


Figure 22: Final Peltier Controller Schematic

8.15: Battery Selection

The power supply of the wireless portion of the glove depends completely on the glove is completely dependent on the battery stack. The power each battery can supply is in turn dependent on the battery chemistry. There are several considerations to account for when selecting a battery. Will it be rechargeable or non-rechargeable? A rechargeable battery can be used multiple times and will allow for a more polished product while non-rechargeable batteries are cheaper but require constant replacement. In this scenario the constant expanse and hassle of replacing batteries in a high-power consumption device is prohibitive and therefore rechargeable batteries are the reasonable choice. For the glove application there are several varieties of rechargeable battery chemistries that we can consider. Each will be discussed, but our initial plan of 6 Peltier devices will require approximately 12-amp hours of battery capacity to operate at full power for 1 hour or 6-amp hours to operate at full capacity for 30 minutes. While the Peltier device will never be running at full capacity designing our power consumption around our highest draining device will allow for us to easily build the rest of the device while remaining within power constraints. Our initial specifications called for at least 30 minutes of run time so any battery selected will have to provide at approximately 6-amp hours while still being small enough to not exceed our weight requirements of approximately 2 kilograms total. We will not even consider some battery chemistries that are inherently dangerous such as lead acid and nickel cadmium. We will also not discuss alkaline chemistry batteries since they have a linear voltage drop off which is not useful for our application of running a microprocessor and peripherals as opposed to the voltage curve typical of the batteries we discuss in Figure 3. These come in standard packages (AAA, AA, etc.…) unless otherwise noted.

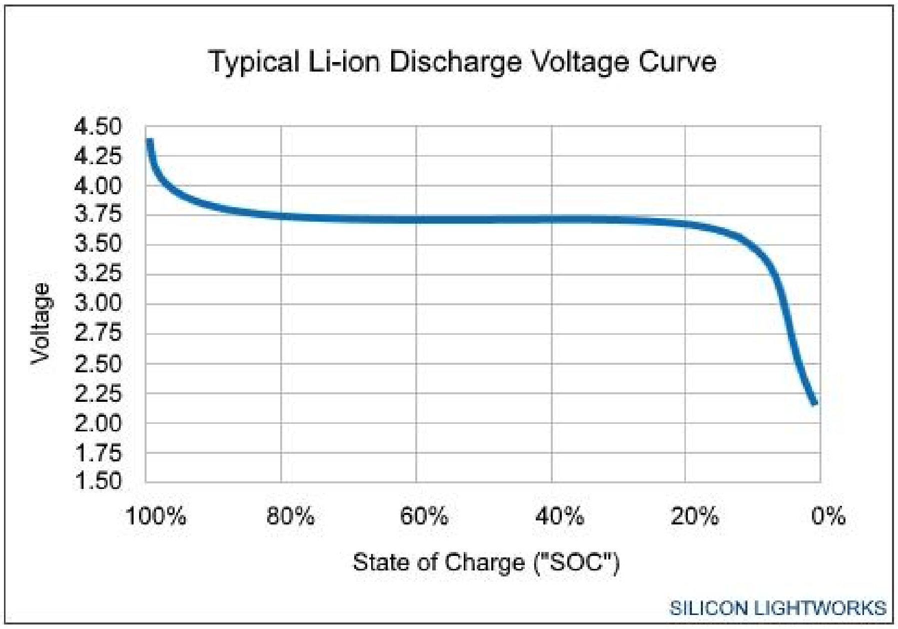


Figure 23: Li-ion Battery Voltage Curve [11]

8.15.1: Nickel-Metal Hydride

Nickel-Metal Hydride batteries are the first type of batteries we will consider. They are a commonly used battery chemistry in rechargeable applications. They are excellent for high drain applications and both common and cheap, so that finding a proper charger would be quite easy. Unfortunately, they hold a lower charge per weight than several of the other options. They of course need a specialized charger suited to their unique chemistry. They have a high self-discharge rate which means that they will lose charge just by sitting around. Low self-discharge rate versions are available but have lowered capacity. These come in standard packages.

8.15.2: Nickel-Zinc

Nickel-Zinc batteries hold a higher voltage per weight than their Nickel-Metal Hydride counterparts. However, they lose their capacity quickly as the batteries are cycled. They are also prone to failure and semi-discontinued. While it would be trivial to still purchase these and their charger, it is not good practice to choose parts that are on the verge of being unavailable.

8.15.3: Lithium Ion
Lithium Ion batteries are excellent choices for custom made electronics. All previously mentioned batteries can be purchased in standardized voltages. However, Lithium Ion batteries usually come in 3.7-volt packages. While this can destroy devices that are not designed for it we have the luxury of custom building our device. These batteries obviously hold very high charge per weight and are quite common and therefore inexpensive. The special chargers required for these batteries are also common and inexpensive.

8.16: Battery Choice

Unsurprisingly we plan on using a Lithium Ion rechargeable battery to power our device. In what amounts to a hand held or wearable device Lithium Ion batteries have some of the best charge to weight characteristics for a very competitive cost. This will reduce strain on the end users and is in line with our stated specification that the glove should not be more than 2 kilograms in weight. The battery will need approximately 6-amp hours to meet the specification of 30 minutes of use. Fortunately, a relatively lightweight, compact, powerful, and inexpensive battery is on the market. The ICR18650 6600mAh 3.7V 1S3P made by Shenzen PKCell Battery Co., LTD is perfect for our needs [12]. It has a mass of 155 grams and dimensions of 69 mm by 54 mm by 18 mm. It has a capacity of 6.27-amp hours and a working voltage of 3.7 volts. It can be charged to 4.2 volts which allows us to implement a cheap and easily obtainable Lithium Ion charger such as the CH-L3705 that is sold on batteryspace.com. Unfortunately, the maximum charging rate of the ICR18650 is 1650 mA which is not easily available (the best choice is the CH-L3718 but that has a charging current of 1800 mA). This means that either we use the CH-L3705 and accept that a fully charge from depletion will take approximately 18 hours of charging or we make our own charger. A different solution however would be to place two of these batteries in parallel and purchase a much stronger charger since the maximum charging rate of the batteries would now be double that of an individual battery. Since it will actually be about as expensive to develop a charger as it will be to purchase one and buy a second battery the choice is clear. We will stack two batteries in parallel and purchase a high-power charger.

8.17: Charger Selection

After careful consideration the charger chosen was the CH-L373 [13] from www.batterspace.com. It was chosen as previously mentioned because each battery had a maximum charging rate of 1650 mA and by placing two in parallel this would double to 3300 mA. Since the goal of this charger choice was to minimize charge time the only logical charger would take advantage of the 3-amp charging current limit. The CH-L373 does just this. It has a charging current of 3 amps meaning it will fully charge the battery stack in approximately 4 hours which is a huge improvement on previous options listed in the battery choice section. It is a lithium-ion specific charger, so it will fully charge batteries to 4.2 volts. The only downside is that it uses a Tamiya Female connector whoever this can be easily modified with wire strippers and a soldering iron to any connector type that will be more convenient for final construction. This charger has two built in LEDs to show charging status which will be convenient for charging the glove. Figure 24 shows the charger with out the AC power cord.

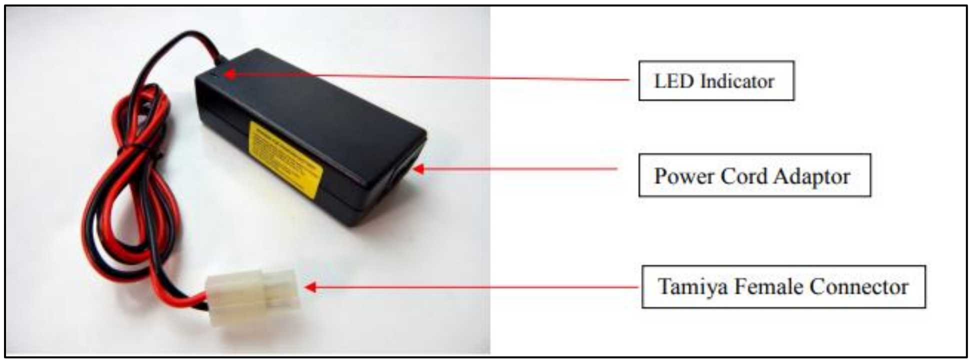


Figure 24: Ch-L373 Lithium-Ion Battery Charger

8.18: Power Regulators

All the devices specified for the glove control board can run off a 3.3-volt power rail. Unfortunately, the batteries output 3.7 volts and that voltage is unstable in any case. The solution to this is to implement a voltage regulator circuit. Within voltage regulators there are several options of how to design the circuitry to receive the necessary result.

8.18.1: Regulator Selection

As Dr. Weeks once said "Don't build your own oscillators. You can't build one that's better than what you can buy for 40 cents.", and the same is true of voltage regulators in the case of this project. It would be trivial to design a voltage regulator circuit, however there a perfectly good high efficiency regulator that can be purchased in tiny package sizes for very small amounts of money. Specifically, Texas Instruments Test Bench utility was used to select an ideal high efficiency regulator. The parameters for the search were that it must include high current capabilities since, it must be 3.3 volt compatible on a 3.7 to 4.5-volt input, and it must be high efficiency even at low output current. The resultant regulator was the TPS62823 which has an input voltage of between 2.4 and 5.5 volts with a max operating current of 3 amps. Figure 25 shows the Efficiency vs Output Current graph for the TPS62823 while Figure 26 shows the application schematic. As can be seen on the efficiency graph the TPS62823 will not fall below approximately 85% efficiency even at low currents even though is expected that the current draw will be well above 100µA. The application schematic shows that the implementation of the TPS62823 will be straightforward despite the requirement for a 470nH inductor. Since the TPS62823 comes in a 8-QFN package which is approximately 2x1.5 mm the inductor will be an order of magnitude larger than the regulator, however this means that all of the regulator circuitry will be able to fit snuggly into a very small area. The TPS62823 comes with a Power Good function, but it will be unused in this application. Figure 25 shows the TPS62823 with the charging and battery ports applied. Not the main power switch which connects the TPS62823 with the battery stack [14].

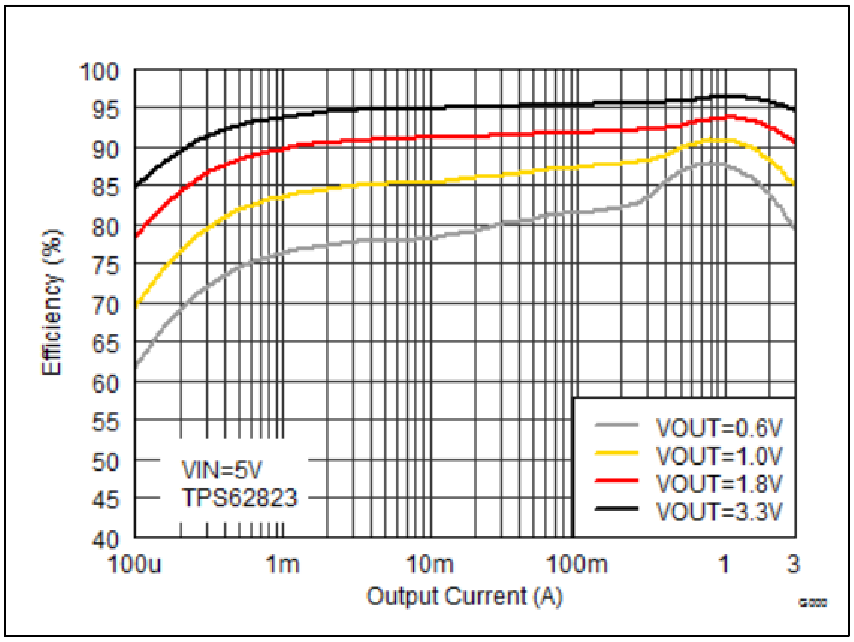


Figure 25: Efficiency vs. Output Current for the TPS62823

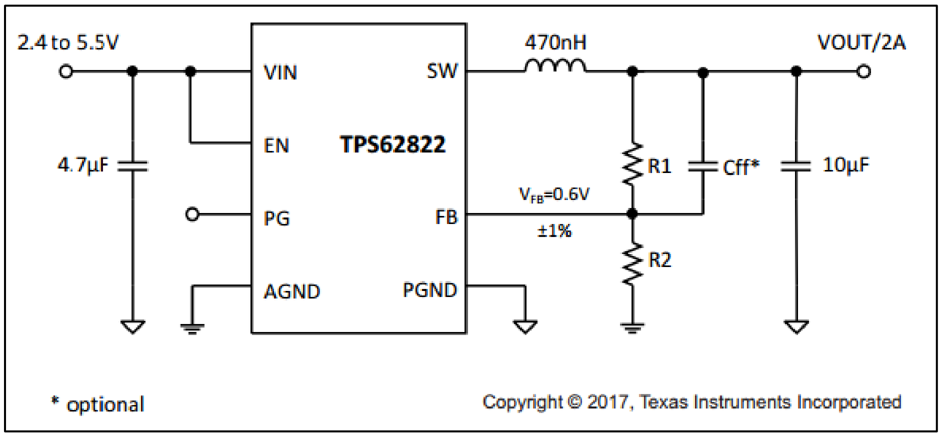


Figure 26: Application Schematic for the TPS62823

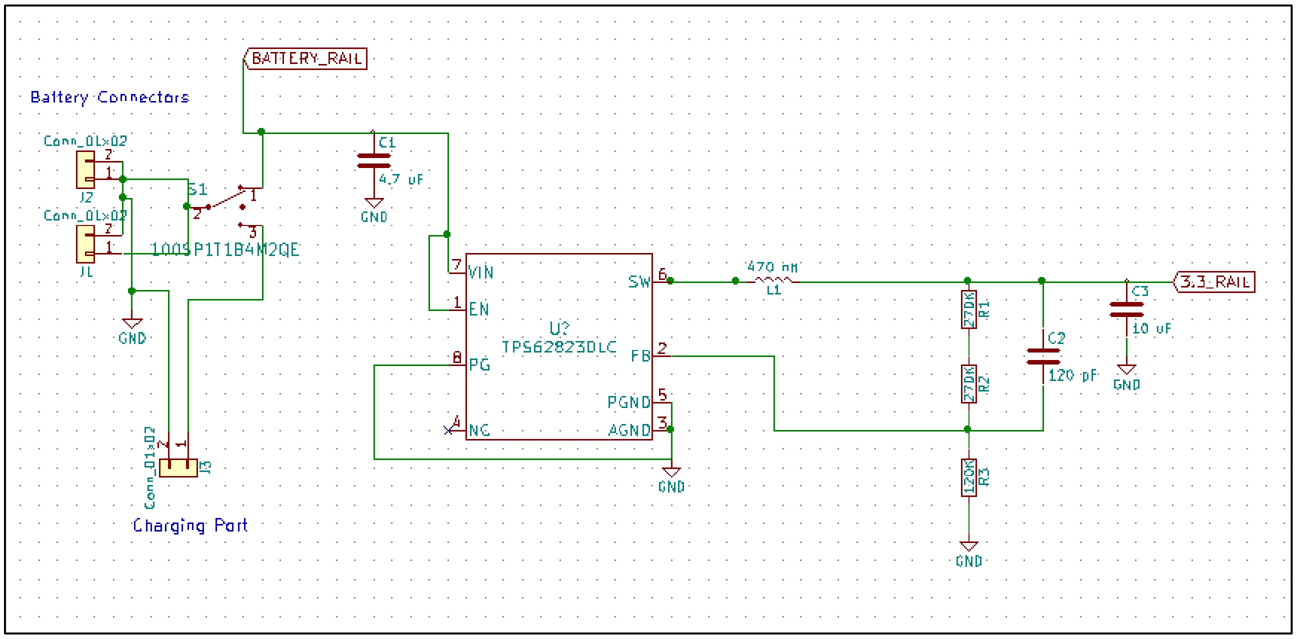


Figure 27: Schematic of the TPS62823 with battery ports and charging ports

8.18.2: Timing Regulator

The STM32F030C8 requires that the analog voltage (V_{DDA}) supply is available before the V_{DD} supply. Since this project will be supplying both voltages from the same rail a timing regulator was needed to operate a FET switch that would open the 3.3 rail to the V_{DD} supply after V_{DDA} received power. Essentially the timing circuit will be used as a delay before powering V_{DD}. The part selected was the MAX6897. This device was selected due to its small size and convenient supply power requirements. It would be operable from the battery rail and had a capacitor adjustable external delay. It is also relatively inexpensive at $1.38 per unit and the design only requires 1. Figure 28 shows the application schematic while Figure 29 shows the schematic of how the MAX6897 will be implemented with respect the STM32F030C8 power supplies. The timing delay equation is shown in Equation 4 and as seen in the schematic in Figure 29 will be set to approximately 60µs from the 5pF value [15].

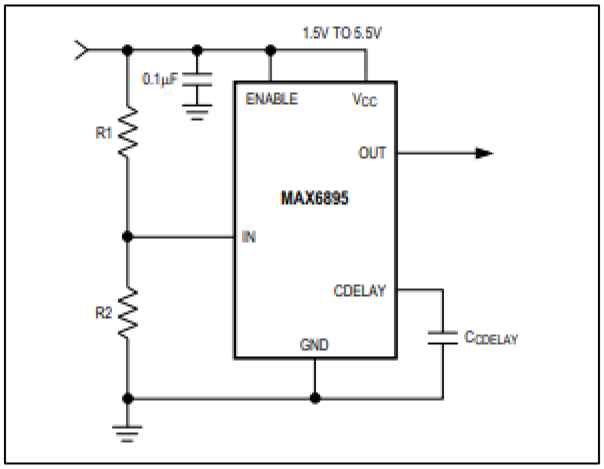


Figure 28: Application Schematic of the MAX6897

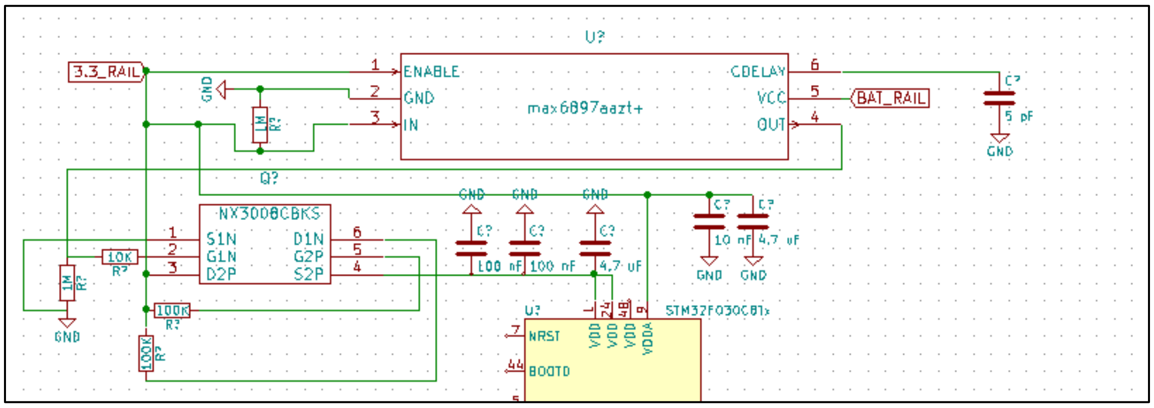


Figure 29: Implementation of the MAX6897 with respect to the STM32F030C8

$$t_{DELAY} = C_{CDELAY} \times 4.0 \times 106 + 40\mu s$$

Equation 4: Timing delay of the MAX6897

8.19: Housing

The actual housing for the electronics will most likely be implemented as a forearm mounted box. Inside the box will be the main board which will house the processor, the regulators, the GPIO controlled switches, the digital to analog converters, etc... Essentially all electronics except the haptic feedback motors and the Peltier devices will be included in this board. The batteries will also be included in this housing so for safety the base of the housing will include a small insulated steel plate. The rational for this is if the Lithium Ion batteries go into catastrophic failure the steel plate will prevent the user from sustaining a serious injury. In this case a catastrophic failure may be quite exciting, but it should not leave the end user with a debilitating injury like sitting on a Galaxy Note 7 might. The housing will also contain a power switch, a power LED which will display if the battery needs to be charged or not, a reset button that will calibrate the accelerometers in the glove, a Bluetooth status LED, and a safety shutoff button that will shut off power to all peripherals.

8.19.1: Light Emitting Diode

As the battery enables power to the system a red LED will enable and remain on until the power switch is placed back in the off position. This will indicate that the 3.3 Rail is active and that the power regulator is functioning properly. When the processor finishes booting it will activate a GPIO pin that will activate an N Channel FET, the BSS138, which will allow current to the LED. Since both the red, green, and blue LEDs are contained in the same housing the light emitted will change in purple or another color and this will let the user know that the glove is now ready for use. The LED selected for this role was the WP154A4SEJ3VBDZGW/CA manufactured by Kingbright. It is a 5mm tri color LED with a relatively small package size. It is 9.6 mm in height and has a through hole mount. Each LED must receive 20 mA to function properly. The following figure shows the tentative schematic for the circuitry involved in activating this LED. It is a common anode LED which means that the red, green, and blue LEDs encased in the housing all share the same positive node. This means, as can be seen in the design that any switching must occur after the LED as the current moves toward ground. This design will need to be thoroughly tested in accordance with the test section later in the document. Design changes may be necessary after testing has concluded [16].

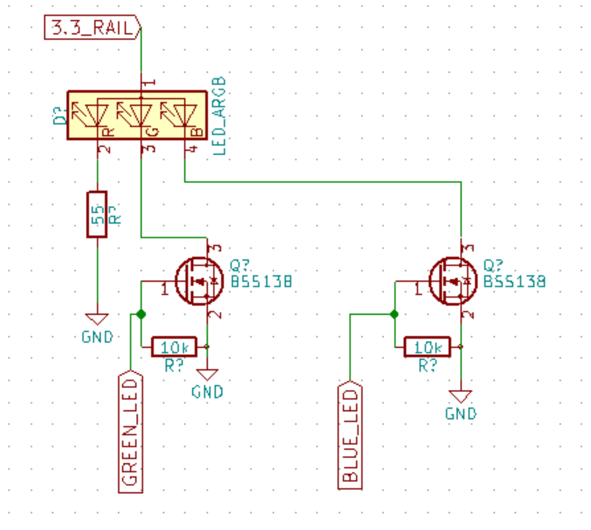


Figure 30: Schematic of LED Control Circuitry

This LED was relatively expensive for an electronic component at $2.05 per unit. Though since this part is only used once in the project that is acceptable.

8.20: Haptic Feedback

There are two main options for haptic feedback for our application. Eccentric rotating mass vibration motors and linear resonant actuators. Both have unique strengths and weaknesses that will be discussed in the terms of our application. Specifically, we want a small vibrational device that can fit on a gloved fingertip comfortably and vibrate at various intensities. We are hoping to control this device with either a digital to analog converter or more realistically the same magnitude control setup we are using to control the Peltier device.

8.20.1: Linear Resonant Actuators

Linear resonant Actuators or LRAs are a type of vibrational device that operate similarly to how a headphone or a speaker operates. Specifically, they use a coil to generate a magnetic field and repulse a rare earth magnet. This repulsion force presses up against a mass which in turn presses against a spring. By using an AC signal or a pulse width modulated signal it is possible to drive the LRA to vibrate at some frequency. There are several downsides to LRAs however. The two most concerning to our application is that LRAs need pulse width modulated signals or AC signals to operate and that they are very inefficient when not operated at their resonant frequencies. Creating pulse width modulated signals or AC signals is trivial however it requires extra hardware and programming that may not be necessary for what is in effect the simplest peripheral on an already complex device. Despite this the efficiency issue is more concerning. The resonant frequency is a frequency of operation at which the impedance of the internal capacitor and winding inductance is balanced. This results in optimal force being applied to the vibrating mass. However, when the device is operated at a different frequency then efficiency falls off dramatically. Our device calls for a range of operational vibrational frequencies and as such it does not appear that linear resonant actuators are the best fit for our application. They are much better for haptic response where you want a small package that gives a consistent vibrational response at a certain frequency, such as cellphone haptics.

8.20.2: Eccentric Rotating Mass Vibrational Motors

Eccentric rotating mass (ERM) vibrational motors are exactly what they sound like. A small electric motor with an unbalanced weight at the end. The rotation of the weight generates the vibrations that we perceive as haptic feedback. These devices work exactly like traditional electric motors. By supplying more voltage, or current depending on the specifications, we can control the magnitude of the rotation. For our purposes this is precisely what we need. While it may be natural to imagine ERMs as electric motors with oddly shaped weights on the end this is only partially true. It may be true that you can purchase ERMs in that form factor, but that form factor is completely unusable for our application. Fortunately, coin type form factors and encapsulated form factors are also manufactured. While encapsulated form factors are not ideal for our applications since they are essentially the electric motor with a weight but now with a plastic sheathing, the coin type form factors are perfect for fitting to finger tips. Of course, these aren't the perfect component in every way and there are tradeoffs to be made between the coin form factor and other form factors. Specifically coin form factor ERMs have a higher maximum start voltage, which is the minimum voltage required to consistently start the motor. Fortunately, this will not be a major issue since we can account for the higher initial voltage when designing the control circuits for the haptic response.

8.20.3: Haptic Feedback Part Selection

From the previous sections the haptic feedback device best suited to this project is a small coin package ERM. The main criteria for this part selection was size, cost, and operational voltage. The part that was selected was the C0720B015F produced by Jinlong Machinery & Electronics, Inc. Its package size is small enough to fit on the tip of a finger at 7mm in diameter and it has an operational voltage of 2.7 to 3.3 volts. The price is a little high at approximately $3.54 per unit however this is a part that only need to be purchased six times so to total cost for the part remains around $20 which is acceptable for a part of this importance. The motor will be controlled in a similar manner to the Peltier device with a digital potentiometer controlling a voltage divider that feeds into two operation amplifiers. This will result in the proper voltage but low current which is acceptable since the C0720B015F has a maximum current rating of 80mA. This is possible since as previously stated the TSV321 typically produces 80mA of output current. Figure 31 shows how the planned schematic for the implementation of the motor controller. Note that since the digital potentiometer (AD5248) and the operational amplifier (TSV321) have leads for another use or come in packages with multiple parts respectively, that a second motor controller could be implemented but was not for purposes of demonstration. Also note that the motor controller goes to a generic port since the actual motor will be connected to the board via wires as to better interface with the fingertips and to prevent the need to have bulky multi part packages on PCBs that rest upon the hand or fingers [17].

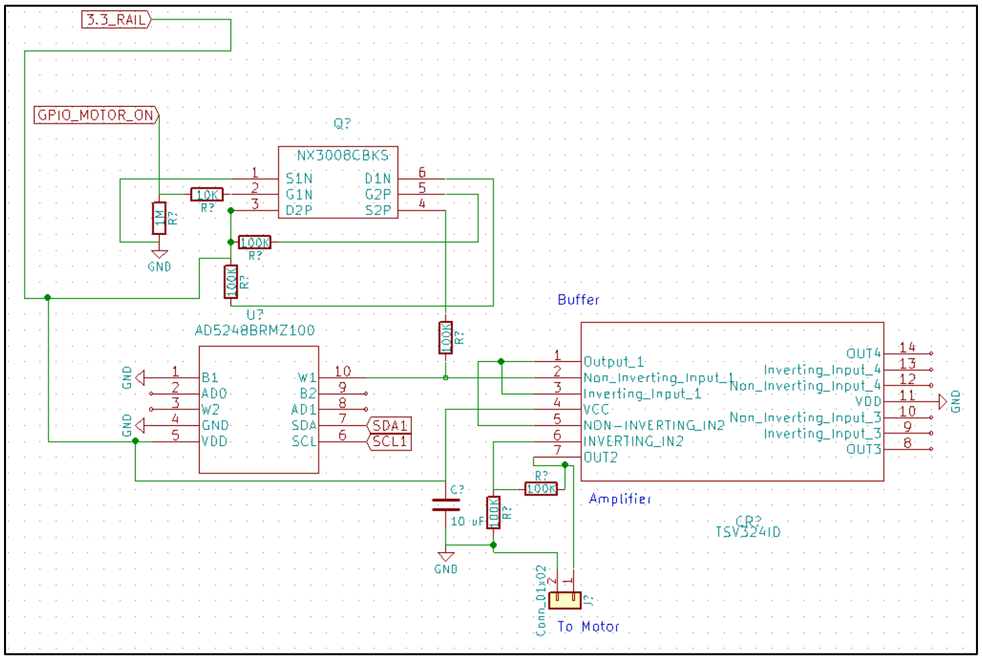


Figure 31: Motor Controller Schematic

8.21: Motion Tracking

There are several ways to track motion each of which have varying degrees of accuracy. Hollywood for instance uses strategically placed white dots to capture motion for CGI frameworks. This method would fall under the optical category of motion tracking. A mechanical method of motion tracking uses force sensors and rigid mechanical frames to track the force that the motion exerts on each piece of an articulated machine. We will not discuss mechanical tracking in any detail since as its name implies it is a mechanical structure and this is the Electrical and Computer Engineering Senior Design Course. A mechanical solution could even be optimal but would fail to demonstrate our mastery of electrical and computer engineering skills. Finally, inertial systems use a variety of electronic sensors to capture motion data. This data is usually wirelessly transmitted to a receiver where it is analyzed by a computer where it is processed into useable and understandable structures.

8.21.1: Optical Tracking

Optical tracking methods use cameras and reflective or light emitting nodes at various points to track motion. This is a high accuracy method since specialized high-speed cameras can achieve extremely high frame rates that can then be easily filtered to isolate the nodal motion from the reflective or light emitting nodes. This is the most commonly used method of motion tracking for consumer devices. For example, Hollywood uses high speed cameras, the Xbox Kinect uses an infrared camera and pulses of infrared light to track motion, and even the Nintendo Power Glove used high frequency sound and audio recovers to track its position using the Doppler Effect. While it would be possible to use this type of tracking scheme to interact with a 3D object, in order to receive haptic and temperature feedback almost all of the circuitry and I2C communication in the glove would still be required. It would also be very much a “me too” project that emulated existing commercial hardware and at that point why even bother developing our own motion capture system?

8.21.2: Inertial Sensors

Inertial sensors are a wide array of different sensors that capture motion of one kind or another. Common types of sensors include accelerometers, gyroscopes, and magnetometer. The main selling point of inertial sensors are that they require no external cameras or bulky equipment and are therefore popular with small self-contained devices and certain scientific equipment. For instance, in several of the microgravity labs at UCF accelerometers and gyroscopes are the only practical choice for data collection because it is impossible to fit bulky cameras or large force sensing equipment onto a rocket. We will be discussing accelerometers particularly in depth.

Accelerometers measure acceleration as the name would imply. They do this be measuring the force of motion exerted on an object of known mass. Newton’s Second Law tells us that force is a function of mass and acceleration while Newton’s First Law tells us that an object at rest will remain at rest until an outside force act upon it. Finally, Newton’s Third Law tells us that when one body acts upon another with a force, that second body will excerpt an equal and opposite force upon the first. With this information it is possible to calculate the acceleration of an object in a single plane from force by placing a small passive force sensor in that plane and allowing the force of the motion acting upon some small object of known mass. This allows us to back calculate wit very simple algebra the acceleration of the motion that generated the force. Of course, there are several methods for measuring the magnitude of the force.

There are two main methods for measuring the magnitude of a force in an accelerometer. The first uses capacitance to accurately characterize the magnitude of force applied. It is possible to do this because as the force upon the mass increases the capacitive plates are forced more closely together. This changes the total capacitance in the system which has an easily measurable response in any electronic system.

The second method for measuring the magnitude of a force in an accelerometer is to use a piezoelectric sensor. This type of accelerometer takes advantage of the piezoelectric effect. The piezoelectric effect is that when certain materials have mechanical stresses applied to them they generate an electrical charge or when those same materials have an electrical field applied to them they generate a mechanical change. Quartz in quartz watches are the most famous and commonly known example, but other examples may include crystal oscillators or inkjet printer heads. Essentially piezoelectric devices can be found anywhere that electrical systems need to control small mechanical motions.

8.21.3: Accelerometer Considerations

In our search for exactly the right accelerometer we needed to consider several aspects of the device. Our first consideration was the size of the device. It must be small enough to easily fit onto the tip of a finger along with several other components. The next aspect we had to consider was the price. It is quite possible to get some amazing high-quality accelerometers for precision scientific work, but those are expensive and we are not doing high quality precision work. We are developing what is essentially a consumer product. So, to stay within budget a cheaper model must be found since it will most likely not impact the end results of the project. The next aspect of the accelerometer we had to consider was it operable range. Many accelerometers have certain operable range settings where it is most accurate. Exceeding these range settings may mean you will not get useful or meaning full readings. For our application this was easy since hand motions will tend to stay in the ±2 G range. Any more than that will mean that the user is wildly and forcefully flailing their hands around which should be discouraged. The next aspect we must consider is the precision of data the device can record. These devices send out digital signals from an analog data source so they must have internal analog to digital converters. The number of bits they can record determines their level of sensitivity. We would like at least 8 bits of precision since that its 1 ASCII character and if we must read data from the device it will have to be in packets of 8 bits anyway. An often-unconsidered aspect we need to discuss is the data capture rate. We need to be able to sample at hard minimum of a 30 Hz sampling rate. Though it would be better to have a much higher rate than that. Another aspect to consider is the communication protocol the device uses. There are usually several different communication protocols to choose from depending on what you want to achieve We wish to use I2C since we want to communicate with several devices on the same data line and so the accelerometer we choose must be I2C enabled. Finally, we need the accelerometer to have a purchasable testing board so that we can test and implement our driver code without having to integrate the entire device beforehand.

8.21.4: Accelerometer Choice

In the end after carefully considering all the aspects listed in the previous section we have decided to implement the MMA8451Q, 3-axis, 14-bit/8-bit digital accelerometer from

NXP Semiconductors. Table 6 has a list of features that make this board desirable for our needs [18].

Feature	MMA8451
Max Sampling Rate	800 Hz
Communication Interface	I2C
Multiple Addresses	Yes, 2
Data Resolution	14 Bit
Package Size	3mm x 3mm x 1 mm
Price	$3.34
Breakout Board	Yes, from Adafruit

Table 6: Features of the MMA8451

As can be clearly seen from Table 6 the MMA8451 is very good for our application. Figure 32 shows how the chip must be applied in our circuit to function properly.

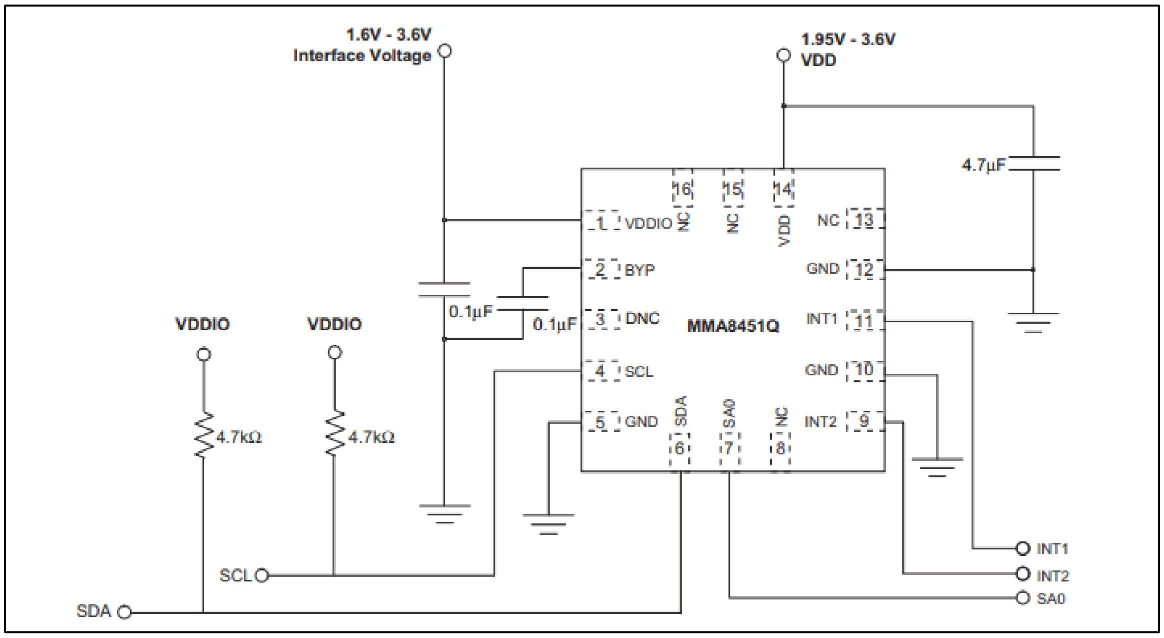


Figure 32: Implementation Diagram of the MMA8451Q

8.21.5: I2C Multiplexer

Since the MMA8451Q has only two possible addresses and the project requires 16 accelerometers an I2C multiplexer must be implemented. As referenced in Figures 3 and 4 the accelerometers and peripherals will be placed on 1 of 8 possible I2C lines. The part selected was the TCA9548A from Texas Instruments. The TCA9548A has 8 pairs of multiplexed I2C lines as shown in Figure 33. The TCA9548A can run on a 3.3-volt power supply and has a small package size at 7.8 x 4.4 mm. It can handle up to a 400 kHz clock frequency and all I/O pins are tolerant to 5 volts. Figure 34 shows the application schematic for the TCA9548A. Note that external pullup resistors are required, which is standard in I2C. Pullup resistors will be 1 kΩ which is near the minimum resistance specified by the data sheet [19].

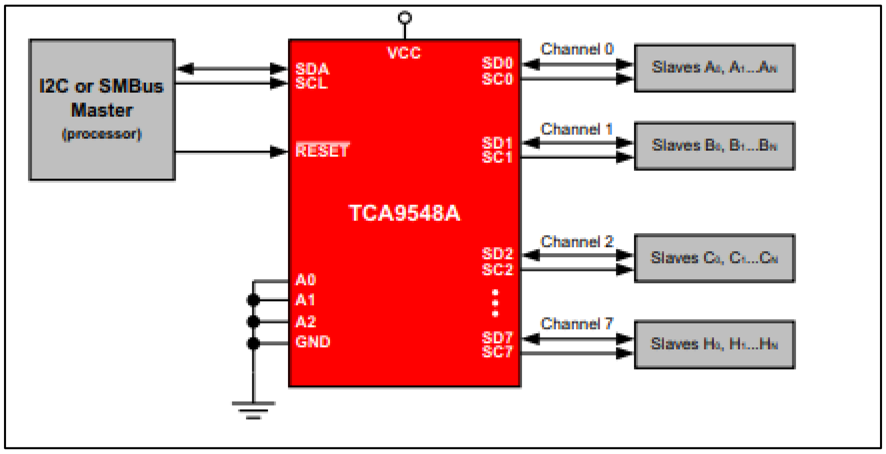


Figure 33: Simplified Block Diagram of the TCA9548A

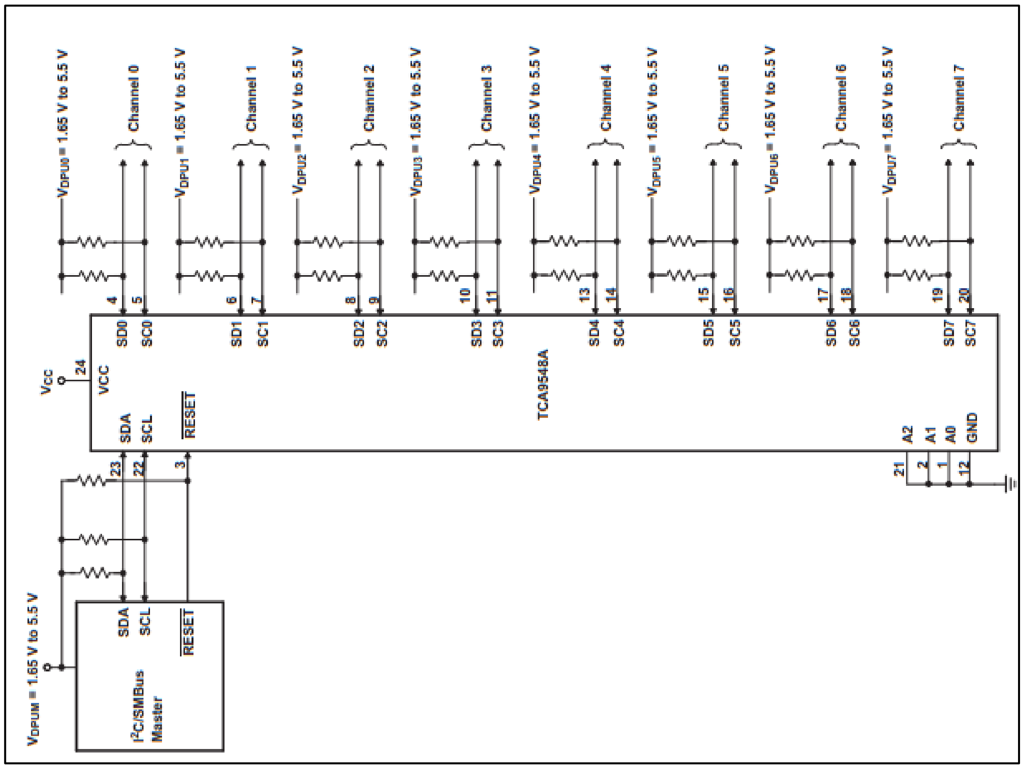


Figure 34: Application Schematic of the TCA9548A

9: Processing Board Overview

Our MITTS (Motion Interface Thermal Touch Sensitive) device will have a central processing board that will handle data gathering and delivery. This board will handle data needed from the sensors on the glove such as the accelerometers. It will also control the haptic response to the vibrational motors and Peltier devices for both resistive sensation and temperature changes. This board will also contain a Bluetooth device to send data through the UART standard to a computer for further data manipulation and processing.

9.1: Processor Comparisons

According to Umesh Lokhande's article on the *BinaryUpdates* website [20], he writes that some good parameters to look for and take into consideration for a microcontroller are: whether there are good resources available, whether it's economical, and whether it's easy to program.

Having good resources to understand our project more is a huge plus, especially for this design since we are working with things we haven't worked with before and trying to assemble a whole project with them. Hobbyist communities have step-by-step tutorials using the ATmega series and TI's MSPxx series, which makes them exceptional choices. However, these are not widely used in big manufacturing and/or MCUs designed for specific applications. For this reason, we wanted to go with an ARM device due to their wide use in the industry.

The ATmega series [21] and TI's MSPxx series [22] has a wide variety of cheap options in comparison to an ARM MCU but are slightly more expensive. While looking at the Mouser Electronics website for comparisons, the ATMEGA32U4-AU is more expensive with a comparison of $4.80 for a single unit whereas the STM32F030C8T6 ARM chip [23] is $2.02 for a single unit. The ATmega also has less I/O pin count than the ARM chip; the ATmega being at 26 I/O pins and the STM being at 39 I/O pins. The ARM chip also operates at a lower voltage with a 2.4-3.6 V compared to 2.7-5.5 V. As far as the TI MSPxx series goes, looking at a similar pattern, the MSP430G2553IPW28 is $2.59 for a single unit, has only 24 I/O pins, and fortunately operates at 1.8 – 3.6 V. The difference economically makes sense here since the STM32F030C8T6 is cheaper, has more I/O pins, and is decently low in voltage operation.

MCU	Cost	I/O Pins	Operating Voltage (V)
ATMEGA32U4-AU	$4.80	26	2.7-5.5
MSP430G2553IPW28	$2.59	24	1.8-3.6
STM32F030C8T6	$2.02	39	2.4-3.6

Table 12: MCU comparison Data According to the Mouser Website

I/O Pins **-** The number of I/O pins on the STM is greatly higher than that of the ATmega and MSP chip. This choice of picking the STM will allow us to add more input and/or output devices if further development were to occur. This concept is great for scalability and allows us not to have to change to a brand-new chip if we did need more I/O.

Memory Size **-** All three MCUs have FLASH memory, which as we know, is a non-volatile memory. Since the coding will be relatively simple, we should only need a little bit of memory to handle getting input and then sending that input off to something else. In our case, we are sending to a computer through a Bluetooth module, so we don't have to worry about memory there.

Chip	Memory Size (kB)	Data RAM Size (kB)
ATMEGA32U4-AU	32	2.5
MSP430G2553IPW28	16	.512
STM32F030C8T6	64	8

Table 13: Memory Comparison Data According to the Mouser Website

As we can see from the table above, even though the STM is the least expensive, it has the most memory in both regards. Clearly, this is an economical and logical choice.

Clock Frequency - As we are only looking to keep a frame rate of 30 frames per second, the speed that we need our clock to be isn't too significant, especially in today's standards.

Chip	Max Clock Frequency (MHz)
ATMEGA32U4-AU	16
MSP430G2553IPW28	16
STM32F030C8T6	48

Table 14: Clock Speed Comparison According To The Mouser Website

Again, we can see that, even though it's the cheaper option, this chip has a much higher (3 times higher) clock frequency than the other ones have. In the next figure, there is the details of the pinout of the chip itself. This will come in handy when integrated the circuit into the design. Knowing the pinouts on the board itself is essential in connecting components and assisting in the overall schematic design.

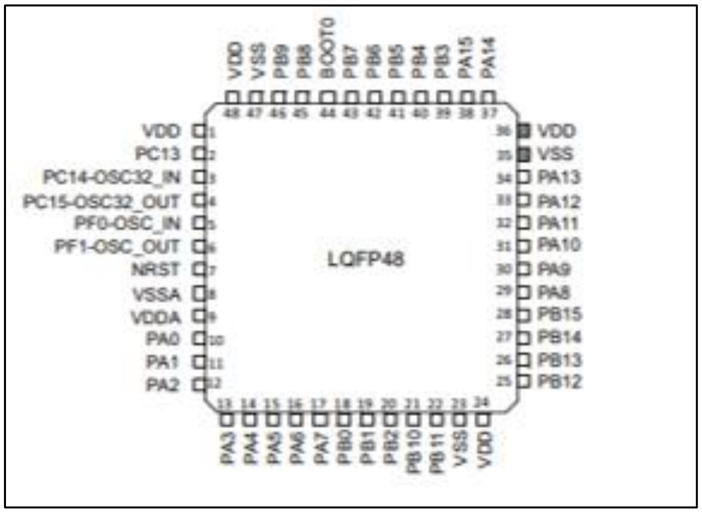


Figure 35: STM32 Pinout

9.1.1: The STM32F030C8T6

As a brief overview, the STM implements ARM, which is widely used in commercially manufactured products today, thus will provide us with real-world applicable experience. This experience will give us an edge on the job market and put us ahead for a potential career choice. Not only is the chip applicable, but it's a smart economical choice and will be very useful and efficient in our project. With high frequency rates and low cost, this chip is our first choice.

Multiplexers **-** There is one caveat to our choice and that is that there are not enough I/O pins on the board for us to read from or output to the devices on the glove. For this reason, rather than upgrading to a higher priced and bigger chip, we are going to make use of multiplexers. This will drastically decrease the number of I/O pins necessary. Since we can use a 3-8 or 4-16 multiplexer, we are only using 4 or 5 pins for input into the chip and also selection pins into the multiplexer. We can make use of the polling strategy in our case because of the high frequency of the chip and the easy 30 frames per second that we are trying to achieve.

STM32 Breakout Board - The design heavily relies on the STM processing board for further development. The 3D interface relies on the processor to give it the details of the accelerometers. The interface between the 3D interface also relies on this data. All of the glove components rely on the processor, not only to read data from them, but also to send data to them. For this reason, it's going to be very beneficial to get a breakout board, which essentially will act as our processing board since it uses the same chip. The exclusion of course will be that the board itself will not be the exact design, so things will change from the development to the physically made device. The coding, however, should stay the same since the pinout is the exact same on the development board as to the chip that we've selected. The trick will be to map those to our components when designing the schematic.

Requirements and Specifications Fulfillments

1. The processor is an ARM chip.
2. The processor has low-power capabilities, thus can fulfill the low-power consumption.
3. The processor has at least 1 dedicated I2C line
4. The clock frequency is 48 MHz so 30 frames per second specification is achievable.
5. We can add hardware options to fulfill the power switch and reset option capabilities.

9.2: Input and Output through Processor

The processor must deal with a lot of input and output. There are 6 vibrational motors, 6 Peltier devices, 16 accelerometers, and a computer communicating with or through the processor board. With this, the chip needs to be fast enough to poll and control each motor and sensor as well as communicate through the Bluetooth module to communicate with the computer for further processing of data.

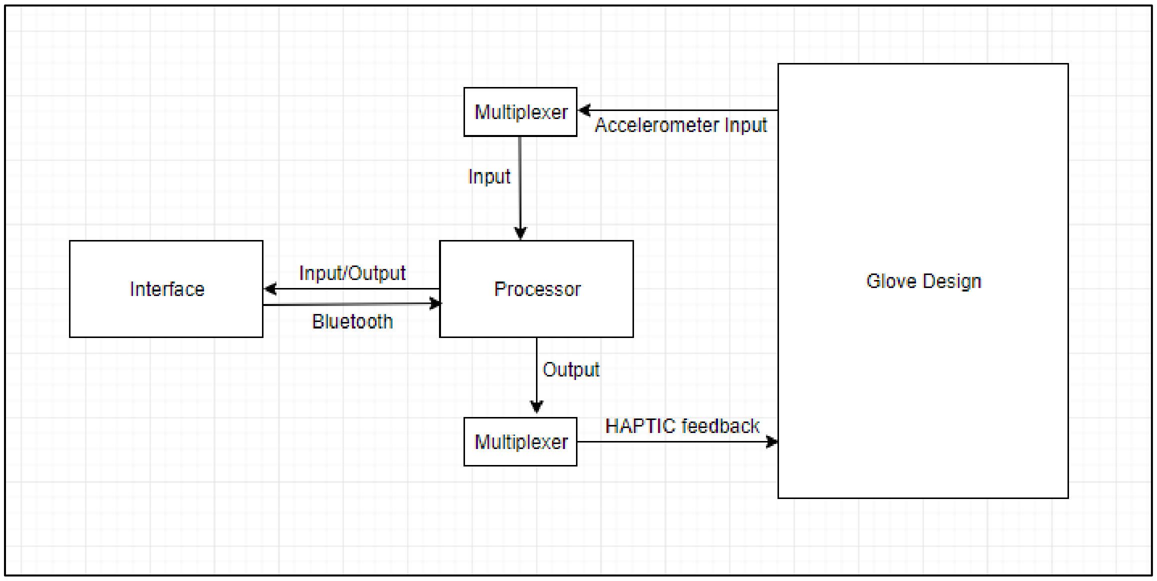


Figure 36: Data Flow Schematic of The Glove

As we can see from the design above, we don't even see the Blender module. Also, we don't even see the components of the interface or of the glove design. In this way, the processor only needs to know what input it will get from the accelerometer, what feedback it needs to give back to the glove design, and what input and output to expect from the interface. Something that needs to be communicated is the format of the data that's expected for the interface. As far as the accelerometers, they are rather set due to the design given to them, but the interface is completely arbitrary for us.

I2C - Communication on a wire can be tricky. If everything is trying to communicate at once to the processing board, then the board will not understand what is communicating with it. For this reason, there are protocols that can be used to that communication goes smoothly. According to *i2c.info* [24], "The system must be designed in such a way that slower devices can communicate with the system without slowing down faster ones." For our sensors and modules, we will be connecting them on a bus, so we don't have hundreds of individual wires wasting a single line, when we can easily communicate on a single bus. This is essentially what the I2C is, an Inter-Integrated Circuit bus. The i2C website clarifies, "A bus means specification for the connections, protocol, formats, addresses and procedures that define the rules on the bus. This is exactly what I2C bus specifications define." The site continues to define what I2C is by listing things such as terminology, bus signals, serial data transfer, start and stop condition, I2C data transfer and even more terminology.

UART - This method of communication, which stands for Universal Asynchronous Receiver/Transmitter, is a means to simplify and aid in data communication. According to the website *All About Circuits* [25], UART uses only three signals: Tx (transmitted serial data), Rx (received serial data), and ground. It continues to say that there is no need for a clock signal because the internal clocks of the receiver and transmitter will ensure that the proper timing is done internally. Some requirements for UART say that the clock signals, "… must be sufficiently accurate relative to the expected frequency and sufficiently stable over time and temperature.” We will be using this protocol for communication with our Bluetooth module. Here are some key terms, like I2C, that are used by UART, which are taken from the *All About Circuits* website:

1. **Start bit:** The first bit of a one-byte UART transmission. It indicates that the data line is leaving its idle state. The idle state is typically logic high, so the start bit is logic low.
2. **Stop bit:** The last bit of a one-byte UART transmission. Its logic level is the same as the signal’s idle state, i.e., logic high. This is another overhead bit.
3. **Baud rate:** The approximate rate (in bits per second, or bps) at which data can be transferred. A more precise definition is the frequency (in bps) corresponding to the time (in seconds) required to transmit one bit of digital data.
4. **Parity bit:** An error-detection bit added to the end of the byte. There are two types: “odd parity” means that the parity bit will be logic high if the data byte contains an *even* number of logic-high bits, and “even parity” means that the parity bit will be logic high if the data byte contains an *odd* number of logic-high bits.

With this protocol in place, we will have to keep everyone informed about which start bit and stop bit we will be using. The baud rate is typically 9600 baud, at least in typical Arduino tutorials. With this information, we should have a seamless transmission of data between the processing board and the Bluetooth module.

Input from Accelerometers - The input from the accelerometers has 3 different types: the x-axis, the y-axis, and the z-axis. All three of these components have 14-bits that need to be read for an accurate reading. That’s a total of 42-bits that need to be read for each accelerometer. If there are 16 accelerometers, then we need to read a total of 672 bits. Since we need to store them in 8-bit increments, that means we will store each 14-bit in a 16-bit frame. If we do this, we have a total of 48-bits (6 bytes) per accelerometer. Again, with 16 accelerometers, then we have 768-bits to store all of our inputs from accelerometers, which is a total of 96 Bytes.

9.3: Wireless Communication

For our setup, we are going with Bluetooth communication. However, there are a plethora of ways to send data wirelessly, ways that include: infrared, satellite, radio waves, Bluetooth, Wi-fi, and many other methods as well.

9.3.1: Pros and Cons of Wireless Communication

According to the website elprocus.com [26], some advantages of wireless communication include fast speeds, fewer materials and overall less cost. For us, the biggest pro of having wireless is since our system is convenient if the user is not connected to a bunch of wires. Being wireless allows the user to free up degrees of movement.

The disadvantage mentioned by the elprocus.com website is that data transmission is not as secure. However, for us, we are not transmitting anything that would be of value since the data is only going to be pertaining to accelerometer values. On the other hand, we are getting input data, so if a hacker were trying to send in values to would cause the Peltier devices to heat up drastically, that could pose a problem. We have already thought of this. In this case, we will be hard-coding into the processor limiting values. With these limiting values, no matter what data is sent in, the Peltier device wouldn't get hotter than whatever temperature we've set the limiter at.

9.3.2: Bluetooth Module Choices

Bluetooth has been growing in popularity ever since headsets started to make use of the technology, in my own opinion. Bluetooth is convenient; it has a very simple setup and compatible. The setup only requires that one scans for other devices and one is set to be discoverable. As far as compatibility is concerned, if both modules have a Bluetooth module, then they will work together, as long as they are within the correct version of course. For example, most Bluetooth x.x are compatible with each other, but the Bluetooth 5 is not backwards compatible with 4.0, or 3.0, but the 4.0 is compatible with the 3.0. Here is a brief overview of the different versions of Bluetooth:

	Basic Rate (BR)	**Enhanced Data Rate (EDR)**	**High Speed (HS)**	**Low Energy (LE)**	**Slot Availability Masking (SAM)**
Bluetooth 1.x	Yes	No	No	No	No
Bluetooth 2.x	Yes	Yes	No	No	No
Bluetooth 3.x	Yes	Yes	Yes	No	No
Bluetooth 4.x	Yes	Yes	Yes	Yes	No
Bluetooth 5.x	Yes	Yes	Yes	Yes	Yes

Figure 37: Bluetooth Comparison Table

Of course, we would most likely want to choose a Bluetooth with a version of at least 4.x or higher since most devices now-a-days has this technology and for its speed and low energy.

RN4871-V/RM118 [27] **-** This Bluetooth module is 9x11.5 mm and is Bluetooth 4.2. It is shielded which will aid in short-prevention and overall integrity and strength of the design. It's small enough to help in fitting all the components onto a single PCB design and still fitting onto a wrist. This module also supports UART, which is the type of protocol we are designing the PCB to use to transmit data. This module also has an antenna on the chip.

BL652-SC-01 [28] **-** This Bluetooth module is 120x93 mm and is also Bluetooth 4.2. The data sheet does not specify any shielding, but from the looks of the image, the components on the board look enclosed. It's a bit bigger than the other module, which may become a problem if we don't have enough space, but still rather small. This has a larger selection of interfacing protocols, which still includes UART. The antenna is external rather than on-chip.

BM62SPKS1MC2-0001AA [29] **-** This Bluetooth module is 29 mm x 15 mm x 2.5 mm and is also Bluetooth 4.2. The module is shielded, which again will help with the space on our PCB. This module also supports data transmission over the UART interface. The antenna is stated to be on-board.

Traits	**RN4871**	**BL652**	**BM62SPK**
Cost	$8.44	$7.45	$12.50
Shielding	Yes	Yes	Optional
Antenna	Chip	On-board	On-board
Size (LxW mm)	9x11.5	120x93	29x15
Operating Voltage (V)	1.9 – 3.6	1.8 – 3.6	3.2 – 4.2
Supply Current Receiving (mW)	10	5.4	unknown
Supply Current Transmitting (mW)	10	5.3	unknown

Table 15: Bluetooth Module Comparison Taken from Mouser.com

As we can see from the table above. The BL652-SC-01 seems to be the best option. Not only does it cost the least amount of money, at least on this website it does, but it also seems to use the least amount of power. Of course, with that we are probably losing some distance in which we can transmit data, but the use-case for our device is strictly within a room next to the computer that will be taking in the data transmission so that will not be a problem.

The next image is that of the schematic for the BL652 Bluetooth module. This gives a visual representation of the pinout of the design and will assist in the design process when integrating the circuit into the design.

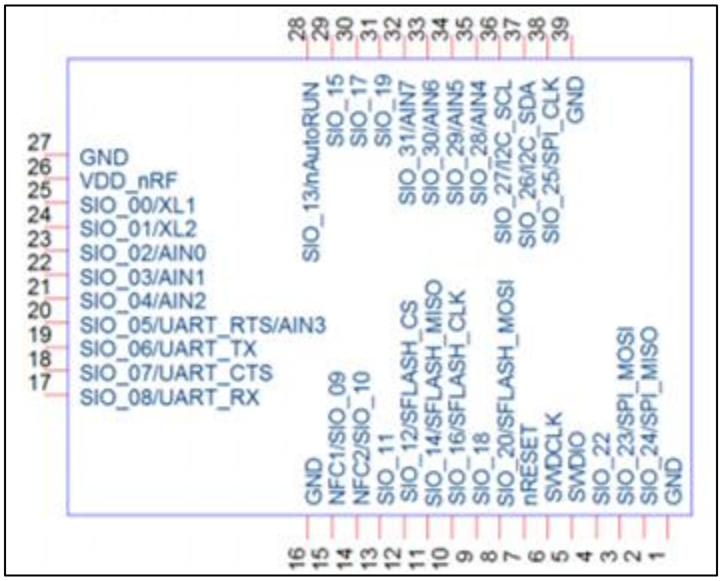
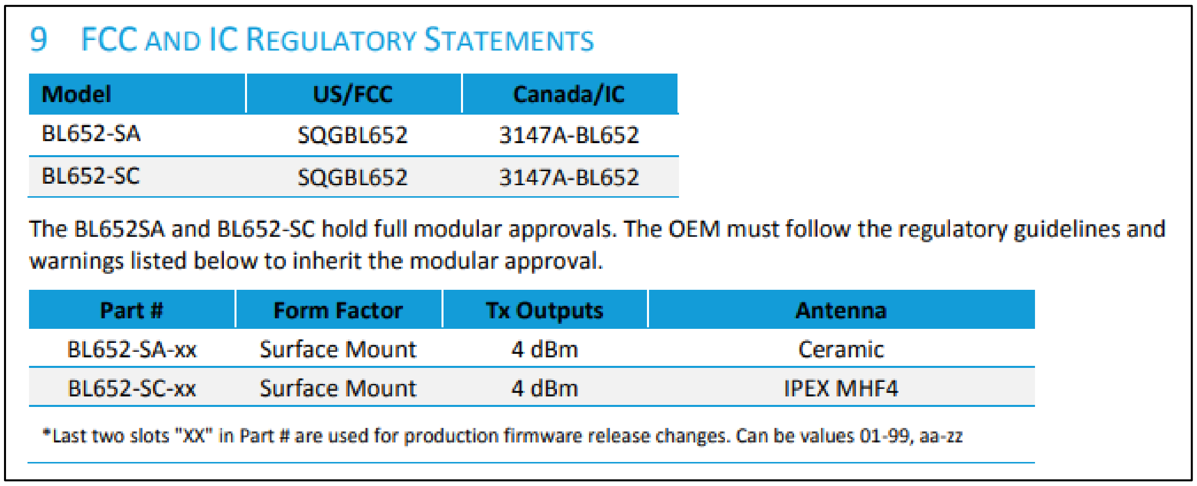


Figure 38: Pinout of BL652



9 FCC and IC Regulatory Statements

Model	US/FCC	Canada/IC
BL652-SA	SQGBL652	3147A-BL652
BL652-SC	SQGBL652	3147A-BL652

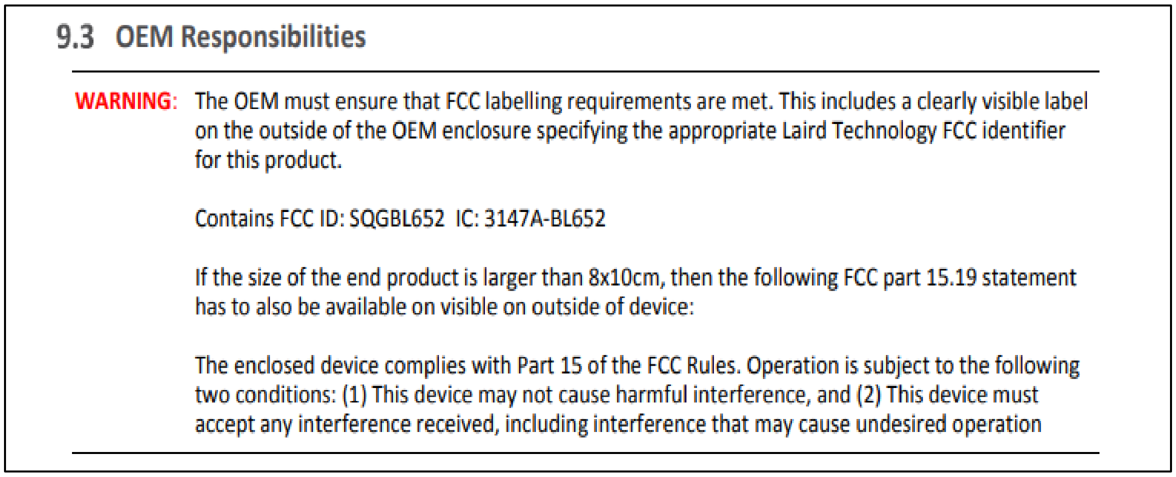
The BL652SA and BL652-SC hold full modular approvals. The OEM must follow the regulatory guidelines and warnings listed below to inherit the modular approval.

Part #	Form Factor	Tx Outputs	Antenna
BL652-SA-xx	Surface Mount	4 dBm	Ceramic
BL652-SC-xx	Surface Mount	4 dBm	IPEX MHF4

*Last two slots "XX" in Part # are used for production firmware release changes. Can be values 01-99, aa-zz

Figure 39: Image from EL652-SC-01's data sheet about OEM Responsibility

From the image above, they give specific outputs and antenna to comply the regulatory guidelines. Included in the data sheet is also more OEM responsibilities, which OEM stands for Original Equipment Manufacturer. The image below shows these responsibilities:


9.3 OEM Responsibilities

WARNING: The OEM must ensure that FCC labelling requirements are met. This includes a clearly visible label on the outside of the OEM enclosure specifying the appropriate Laird Technology FCC identifier for this product.

Contains FCC ID: SQGBL652 IC: 3147A-BL652

If the size of the end product is larger than 8x10cm, then the following FCC part 15.19 statement has to also be available on visible on outside of device:

The enclosed device complies with Part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) This device may not cause harmful interference, and (2) This device must accept any interference received, including interference that may cause undesired operation

Figure 40: Additional Information from BL652-SC-01's about OEM Responsibility

From this image, we can see that we need a clearly visible label on the outside. Our product will most likely exceed 8 cm x 10 cm, so we will have to include the statement if we were to ever produce this as a product:

"*The enclosed device complies with Part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) This device may not cause harmful interference, and (2) his device must accept any interference received, including interference that may cause undesired operation*."

9.3.3: Bluetooth Specifications

BL652 – With I2C interface selected, in the datasheet, it states that pull-up resistors on I2C SDA and I2C SCL must be connected externally as per I2C standard.

9.4: PCB Design

The overall PCB design needs to be small enough to fit on a wrist, but powerful enough to handle the IO of many modules. In first talking about this design, we thought about developing a flexible PCB design, but with the high cost of fabrication, we quickly said no to the idea. Rather than have it flexible, we can just make the PCB small enough and secure it in some type of curved enclosure to fit comfortably on a user's wrist. In the next sections, we will be looking at different software and fabrication companies and how they compare to each other as well as defining what a PCB actually is.

Flexible PCB – Flexible PCB is as its name implies; it's a PCB that is flexible. For the glove design, it might be considered useful for the electronics to have flexibility due to the constant movement that the normal use will influence the design. Essentially, instead of the components of the board being placed on a rigid board, they are placed on a plastic substrate, thus the components can bend as the board bends. The glove design may also benefit from this due to the components along the fingers could make use of the flexibility. However, flexible PCBs are drastically more expensive because it's a more recent technology. Due to this expense, having wires along the fingers will give us the same effect at a much cheaper price. Furthermore, the PCB design will be mounted on the wrist, thus we can use bands or other stretchy connectors to mount the device to the wrist of the user.

Flexible PCB over Rigid PCB – Continuing further, we will be choosing a rigid PCB due to the high cost of the flexible PCB. The wires connecting the components on the glove design will be much cheaper but will bring a bigger design overall since wires on flexible PCB are smaller than individual wires connected to each component. Moreover, flexible PCBs is an over-design for the design we are trying to make. Simpler is sometimes easier.

9.4.1: Schematic Design Tools

In order to fulfill the design requirements, there needs to be a PCB design. For this to take place, the PCB needs to be designed. There is an extensive list of design tools that are for freelancers all the way to big industry. Some come with a heavy price tag, which includes engineers ready to help in the design process, and some are free with tutorials and documentation to guide users along. Since the design only consists of a single PCB and its details are rather simple, a free version of a schematic design tool, will do the job. In the next few paragraphs, there will be schematic design tool options.

9.4.2: KiCAD

For designing the PCB, we will be using KiCAD, which is a free software suite for electronic design automation. The reason we will be using KiCAD is that it's open-sourced, which means it's free, and it being open-sourced means we are staying true to our design goal of making our own project open-sourced. When traversing through the site, there is a "Help" menu, which provides a plethora of documentation at our disposal as well as tutorials. We will benefit most from this software mainly because we have had experience using it, and throughout this design, experience will get us a lot further than education.

9.4.3: SOLIDWORKS PCB

According to the Trimech website [30] , SOLIDWORKS PCB boasts being powered by Altium's best-in-class PCB technology. Altium seems to be a technology all on its own. This leads me to believe that SOLIDWORKS PCB is more of a framework to allow integration between the PCB design and the mechanical design of using SOLIDWORKS. It continues to say that it integrates seamlessly with SOLIDWORKS, which enables a completely collaborative electro-mechanical workflow, so my assumption of if it's more of a framework seems to be correct. This sounds enticing; however, we are not going to have a mechanical design complex enough to be using software to create it, so this choice.

9.4.4: DesignSpark PCB

The *rs-online* website [31] which hosts the DesignSpark software states that the software doesn't have limitation on design schematic size as well as integration into their other free software that "take your brightest ideas all the way through to final production." You can also use as many layers, pads, nodes, and connections in your design as you'd like. A cool part of this software is if you can't find a part to put into the PCB design, then their software has a functionality that allows you to create them from PCB Part Library. This functionality seems very useful.

9.5: PCB Fabrication

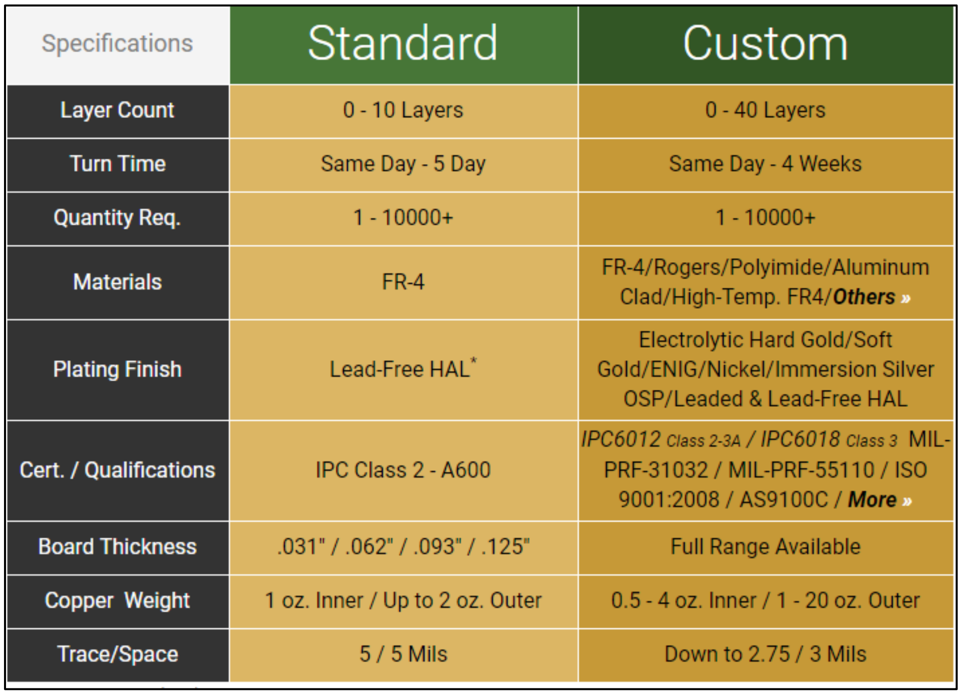
Eventually, when the design is finished, the design needs to be created. To do this, one can develop their board and buy a bunch of industry equipment and essentially 3-D print the board oneself, or like most people, going to a PCB fabrication company will save lots of money. In the next couple of paragraphs, researched options will be listed, and their details will be explained.

9.5.1: PCBWay

PCBWay [32] is a full feature custom PCB prototype service. They boast a low-cost fabrication and a quick delivery time. A basic design that's within 100 mm x 100 mm and 10 pcs is estimated at $5.00, which is an incredible price. It also states that the design would only take 2-3 days, which is rather typical for small-batch PCB fabrication.

9.5.2: 4pcb

4pcb [33] does their production in the United States. This can be seen as a benefit, but most likely their design will be more expensive, but with less shipping costs. Their website doesn't give an estimated price for anything, but they do provide this chart:



Specifications	Standard	Custom
Layer Count	0 - 10 Layers	0 - 40 Layers
Turn Time	Same Day - 5 Day	Same Day - 4 Weeks
Quantity Req.	1 - 10000+	1 - 10000+
Materials	FR-4	FR-4/Rogers/Polyimide/Aluminum Clad/High-Temp. FR4/***Others*** »
Plating Finish	Lead-Free HAL*	Electrolytic Hard Gold/Soft Gold/ENIG/Nickel/Immersion Silver OSP/Leaded & Lead-Free HAL
Cert. / Qualifications	IPC Class 2 - A600	*IPC6012 Class 2-3A / IPC6018 Class 3* MIL-PRF-31032 / MIL-PRF-55110 / ISO 9001:2008 / AS9100C / ***More*** »
Board Thickness	.031" / .062" / .093" / .125"	Full Range Available
Copper Weight	1 oz. Inner / Up to 2 oz. Outer	0.5 - 4 oz. Inner / 1 - 20 oz. Outer
Trace/Space	5 / 5 Mils	Down to 2.75 / 3 Mils

Figure 41: PCB Specification Comparison [33]

From this chart, we can see that their layer count and turn-time is around the same as PCBWay, but they don't include an estimated price as PCBWay does. From this we can speculate again that PCBWay will have higher shipping cost because they are shipping from China, but with a lower design cost and 4pcb will have a lower shipping cost because they produce in the United States, but typically cost of manufacturing in the United States is higher.

9.5.3: PCBgogo
The PCBgogo [34] website boasts a 12-24-hour quick turn PCB prototype service, which is very quick. They also have a low minimum from 1 pcs PCB Assembly is accepted, which I don't believe we will actually benefit from or need. They boast 24-hour customer service availability, which could come in handy if we have any questions. A big plus in my book is the fact that they have 99% on-time DHL Delivery so if we are not very unlucky, we can typically trust in the delivery time that they set, which could come in handy in a time crunch. A professional PCB engineer one-to-one service is offered. This fabrication company seems to be very trustworthy and helpful and would be a good alternative to PCBWay.

9.5.4: JLCPCB
The JLCPCB [35] website advertises the lowest prices for PCB design researched. They boast over 200,000+ customers worldwide and 8000+ online orders per day. They claim to be the largest PCB prototype enterprise in China. They specialize in quick PCB prototyping and small-batch production, which is exactly what the design entails. The only downside to this choice would be, like most others, is that it ships from China, which can take a long time. However, they state only up to 2-3 days of build time and shipment tracking, which can ease tension in a build when waiting on parts.

9.6: PCB Design Constraints
There is a plethora of constraints to consider in the PCB design, some are already included when we consider the Bluetooth module from earlier. Constraints can come in a variety of broad topics such as: environment, economical, sustainability, social, political, ethical, manufacturability, and most importantly, health and safety. In further reading, we will cover constraints within each category and explain each constraint that is arbitrarily placed on our project, or a constraint due to reasons out of our hands.

9.6.1: Environmental Constraints
Environmental constraints can be constraints given to us by the environment around us, such as, we cannot create a design that is bigger than a room, because a user is intended to us it within a room. That's, however, a broad example that doesn't need to be addressed due to the nature of our project. Environmental constraints can also be given to us by literal protocols or regulations required due to the environment, such as waste produced by a product and how it's disposed of or even the amount of carbon dioxide that a product can produce.

We don't have any environmental constraints on our project, but we will be including Lithium-powered batteries, which can pose a hazard to the environment if disposed of properly. This isn't necessarily our responsibility due to the batteries including labels on them that inform the user to dispose of the batteries properly.

9.6.2: Economical Constraints
Economical constraints are constraints that talk about costs, efficiency, and can even include longevity because the longer the product can less, the more economical it is. For the PCB design, our economical constraints are only to make the design cheap to make an

impact for future hobbyists to tinker with our design. For that to happen, we will be trying to make the board, low-powered, use low-cost modules, and be cheap to manufacture.

9.6.3: Sustainability Constraints

Sustainability constraints are essentially constraints to allow further development of our design over a long period of time. For example, if the chip that we chose decides to be discontinued and no longer manufactured for whatever reason, then our design will no longer be sustainable. For this reason, we have an obligation to keep the design sustainable, so hobbyists can use the design in the future. In this way, we will be trying to use up-to-date technology, like choosing a 4.x Bluetooth module rather than 1.x or 2.x and making our design rather simple to change. If our design is simple, a part can be changed without affecting too many other parts, essentially making everything loosely coupled.

9.6.4: Social and Political Constraints

Social and political constraints are closely related. Social constraints are constraints enforced by society and political constraints are constraints enforced by policy. In the PCB design, there are no constraints based on these topics.

9.6.5: Ethical Constraints

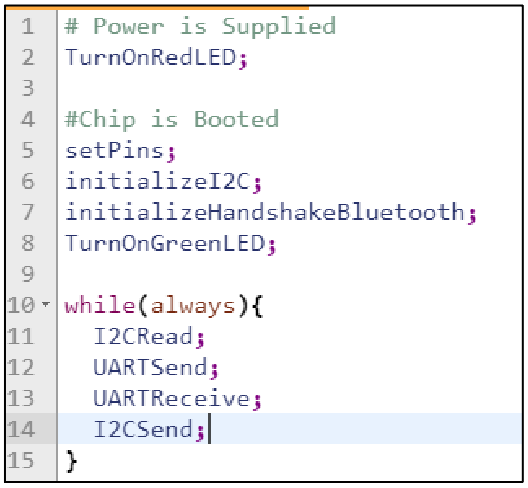
Ethical constraints are constraints that are imposed by ethical dilemmas or forced due to ethics of society. The only ethical constraint that we have on our design is to make it cheap for the open-sourced community so that they can learn and tinker with our design without breaking their bank.

9.6.6: Health and Safety Constraints

Health and Safety constraints are imposed by either regulation and requirements. These are regulated because a lot of technology today can be dangerous and if standards aren’t met, then people can become injured. The first thought we had about our PCB design was concerned about shock risks, sharp-object risks, and temperature risks. The shock risks can come from the PBC design coming into contact with the user. For this, we will be enclosing the PCB design in a plastic enclosure to ensure to contact with the skin can be made. For the sharp-object risks, it’s solved by the enclosure. The risk was that usually sharp wires from soldering or from the design can stick out and are rather sharp. With the enclosure, no contact can be made with the wires. The heat risk can be reduced by implementing a heat sink on the chip as well as using an enclosure to keep the design further away from the user. The battery will most likely be the highest temperature and, since it’s lithium, has a higher risk of catching of fire or even exploding. For this reason, we will also include a metal enclosure for the battery that will act as a fire/explosive defense measure.

9.7: System Startup Procedure

When the processor design initially gets power, there needs to be a couple of events that occur. These events will include visual cues of the device turning on, data being read, pins being set, and then a loop of reading and sending data with the Blender interface and the glove components. The next figure will show a coding block diagram of how this procedure will work. Initially, the device will get power. To indicate this, we will program a red LED to light up to signify that the device is booting up. During the chip boot, a few events will occur to ensure proper functionality. First, the pins will be set; essentially, the code is giving the pins their respective components that they are responsible for. Next, we will initialize the I2C, which is explained in the I2C section of wireless communication. Once that is initialized, we can start the UART handshake process for the Bluetooth device. This will make the device detectable by the interface that will connect to the processor. In order to keep the Blender model and the glove design synced, the instruction will be to place the hand utilizing the glove on a flat surface. This will "normalize" the reads and allow for the Blender interface to be synced with what is actually happening with the hand. To indicate normalization has occurred, a green LED will then be turned on briefly to show the glove is ready. From here, the code will loop between reading from the components on the glove to get their positions, sending through Bluetooth interface, reading from Bluetooth interface, and then sending this response to the HAPTIC devices on the glove. Again, the block diagram is as shown:



```
# Power is Supplied
TurnOnRedLED;

#Chip is Booted
setPins;
initializeI2C;
initializeHandshakeBluetooth;
TurnOnGreenLED;

while(always){
  I2CRead;
  UARTSend;
  UARTReceive;
  I2CSend;
}
```

Figure 42: Pseudocode for startup Procedure

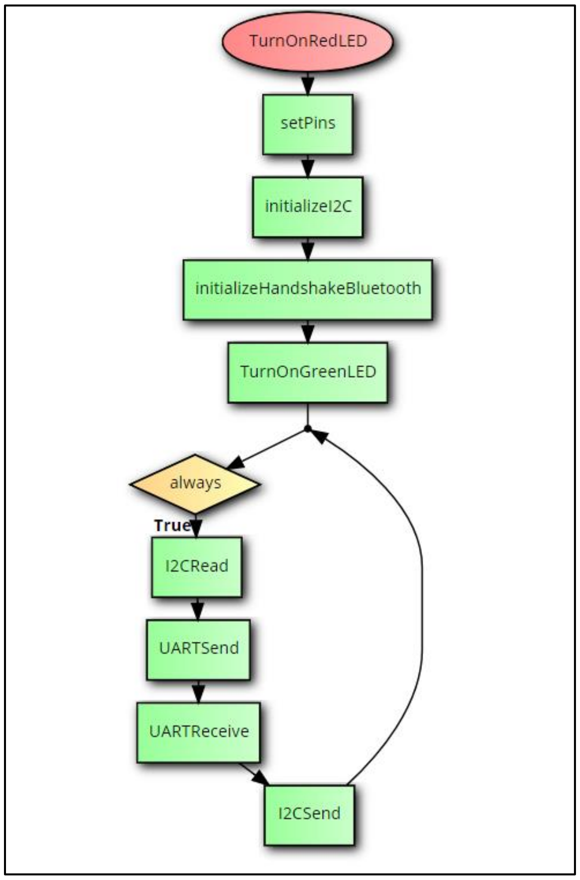


Figure 43: Block Diagram for Startup Procedure

10: Relevant Technologies

Some may argue that every new idea is simply a combination of other ideas. With the advent of virtual reality and augmented reality, an industry of haptic feedback popped up into the world. While there are certainly technologies out there that have accomplished haptic feedback, our design is unique because of the way we are incorporating the sense of touch and temperature.

10.1: Existing Technologies and Products

In the next couple of sections, there are some technologies that are alike to the design being created. These designs offer either higher quality, a more specific feedback system or even a lower quality or a higher price.

10.1.1: VRGluv

The VRGluv [36] is a force-feedback system that uses pulley like technology to pull the fingers back to make the user feel like they are grabbing an object and can't close their hand anymore. They have 10-zones of feedback on each hand, which can provide 5 pounds of force to simulate rigid objects. They express 10-ms of latency over wireless communication. They also claim 360-degree thumb tracking. Some obvious similarities are that both designs have a force feedback and wireless communication. Our haptic glove design is different in the manner that the design gives force feedback; rather than have something pull at the user's fingers, we are giving a rumble affect to show that you are touching something. Also, we are incorporating a temperature-feedback design which isn't present in the VRGluv.

10.1.2: HAPTX

HAPTX [37] is a more complex design on the market today. They have a patented microfluidic technology that lets you feel the shape, movement, texture, and temperature of digital objects. This technology also claims 5 pounds of force feedback with what seems to be the same design choice of the VRGluv. It also has industrial grade motion-tracking. To compare, our glove won't give a sense of shape or movement of an object. With our design, it's much simpler. We are giving temperature feedback as they do, but their design is much more complex. We also will have "industrial" grade motion-tracking due to each finger have 3 accelerometers. Judging from the images, our design seems like it will be less cumbersome and most likely, considerably cheaper to produce. However, with the cheaper product, the quality of the feedback doesn't seem like it will compare to the technology that they are incorporating into their design.

In the following table, we will consolidate the functions and features of the aforementioned products on the market today compared to our design.

Features	**MITTS**	**VRGluv**	**HAPTX**
Force Feedback	No	Yes	Yes
Temperature Feedback	Yes	No	Yes
Motion Tracking	Yes	Yes	Yes
SDK Provided	No	No	Yes
Low Latency	Yes	Yes	Yes
Pressure Sensing	Yes	Yes	Yes
Texture Feedback	No	No	Yes

Table 16: Product Comparisons

As we can see from the table above, the HATPX is by far the most functional. The MITTS design is sacrificing quality for a lower cost and cheap production.

10.2: Programming the Chip

For the components to work properly, the chip needs to know what to do and for it to know what to do, we need to program the chip. The chip the design will use doesn't have an unlimited amount of memory, so it's going to be best to program it with a low-cost to memory. In general, the lower-level the language, the lower amount of memory will be consumed. The highest level typically used by ARM devices is C++, then C, then if truly bold, assembly language.

10.2.1: C++

This language is a high-level language built off C to enhance ease and verbosity. It is highly portable, which means that if we wanted to change chips, most likely the code would work on the other chip due to being so portable or universal. It includes features such as classes, inheritance, polymorphism, data abstraction, and encapsulation because it is an object-oriented language. Due to it being an older language and used by a world-wide community, the libraries available are endless. Some features it has over C, is that it allows for function overloading and exception handling. C++ can do almost anything, from 3D graphics for games to real-time mathematical solutions.

10.2.2: C

This language is a combination of being high-level and low-level. It being close to low-level makes it easier to make critical mistakes that are usually caught by higher level languages. However, due to this reason, it uses less memory and has more precise control. It can control drivers and kernel modules, which are not generally done in higher level languages, or if the higher-level languages do, then they simply interface the code written and change it into lower level code. This is the same technique used by C; change the code to assembly, then to 1s and 0s. C is used in Windows, Unix, and UNIX systems. As with C++, C also has an extensive function library due to the huge community of people that work with it.

10.2.3: Assembly Language

Using assembly would be only beneficial if we were only trying to maximize speed in our design. Assembly is the lowest-level you can get to the hardware without using 0s and 1s to code things. For the design to use assembly would take a lot of time learning the specifics of such a tedious language. It's fast and uses as little memory as you need it to. Generally, if you write a function that does the same exact thing in C, C++, and assembly, assembly will be the most efficient, performant, and least memory intensive.

The next table will hold comparisons between the three options and will gather better evidence for which one should be chosen over the others.

Traits	C++	C	Assembly
Extensive function library	Yes	Yes	No
Object-Oriented	Yes	No	No
Portable	Yes	Yes	No
Exception Handling	Yes	No	No
Function Overloading	Yes	No	No

Table 17: Comparing C++, C, and Assembly

For the design, C will be the most beneficial. The code needs to be closer to the hardware because we will be interfacing with many components and essentially writing drivers. Assembly would be beneficial too, but for our case, learning the specifics will be much too time consuming. C is balanced in the sense that it is fast, performant, less memory-intensive, portable, and has a wide range of documentation and tutorials if we ever get stuck on coding.

10.2.4: Coding Peltier Controller

The Peltier controller needs to be coded with complex algorithms to give us more control over the fluctuations we put on our Peltier devices. Rather than constant up and downs to maintain a temperature, we are essentially calculating the error value as the difference between a measured process variable and a desired setpoint. To code this, it's complex because we need proportional integrals and derivatives. Luckily for us, there is already code out there that has solved these complex calculations. For example, the Arduino Library contains a library called "Arduino-PID-Library." The downside to this is that it's written for a different chipset, so the design will have to reprogram the different pin numbers for the library to work on the ARM device.

10.3: STM32 Attributes

There are many attributes we may or may not need to be aware of that can contribute to a project. Anywhere from how much memory to what kind of stack it uses. In the next couple of paragraphs, we will look at attributes that will ultimately affect the design.

10.3.1: Stacks

The chip makes use of a full descending stack. This essentially means that the processor pushes a new item on the stack after it decrements the stack pointer. It's stated in the programming manual of the STM32 that there are two modes available: The Handler mode and the Thread mode. There are two stacks that are used on the chipset and the mode influences which one is being used. The manual supplied a handy table as seen below that shows how the Thread Mode and the Handler Mode differ:

Processor Mode	Used to Execute	Stack Used
Thread	Applications	Main stack or processor stack
Handler	Execution Handlers	Main stack

Table 18: Summary of Processor Mode and Stack Usage from STM32F0 Programming Manual

10.3.2: Registers

We mainly will not have to deal with registers so specifically due to the design making use of C rather than assembly code. However, it is important to make note of key registers that will come into play if we need to work closer to the hardware with assembly. Here is a short list supplied from the STM32 Programming Manual that shows key registers:

Name	Type	Description
R0 – R12	Read-write	General Purpose Register
MSP	Read-write	Stack Pointer (SP)
PSP	Read-write	Stack Pointer (SP)
LR	Read-write	Link Register (LR)
PC	Read-write	Program Counter (PC)
PSR	Read-write	Program Status Register
ASPR	Read-write	Application Program Status Register
IPSR	Read-only	Interrupt Program Status Register
EPSR	Read-only	Execution Program Status Register
PRIMASK	Read-write	Priority Mask Register
CONTROL	Read-write	Control Register

Table 19: Essential Register Summary from STM32F0 Programming Manual

10.3.3: Interrupts and Exception Handling

The Cortex-M0, which is what the design will implement, does support interrupts and exception handling as stated by the Programming Manual. More in-depth explanation of how this is handle can be found in the manual.

10.4: Flashing the Hardware

There is a difference between programming the chip and flashing the hardware. Programming the chip involves the physical code that is put onto the chip whereas flashing the hardware is the method in which the code gets onto the chip. Using the STM32 breakout board makes this process very easy and is one of the main reasons for the existence of breakout boards, so individuals can use a chipset without making their final hardware design. When the design is finished, the project will not have a dedicated board; there will be a board designed for our purposes. Unfortunately, that doesn’t mean that flashing the chip will be so easy.

10.4.1: Flashing the STM32 Breakout Board

This is by far the easiest. As said in the previous paragraph, the breakout board is designed specifically for easy coding and ease-of-use. It simply needs a USB type cable as well as the driver information, so the computer can recognize the device to program it. From here, using the IDE supplied by the STM website, flashing the chip is as easy as compiling the code and uploading, or flashing, it to the chip.

10.4.2: JTAG

Before getting into the specifics of how to flash the final PCB design, JTAG must be explained. According to *XJTAG* website [38] , JTAG makes use of one underlying technology, which is, the four-wire JTAG communications protocol. It makes use of four signals according to the website. Two of these pins is the SWDIO and the SWCLK. The table below shows the ports and pin numbering:

Pin	Port	Name
46	PA13	SWDIO
49	PA14	SWCLK

Table 20: Pin and Port Information for JTAG pins

10.4.3: SWD In More Detail

SWD stands for serial wire debug allows for programming, step-through debugging, and many more UART style I/O. JTAG and SWD have almost become synonymous when talked about in forums, but SWD is more ARM specific and uses less pins than JTAG, but for non-ARM specific devices, JTAG would be the way to go.

10.4.4: Flashing the Final PCB Design

This is a little trickier than flashing the STM32 breakout board because the design doesn't have the dedicated hardware created for it. The design will make use of SWD due to the reasons stated above in previous paragraphs. A lot of documentation leads to the ST-Link V2 to program the chip and debug when on the PCB design. This device makes it easier to program the chip, but a design can be made without this device for more hardware adaptations. The device essentially brings boot0, or pin 60, low to set the desired boot mode. This boot mode can be boot from flash, boot from system memory, or boot from embedded SRAM. Obviously, the design needs to be set to boot from flash to program it and when in normal operating mode, the design needs to set the boot mode to boot from system memory to run the code that the system gets flashed with.

10.4.5: Making Use of STM32 Breakout Board

The STM32 Breakout Board is intended to make the development process easier. For initial testing, the design incorporates I2C communication. For I2C communication to occur, the data sheet for the MMA8451, which is the accelerometer, specifies the start and stop bits as well as how the communication occurs and is successful. Since the design only needs to write to the accelerometer, we look at the data sheet and find the I2C data sequence diagram, which looks like this for a single-byte read:

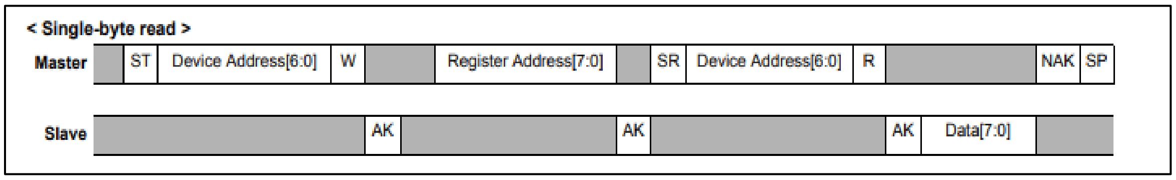


Figure 44: I2C Data Sequence for MMA8451

As we can see, we send a start bit as well as the device's address, which for the MMA8451 is 0x1D unless we pulled the address pin down, then the address is 0x1C. The communication appends to the end a write bit, which specifies whether the STM32 is writing or reading from the device. The device then sends an acknowledgement. Next, a register address is sent that is to be read from the device as well as an acknowledgement. It then follows up with a repeated start condition (SR), the device's address we want to read to, and then the read bit to specify whether to read. An acknowledgement is sent as well as the data correlating with all the details thus far. The I2C protocol then sends a stop bit (SP) to signify the end of the data read or write.

10.5: **Development Environment**

The STM32 has a lot of support by the ST company. Resources our project will utilize includes a data reader, an IDE and a configuration program. All these aid in the development process and make the configuration and debugging exponentially easier for testing.

10.5.1: STMStudio

This program makes it easier to debug our program that we load onto the STM32. It makes it easier by reading and allowing variables to be displayed in real-time after code has been uploaded. In the future, it has ST-Link support for SWD debugging, which the project most likely will make use of. This kind of tool is specific to the STM, thus has a lot of support for our chip as well as good documentation.

10.5.2: Keil uVision5

The uVision software is a project manager and a run-time environment. It's essentially an IDE for embedded programming. This IDE was chosen based on the fact that there are many videos correlating with programming the STM32 that utilize this software. It is optimized for C/C++, which is essential in our project.

10.5.3: STM32CubeMX

This software is an initialization code generator. It essentially helps you build initialization code and provides a nice UI to change things such as clock frequency, dedicated addresses, GPIO pin setup and much more. This part is usually tedious to program, but this program handles all of this and gives a good template to start programming from. It even has support for initializing I2C communication on the board, which is the essential part of the design. The process is simple. It first allows you to choose your chipset or board. One then goes through the process of setting the configuration with a pinout-conflict solver, a clock-tree setting helper, a power-consumption calculator, and a utility performing MCU peripheral configuration (GPIO, USART, ...) and middleware stacks (USB, TCP/IP, ...). This makes the whole configuration very easy.

10.5.4: Flasher-STM32

This is optional software that leads me to believe the design might have to incorporate in when it comes time to flash the chip on the PCB design. This software helps in flash loading the memory. It comes with features such as UART system memory bootloader and documentation to get one started.

10.6: **Calculating the Accelerometer Data**

Calculating the accelerometer data will be tricky. What we need to do with the data is essentially integrate the data points twice to get the position. However, when doing this, any noise or inaccurate data get amplified each time we integrate. This process will certainly make the design difficult because it is the bottleneck of the system. Without having proper conversion of the accelerometer data, then the Blender module cannot work, and neither can the interface between the board nor the Blender module. As mentioned on StackOverflow we need to keep a few things in mind. We need to use Newton – D'Lambert physics for non-relativistic speeds. Since our accelerometers can rotate, the direction must be applied. The measured timings are critical, and the compass is not always correct. With these things in mind, the design for the algorithm to turn accelerometer data will be difficult.

11: Blender & 3D Environment

A fundamental part of our project is creating an interactive 3D Environment to show the capabilities of our glove. Blender is a professional, open-source 3D graphics toolset. It's capable of animation, effects, printing 3D models, and most importantly for us, interactive 3D applications. We'll be using Blender to demonstrate the following abilities of our glove:

- Motion tracking
- Hand formation tracking
- Vibrations at different frequencies
- Peltier device at different temperatures

Our reasons for choosing Blender are numerous. For one, its flexibility allows us to do anything we need in one program. From modeling to animating, adding effects, and scripting, we can create our project while keeping any other programs' usage to a minimum. This is good because it saves time on learning to use many programs and prevents potential compatibility issues in the future, and at the same time blender can be easily used in conjunction with many other programs. If the need to incorporate more software into our project arises, or if we need to switch to different software outright, using blender will make sure most of our work is still usable, and any losses in progress will be kept at a minimum.

Another reason to use blender is that it's free and open source. This keeps our project's budget at a minimum, because we won't have to pay for professional, proprietary software that could potentially be very expensive, all while still allowing us to keep rights to whatever we create. It also means that the skills accumulated in creating this project will be useful in future endeavors, as familiarity with blender and the skills and concepts associated with it are very useful in today's job market.

Blender also has a wide user-base, and is described as "a public project, made by hundreds of people from around the world" on their website. Consequently, it has a ton of resources and assets publicly available. This means we can save a lot of time by using public assets that are at our disposal. If done from scratch, we would have to model every piece of environment, the hand, and any interactive objects, then texture and animate them all on our own. Using public assets allows us to skip many of these steps, which will save us days and possibly even months of work.

Most of the work will be modifying public assets and scripting them to interact with the rest of the 3D environment and consequently the glove itself. The end goal is to have a demo that shows all the aforementioned capabilities of our glove and getting our glove to interact with the demo on-screen.

The idea for the final product for our demo will be as follows: In blender we will have a modeled hand that can change itself to match the user's hand that is wearing the glove. It will move around the environment as the user moves his hand. This is how the motion tracking of the glove will be demonstrated. If the user moves their hand left, the hand in the engine will also move left, and vice versa. Our aim is to match the distance that the hand in the 3D engine moves to the user's hand as closely possible, in order to give an immersive experience that "feels real." This will likely have many applications in VR technology.

The in-game hand will also be able to form into the shape that the user is making with his hand. This makes use of the accelerometers implemented into the glove design. This is how we will demo this part of the glove. Like with the hand tracking, this will try to be done as accurately as possible for an experience that "feels real."

Another feature of the glove to demo is the vibrations integrated into the glove. The idea is to use this so that the user feels feedback from the vibration whenever they control the hand to touch something in the 3D world. The glove will vibrate the points of the hand that are "touching" a 3D object and resonate at a frequency that will be higher depending on the "toughness" of the object, which will be a variable associated with 3D objects that differentiates between objects made of "soft" materials and those made of "hard" materials, and the speed at which the 3D hand collides with the 3D object. This will simulate "feeling" this with your hand in the 3D environment and could have very useful application in making an immersive experience in VR or other technologies.

The last feature of the glove to demo is the Peltier device, which are chips integrated into the glove that can heat or cool. The objects that the hand can interact with in the 3D world will have a "temperature" variable associated with it. When the hand is in contact with an object, the temperature on the Peltier chips will adjust to be warmer or cooler based on the object. This will simulate temperature in the 3D world, if the user has the hand pick up an object that's hot, the Peltier chips will make it "feel hot," and vice versa for cold objects.

To demonstrate all of this at the same time, the demo will have a table with multiple objects that the glove can interact with. This will make demonstrating the features of our glove much easier as we'll be able to do it all at once in one sitting. There are multiple ways to use these objects to demonstrate these features: A blue ball with a lower "temperature value" and a red ball with a higher "temperature value" to show the Peltier devices, a "soft" and "hard" ball that can demonstrate vibrations, or a "stove top" on the table with a field that will warm the Peltier chips when the hand is in the field. This environment will have to be created, modeled, textured, and scripted using blender.

We'll start by creating a demo without the glove, so we can make sure physics and interactivity works before we implement our device. We can start the making the demo by creating the table, followed by making the ground, a block to place on top of the table to test the physics, and a placeholder hand. Once these assets are implemented, we can script the objects to react to gravity and collisions, make the hand controllable with the keyboard, and position the camera and allow it to be controlled with the mouse. We will also need to texture everything, so it looks more presentable, and possibly add a skybox as well to make it more immersive.

11.1: Modeling & Object Creation

Blender gives us many tools to help create the demo for our project. The first thing we do is change the unit type in the scene tab to "Imperial." This means the units will represent feet and inches, which will be helpful for us because it helps correlate between lengths in real life and lengths in the demo environment, and imperial units make the most sense for this because they're more common in United States. We want to do everything we can to make the demo feel like a real application and keeping scaling consistent will help with that.

The create tool allows us to make many basic shapes and objects, and we will use it to make several basic objects for the demo. Now we're going to make a table, which will have many demo objects placed on top to help with our demonstration. This is done using a series of cubes that we modify. The desktop is a cube transformed to be thin and wide, while the legs are all cubes made to be tall and skinny. Then we position them together and combine it with Ctrl-J to turn into one object and rename it to "table."

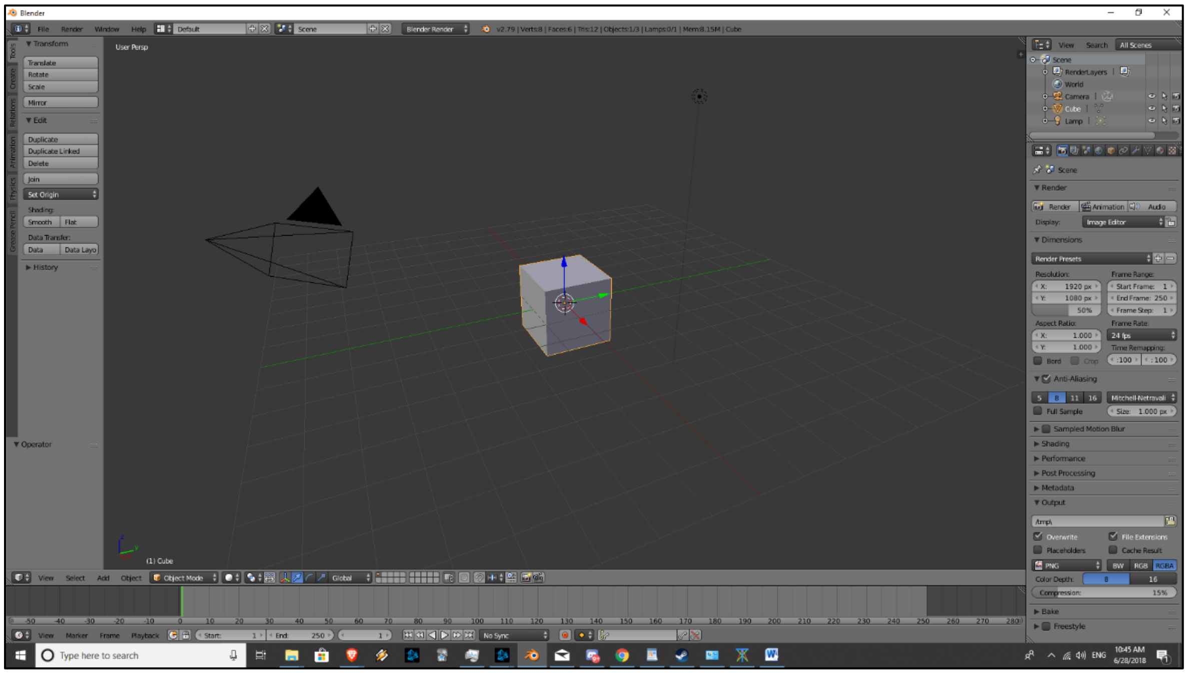


Figure 45: Screenshot of Blender Interface

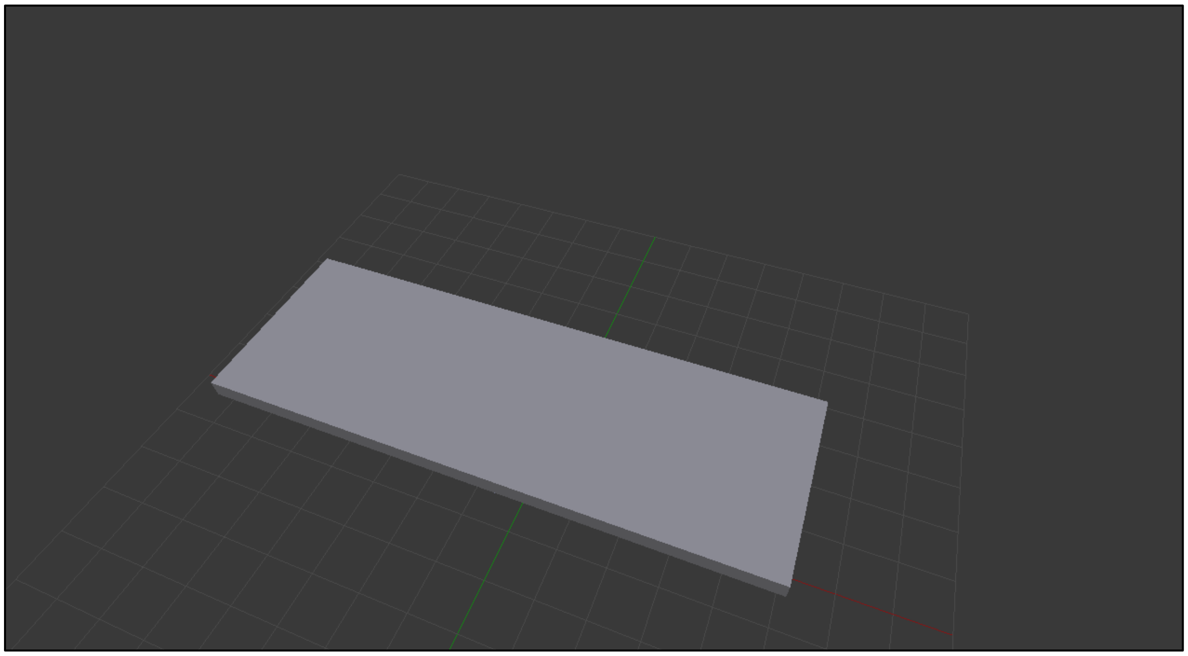


Figure 46: Table before legs were added

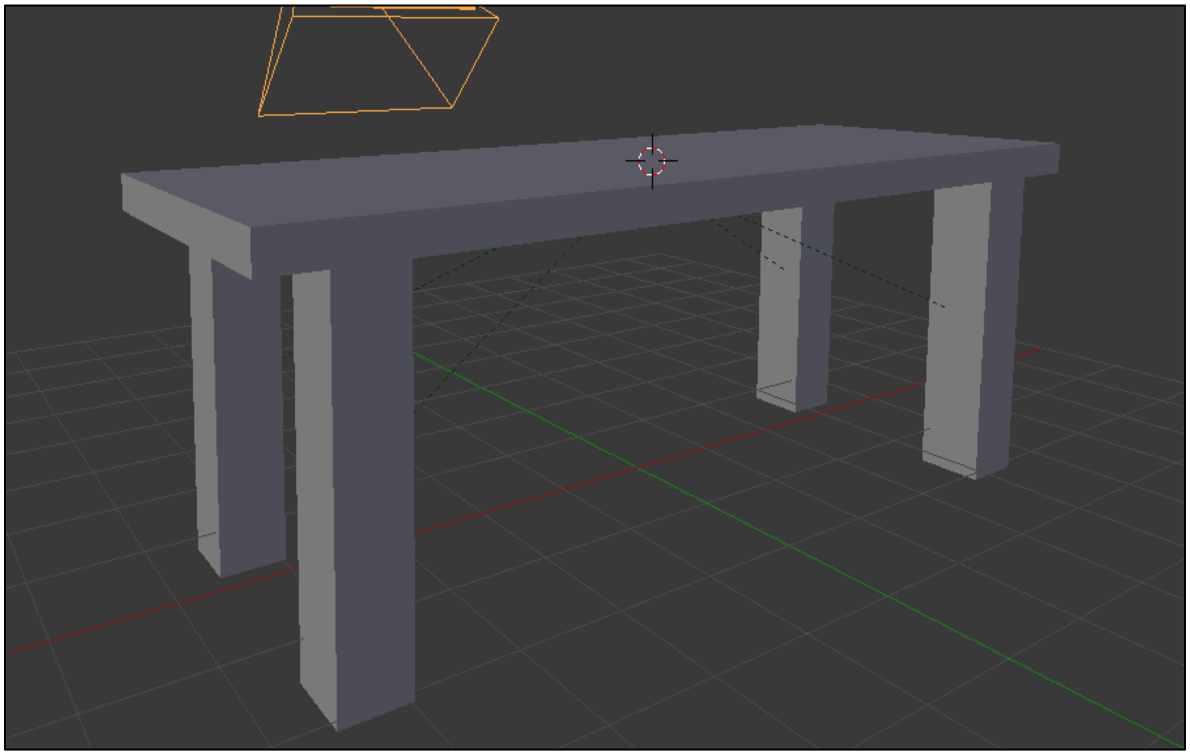


Figure 47: Table after legs were added

Now we need to add a ground. This is very simple, I just create a mesh with the same tool I used to make the blocks and use the properties window to change its location to (0,0,0), at the center of the 3D space, and increase the scaling on the x and y plane to make it large enough to fit everything on.

Once we have that, we need to import a hand model. Modeling out a brand-new model is time consuming, so importing a free one is ideal. free3d.com is a website that specializes in royalty free assets, from which we can get a royalty free model to use for our project.

[20] The model we've imported is "Realistic Hand 3d model" from user "mohammadalizadeh" on free3d.com.

Figure 48: Cover image of imported hand

Once downloaded, we simply use File -> Import -> 3d Studio (.3ds) and select the downloaded file and the hand model is now in our program. The hand is a little too large, so I use the properties window to scale it down to 0.1 on all axes and change the rotation to have the fingers forward facing towards the table at start.

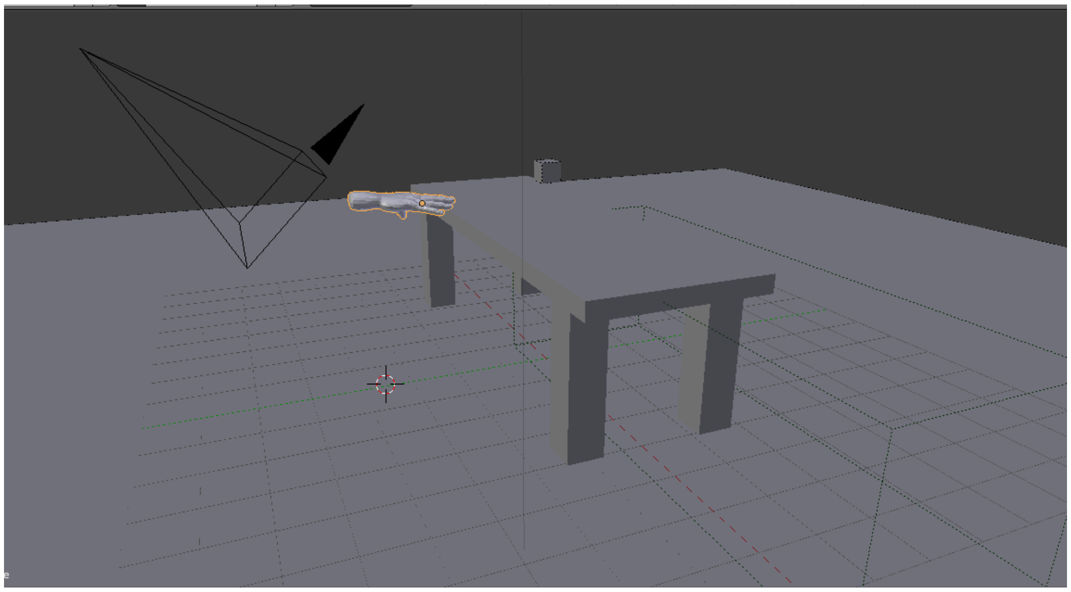


Figure 49: Completed table and plane with imported hand

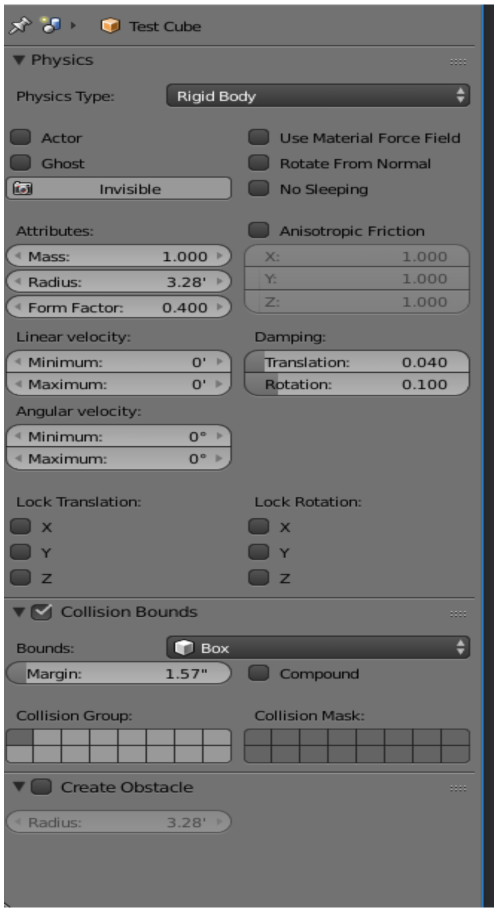
We've also added a block above the table to test the physics and positioned the camera to where it'll need to be for the in-game vision.

11.2: Physics Implementation

Adding the physics is actually very easy to do in blender. We change the “gravity” value under the scene tab in the properties window to 32.2 ft/s^2 to emulate real life. Now we use the “physics” tab in the properties window, where we can change the physics type of each of the objects. For the table and the block, we change the physics type from “static” to “rigid body.” This causes these objects to be affected by gravity, so they’ll fall until they collide with something else or the plane we’ve used as the ground. For the plane, we leave the physics type as “static,” as we don’t want that to fall. The camera will also be left as static so that it doesn’t move.

The hand will be controlled with the keyboard for now and later changed to be controlled with the glove. We change the physics type for the hand to “dynamic” for this reason. This leaves us with a problem, as the hand will now be affected by gravity, but we want to be able to control it. There’s many ways around this issue, this will be addressed when we script it.

With all this implemented, we can press “P” to start the engine and see that the block falls and rests on the table, while the table rests on the ground. To make the collision box for the block more accurate, we check the “collision bounds” box at the bottom of the physics tab and change the bounds to “box.” This makes the collision bound of the object more block-like.



Test Cube

Physics

Physics Type: Rigid Body

- [ ] Actor
- [ ] Ghost
- Invisible
- [ ] Use Material Force Field
- [ ] Rotate From Normal
- [ ] No Sleeping

Attributes:
Mass: 1.000
Radius: 3.28'
Form Factor: 0.400

- [ ] Anisotropic Friction
X: 1.000
Y: 1.000
Z: 1.000

Linear velocity:
Minimum: 0'
Maximum: 0'

Damping:
Translation: 0.040
Rotation: 0.100

Angular velocity:
Minimum: 0°
Maximum: 0°

Lock Translation:
- [ ] X
- [ ] Y
- [ ] Z

Lock Rotation:
- [ ] X
- [ ] Y
- [ ] Z

[✓] Collision Bounds

Bounds: Box
Margin: 1.57"
- [ ] Compound

Collision Group:
Collision Mask:

[ ] Create Obstacle

Radius: 3.28'

Figure 50: Physics settings for the block

11.3: Scripting & Logic

Now we will script the hand and camera. We create another window and use the button in its corner to select "logic editor." Here we can put together "logic bricks" that form simple code. The logic editor also supports python code which we might implement later but for now we'll implement a few simple logic bricks.

We want the hand to move when we press a key. In this case, we'll use "W" because we want to be able to use the mouse to move the camera around at the same time. The logic editor has three types of bricks: sensors, controllers, and actuators. To make the hand move forward with W, we create hit the "Add Sensor" dropdown box and select "Keyboard." Then we name the sensor "W" and set "W" as the key for the sensor. Now we add an actuator and select "Motion." We use "Simple Motion" for the motion type and enter -0.1 for the x value under "Loc." This will cause the hand to move forward 0.1 on its relative x axis when it senses that "W" is pressed. Now we click on the black dot next to the sensor and drag it to the actuator. This creates a controller brick automatically, which we will leave set to "and."

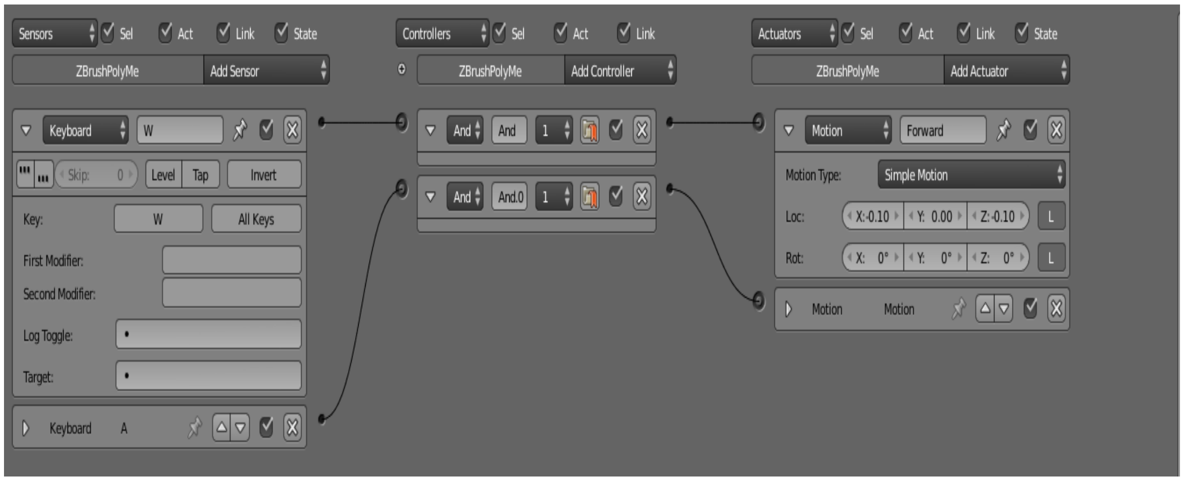
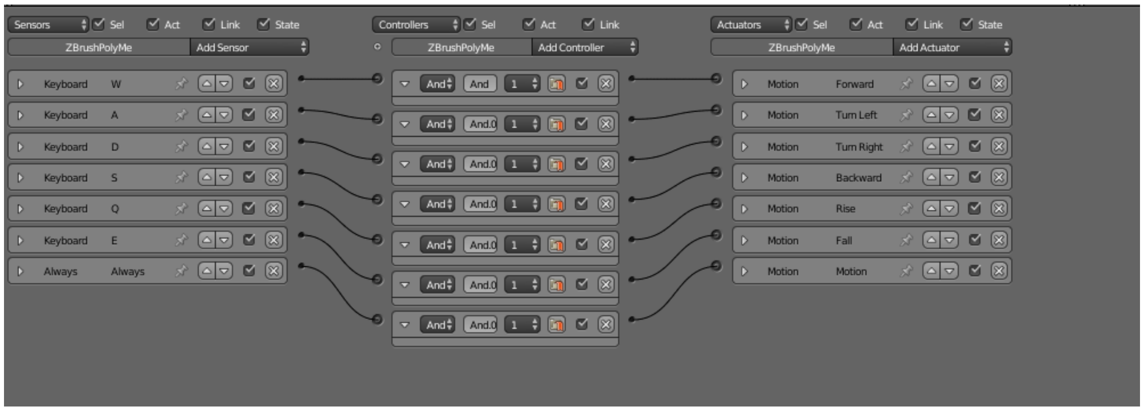


Figure 51: First logic brick for the hand

We can repeat the same process with the "S" key to make the hand able to go backward. The only difference is we set the loc value "0.1" so that it will move the opposite way.

Now we need the hand to be able to turn with A and D, which can be implemented similarly to forward and backward. We make another keyboard sensor for "A" and "D," and then two more motion actuators. This time we change the "Rot" values instead of "Loc," and input 5 for the Z value. This causes the hand to rotate 5 degrees on its relative Z axis whenever it detects that "A" is pressed. We then use -5 for our other actuator and draw lines in-between our sensors and actuators to create the controllers. The hand will now turn with "A" and "D" inputs. We also implement a few more logic bricks to script the hand to raise and lower when the "Q" and "E" keys are pressed.

There's one more thing that needs to be scripted for the hand (at least for now). The hand is set as a dynamic object and is thus affected by gravity, but we want to be able to control the hand freely so it doesn't drop to the ground as soon as the program starts. We make an "always" sensor and another motion actuator. For this actuator we choose motion and give it a force value in the Z direction. This force will always cancel out with the gravitational force, so it produces the effect of the hand not being affected by gravity.

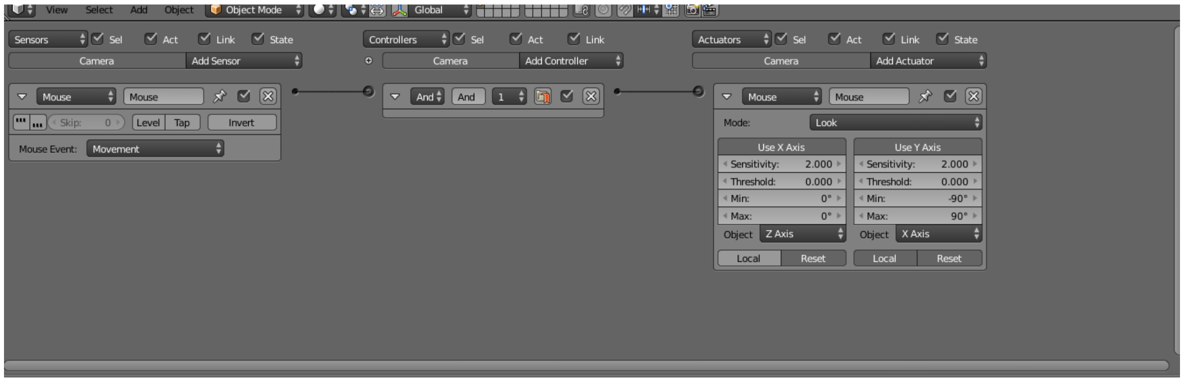


Sensors	Controllers	Actuators
ZBrushPolyMe	ZBrushPolyMe	ZBrushPolyMe
Keyboard W	And	Motion Forward
Keyboard A	And	Motion Turn Left
Keyboard D	And	Motion Turn Right
Keyboard S	And	Motion Backward
Keyboard Q	And	Motion Rise
Keyboard E	And	Motion Fall
Always Always	And	Motion Motion
	And	

Figure 52: Full logic brick for the hand

Now the logic programming for our beta hand is complete. When we start the game engine the hand can be moved with the keyboard and will collide with the block on the table and knock it over. The only thing left for scripting is the camera.

Setting up the camera control is actually very simple; we select the camera and open up the logic editor. We make a "Mouse" sensor and a "Mouse" actuator and connect them. Then we set the Mouse actuator mode to "Look," and it's complete.



Sensors: Camera — Mouse Mouse; Mouse Event: Movement
Controllers: Camera — And And
Actuators: Camera — Mouse Mouse; Mode: Look

Use X Axis		Use Y Axis	
Sensitivity:	2.000	Sensitivity:	2.000
Threshold:	0.000	Threshold:	0.000
Min:	0°	Min:	-90°
Max:	0°	Max:	90°
Object	Z Axis	Object	X Axis

Figure 53: Camera logic brick

Now we can select "view" in the 3D viewport and select "camera." When we start the game engine, we'll be looking through the camera, and can control it with the mouse.

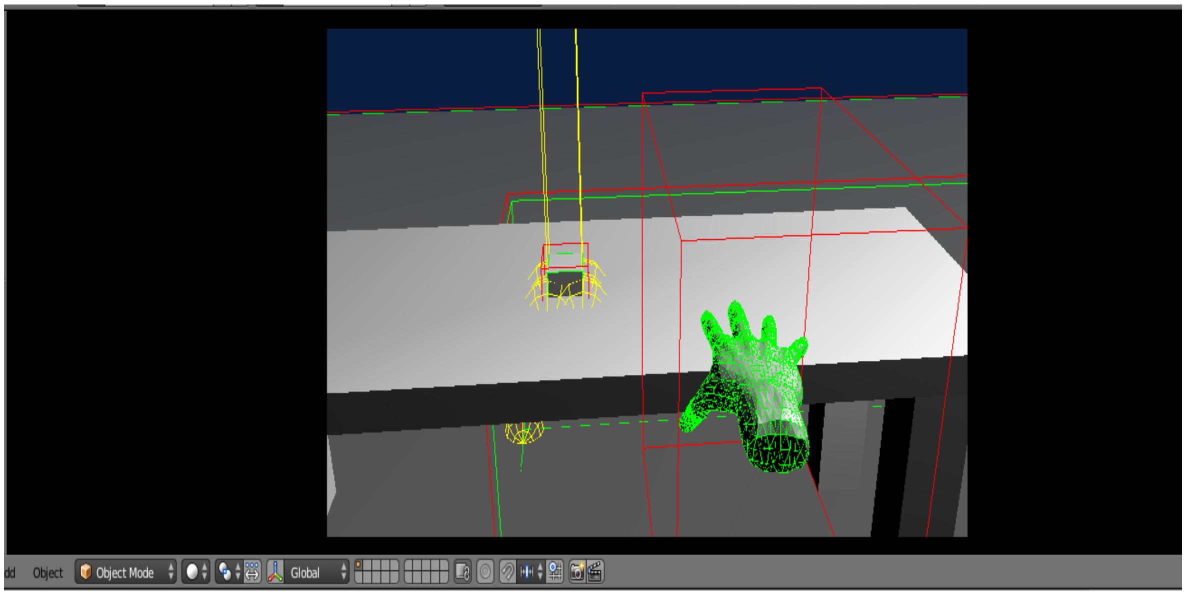


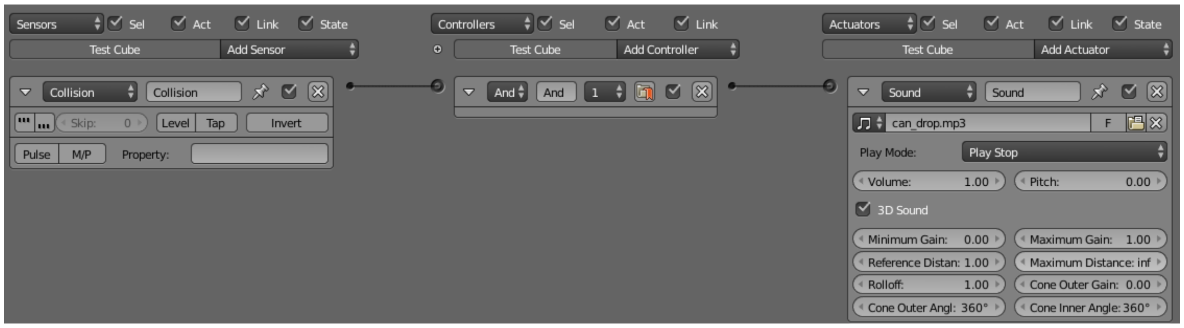
Figure 54: Camera Viewpoint

11.4: Sound Effects

Another way to add immersion to the virtual reality experience is through sound effects. The sound effects come from freesoundeffects.com, a royalty and license free website that provides numerous sound clips for us to use. [21]

The following is an example: We give the cube a collision sensor to play the sound effect of a can dropping. Now whenever the cube comes into collision with another object, the “can_drop” sound will play. This gives the sphere a “hollow” feel to it, since it has an airy tin sound upon impact.

Blender also has a built in “3D Sound” feature, which will make the direction of the sound come from the direction of the object in the user’s headphones, which can be adjusted in volume, gain, and distance limit however we want. This is especially important for a virtual reality project, as being able to tell where the direction from which sound effects are coming from is an important aspect of the immersive experience.



Collision   Collision
Skip: 0   Level   Tap   Invert
Pulse   M/P   Property:

And   And   1

Sound   Sound
can_drop.mp3
Play Mode: Play Stop
Volume: 1.00   Pitch: 0.00
3D Sound
Minimum Gain: 0.00   Maximum Gain: 1.00
Reference Distan: 1.00   Maximum Distance: inf
Rolloff: 1.00   Cone Outer Gain: 0.00
Cone Outer Angl: 360°   Cone Inner Angle: 360°

Figure 55 Sound Effect Implementation

Using this same scripting, we can implement sound effects on any objects, and script them to be ongoing or one time, or add ambient music that always plays, giving our demonstration one more layer of immersion.

11.5: Texturing

Now we'll add a few textures to our objects. This will help make our demo look much more presentable. Our textures we'll come from the 3dtotal. This will give us royalty free textures to use for our project. [22]

We can do this by opening up another window and changing it to the UV/Editor. Here we can upload the textures we want to use. For now, we'll apply three textures, one for the table, one for the hand, and one for the plane.

Now we select an object and go to the "materials" tab in the properties window to create a new material for the texture. From here we change the 3D viewport to "edit mode" and start selecting objects that we need to texture. The edit mode allows us to be very specific with how we want to apply textures, by letting us choose individual faces of each polygon and choosing the texture and editing it individually for each segment, but for now we can simply apply the texture to the entire object.

Here are the textures that we'll be using for this prototype: The table has a wood texture to make it look like a wood table, the plain has a grass texture to make it look like a grassy terrain, and the hand has a skin texture to make it look like a human hand.

Figure 56: Grass texture

Figure 57: Wood and Skin Textures for the table and Hand

Figure 58: Skin Texture for the Hand

Once the selection is made we simply use the "unwrap" option to have the texture is fully visible. We repeat this process for each texture we want to apply.

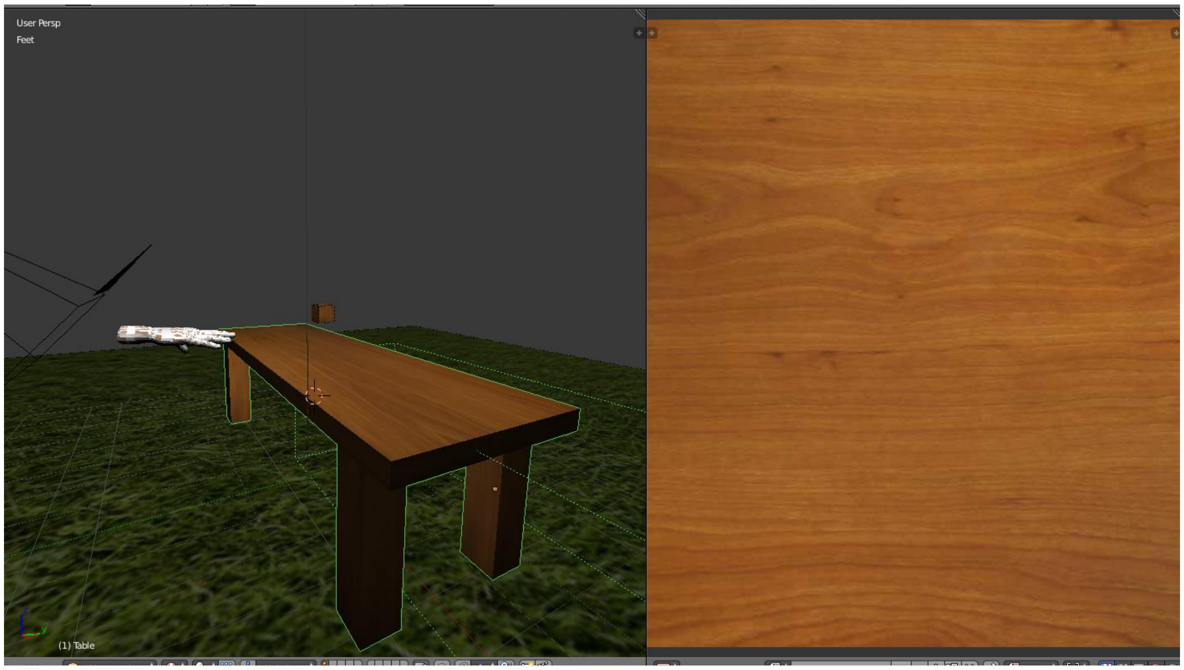


Figure 59: Texture editing in blender

One last thing we can do to make the prototype demo look more presentable is to change the horizon color to more resemble a sky in the middle of the day. Once we put it all together here's what our prototype demo looks like:

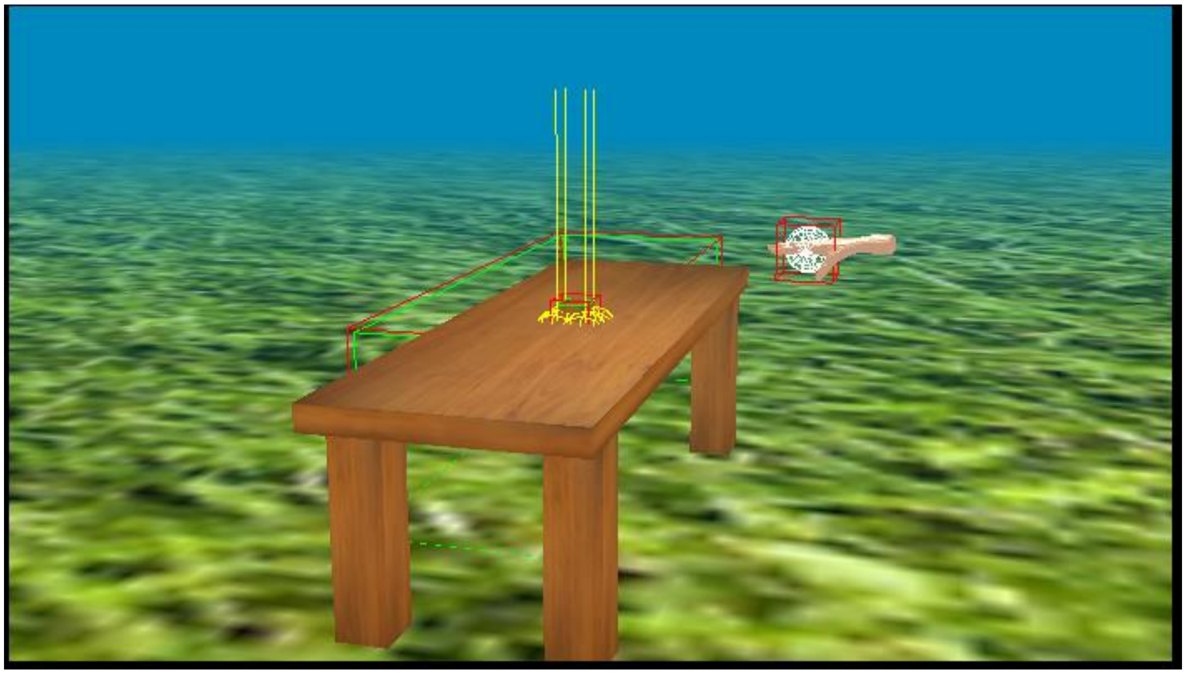


Figure 60: Textured and colored prototype Environment

12: HTC Vive & Setup

Our product will be demonstrated with the HTC Vive. The glove doesn't necessitate use of any virtual reality headset, nor does it require use of virtual reality to function. That being said, the idea for this project was made to be implemented with virtual reality, as it can greatly enhance the current virtual reality experience. Because of this, we want to demonstrate our device's functionality in conjunction with virtual reality.

We chose the HTC Vive for our demonstration because it's a high-quality headset that is compatible with a lot of software due to SteamVR. It has a resolution of 1080 by 1200 pixels per eye, a 90Hz refresh rate, and a 110-degree wide field of view. It comes with two base stations, also known as lighthouses, which make tracking possible in a room setup. It also comes with two controllers, but this won't be used for our demonstration.

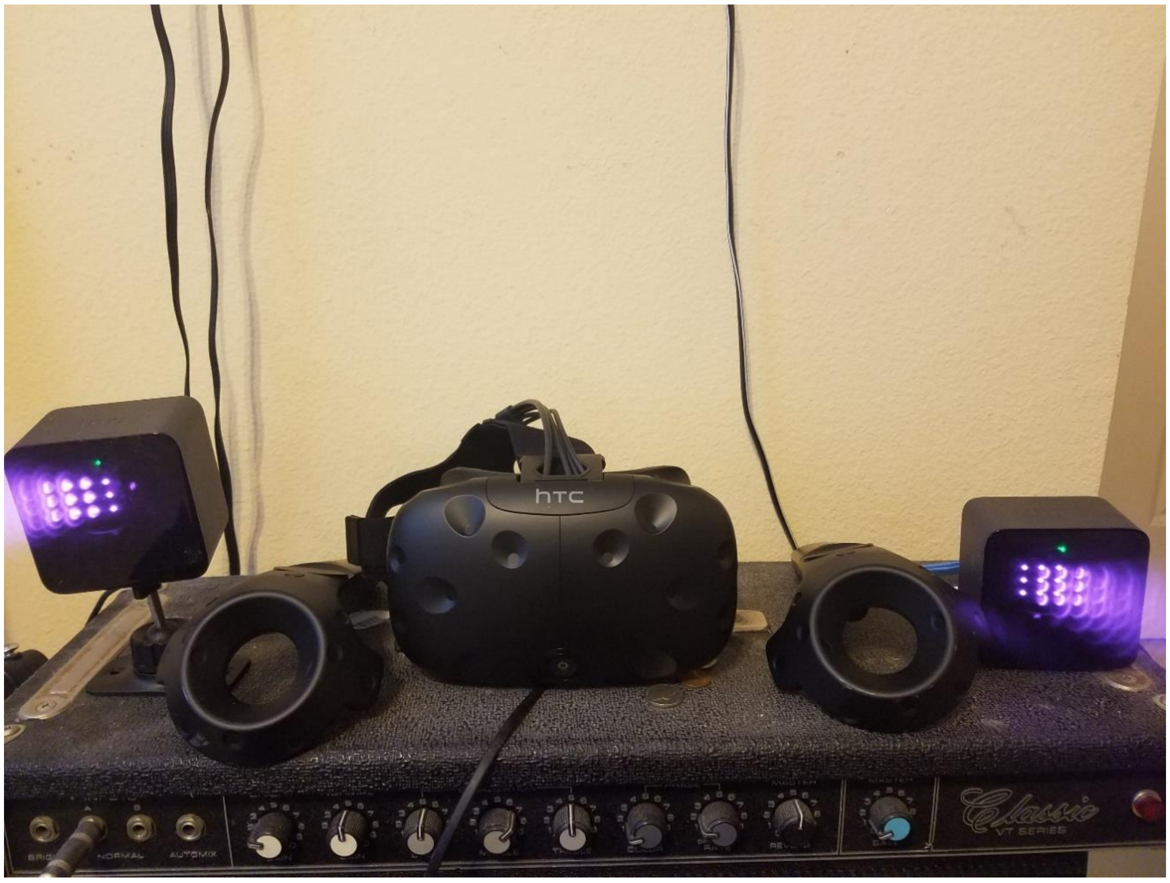


Figure 61 HTC Vive with two lighthouses and controllers

The Vive also has a front camera and an audio jack installed. The audio jack will allow sound effects incorporated into the demo to be heard.

SteamVR is compatible with most virtual reality hardware, from Google Cardboard to Oculus Rift. It's also royalty free with no licensing fees and no requirement for approval. [23] This means that whatever we create will be compatible with almost any virtual reality system and it won't cost us anything to develop with. SteamVR is also one of the most widely used virtual tracking systems today, so any virtual reality consumer will already be familiar with it.

The Vive itself requires a little bit of setup to use. Its biggest feature is its room tracking technology, which lets you walk around a room in virtual reality. This requires two lighthouses on each corner of the room, which should be station 6 feet 6 inches off the floor, in a 6 feet 6 inch by 5 feet clear area. It also requires a wired connection to the PC because it needs a direct connection to the video card, as well as a USB connection and a power connection. The PC will run the software, and the glove will be connected via Bluetooth. The lighthouses require a power connection through the wall and communicate wirelessly with the headset.

Once the setup is complete, our glove will be ready to perform with our demonstration loaded up. The user can explore a 3D space in a 5 feet by 6.5 feet area and interact with the environment using the glove.

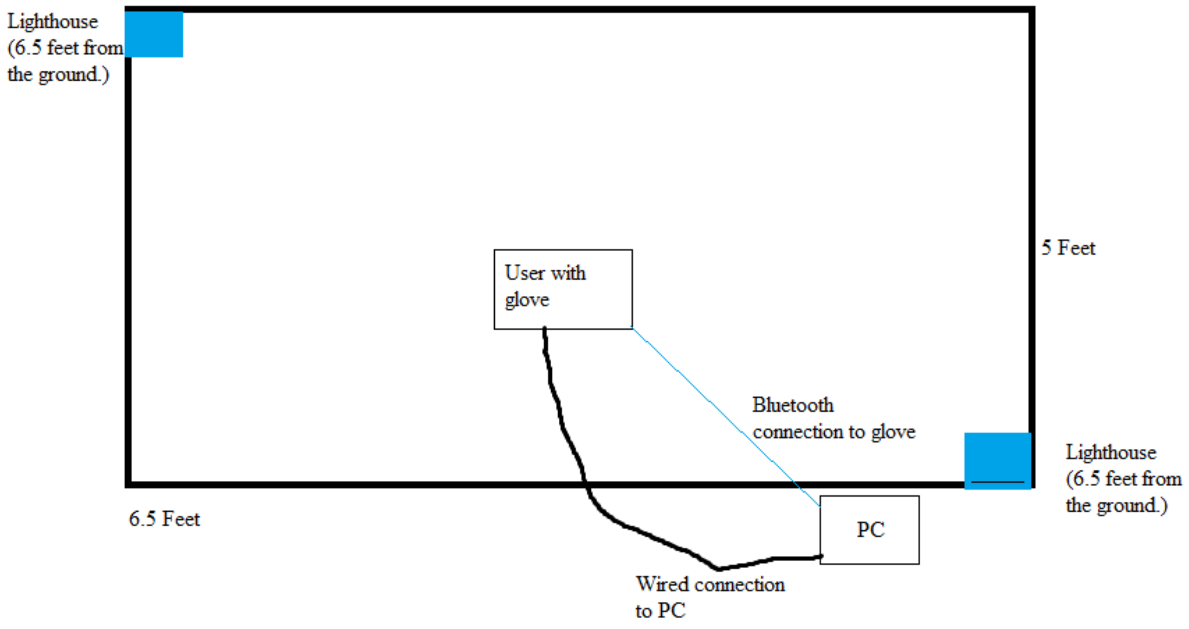

Lighthouse (6.5 feet from the ground.)
5 Feet
User with glove
Bluetooth connection to glove
Lighthouse (6.5 feet from the ground.)
6.5 Feet
PC
Wired connection to PC

Figure 62 Room setup with HTC Vive

13: Implementation of Virtual Reality

One of the most important parts of our project demo is to incorporate a virtual reality headset to show the strength our device can have when used in conjunction of a virtual reality setting. The first step to doing this is, is to incorporate the use of a virtual reality headset, in our case an HTC Vive, into blender.

There are many ways to do this, that work for many different sets of virtual reality hardware. One of the simplest ways is to use a slightly modified version of the free open-source blender addon "virtual reality viewport," by dfelinto. [24]

This addon allows for virtual reality in the viewport of Blender, helpful for building things in reference to the headset. More importantly, it allows us to attach cameras to the headset position and display them on the HMD.

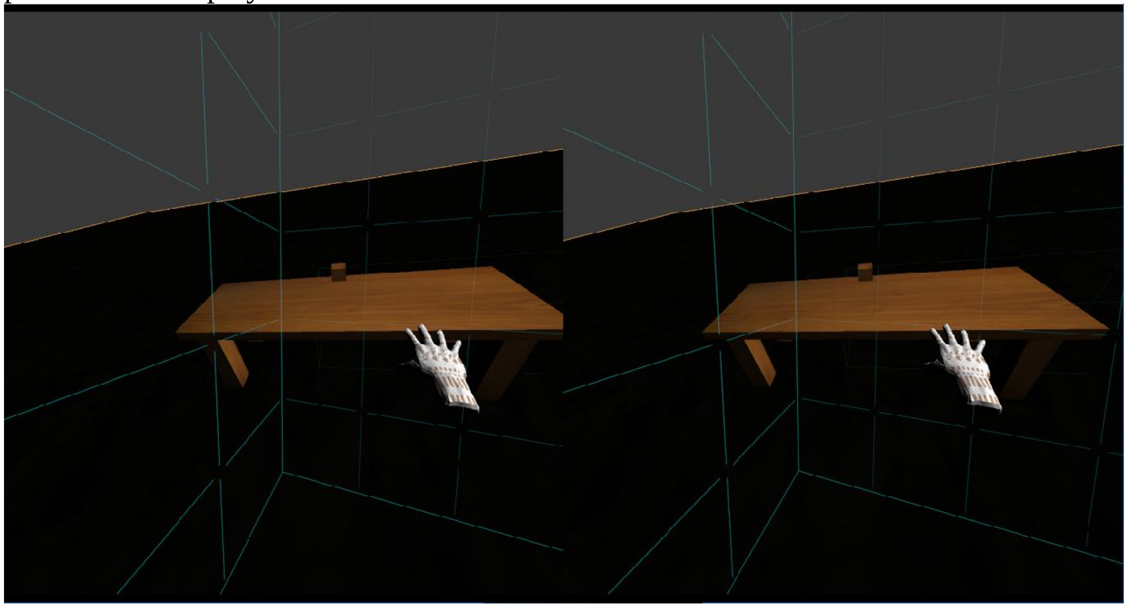


Figure 63: Blender displayed in Vive HMD

The head is tracked by the lighthouses, and the camera attaches to the location provided by the SteamVR tracking. The "center" of the headset's standing space will be set to be right in front of the desk. From there, the user will be able to look around the desk and walk a short distance around the desk.

The headset itself will be programmed as a reference point for the hand. The hand will be calibrated to the headset, and then the position of the hand will be calculated as a distance from the hand based on the head as an origin point. This makes the most sense because the headset will represent where the user's "viewpoint" is in real life.

The screenshot shows the display on the Vive HMD, being reproduced as a flat image. With this set up we can include all the functionality of a VR headset, including tracking, motion-sensing, and 3D image generation.

13.1: Skeleton Rigging and Animation

Since finger tracking is one of the most important features of the glove, arguably even the most important, we're going to need the hand in our demo to be able to represent that, and to do that we're going to need the fingers on the model itself to move in conjunction to the glove's finger movements. This is where rigging comes into play, where we create an animation rig for the hand and script it to move according to inputs it receives.
The first step is to create an armature in blender. Then we can scale it down and start incorporating it into our hand model.

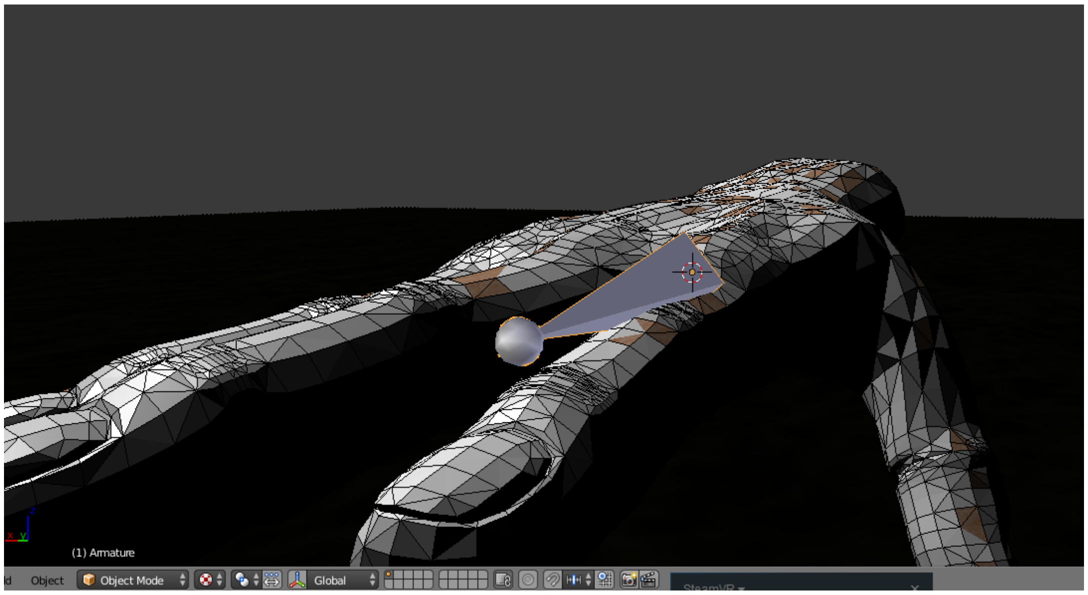


Figure 64: Incorporating a skeleton into the hand

Wireframes are very helpful for this, because they allow us to see through the models and see what we're doing.
Once we have the first bone placed, we can use the extend tool in edit to create a network of bones to animate the hand with.

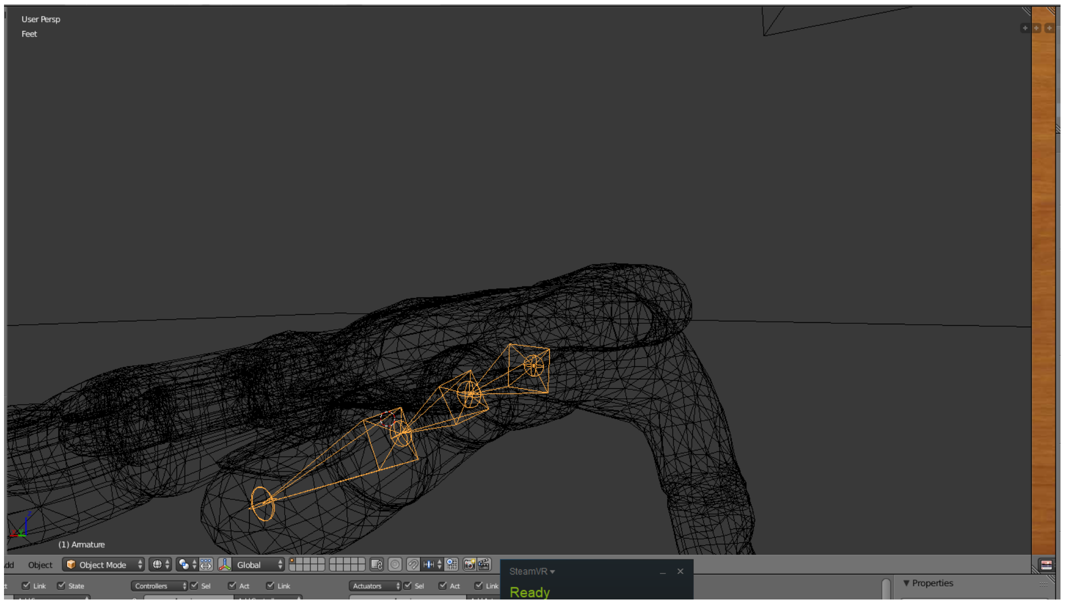


Figure 65: wireframe and skeleton for index finger

Three bones are used for each finger to match the number in the human body as well as make it match more consistently with our device. Each finger will be able to rotate on three axes.

With a skeleton placed for one finger, we can now pair it with the mesh to make the finger fully adjustable. Once the pairing is done, the mesh (and our hand) will move freely with the animation rig.

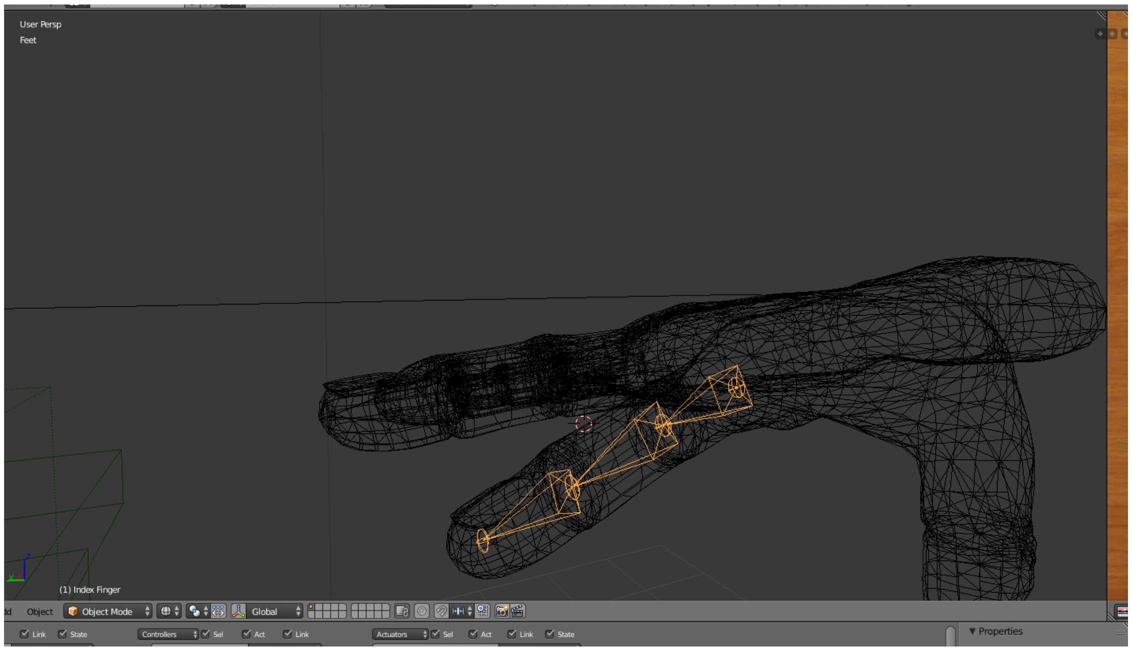


Figure 66: Example of finder adjustability

Now that this is done with one finger, the process can be easily repeated and done for every other finger. The thumb will be done a little differently because it only has two thumbs, so it will have slightly different scaling and only two bones.

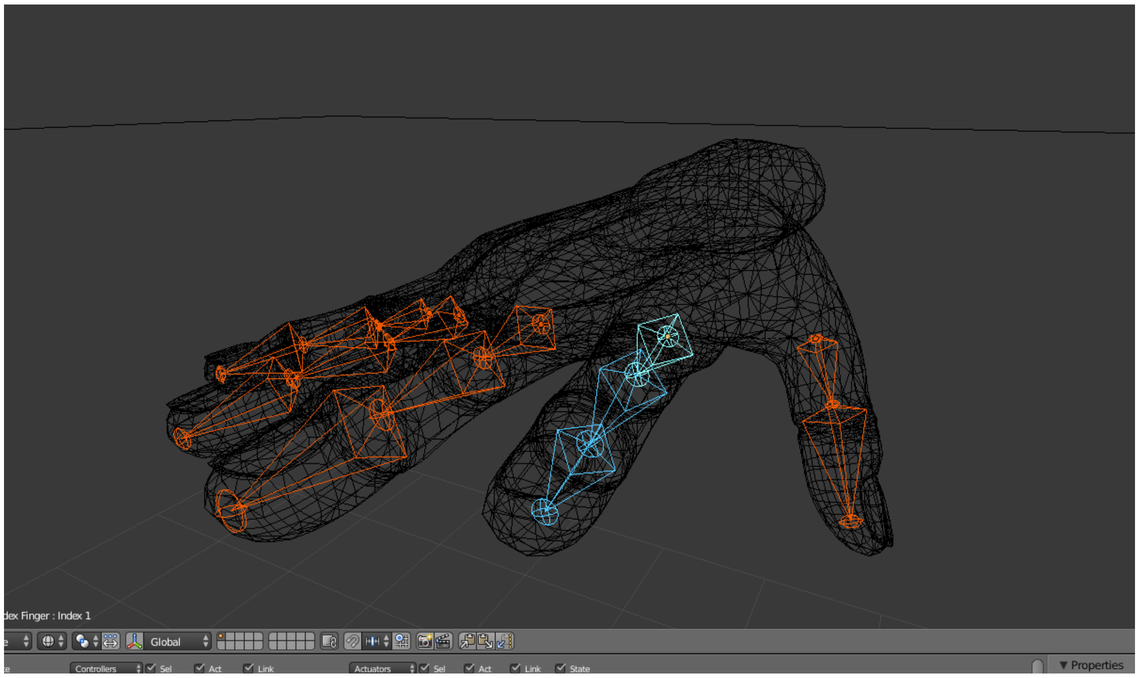


Figure 67: Animation rig compelte for hand

The result: A fully functional hand that can bend to a shape the same way that a normal hand can for use with our device.

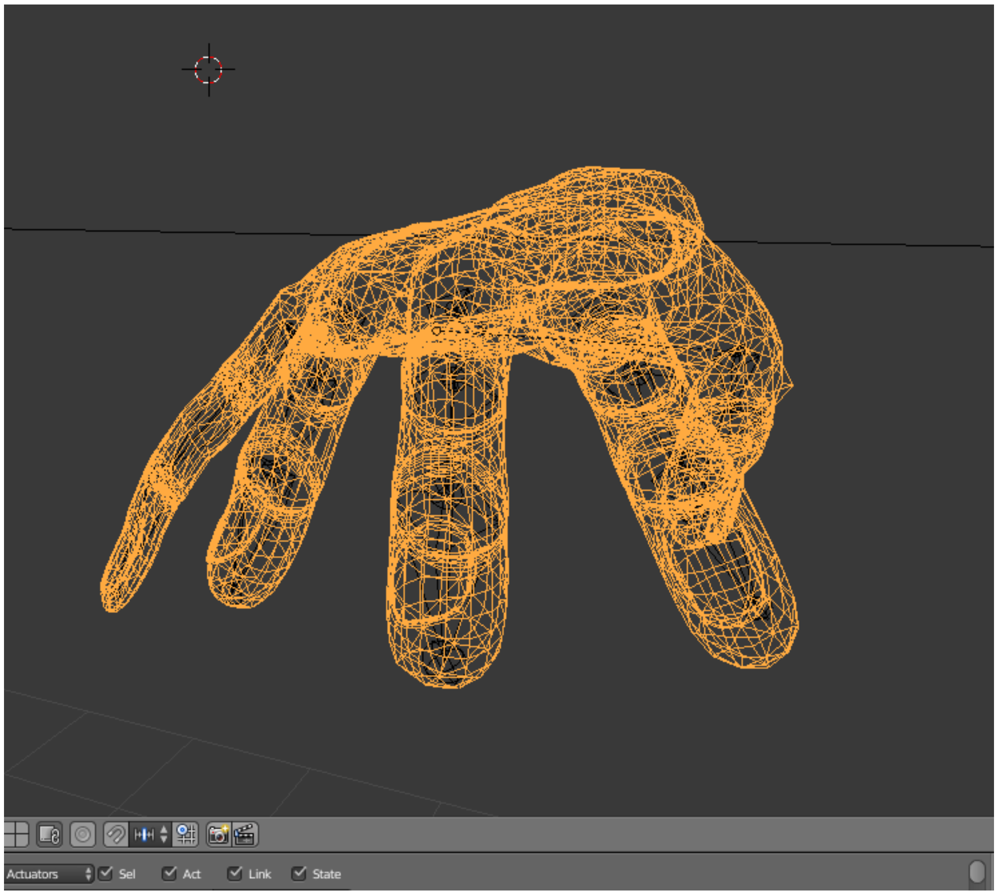
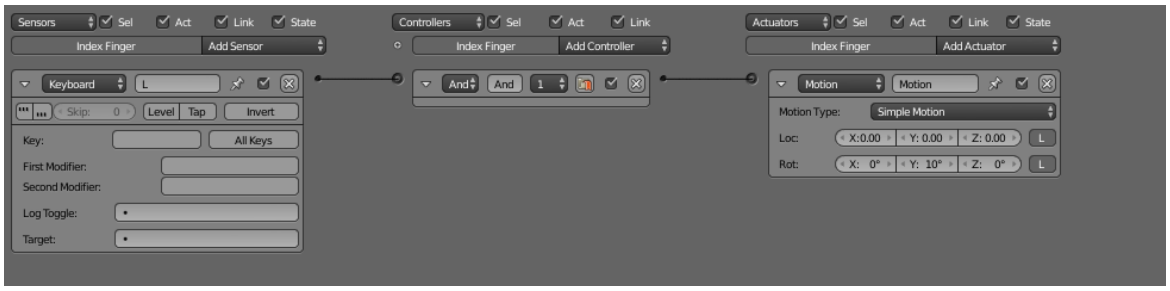


Figure 68: Hand Flexibility Example

Now that we have a complete hand, we can test it with scripting to make it move with a keyboard input. As long as this works, it will be easily implemented when it comes time to use our device with this demo.



Sensors ✓ Sel ✓ Act ✓ Link ✓ State
Index Finger | Add Sensor
Keyboard | L
Skip: 0 | Level | Tap | Invert
Key: | All Keys
First Modifier:
Second Modifier:
Log Toggle:
Target:

Controllers ✓ Sel ✓ Act ✓ Link
Index Finger | Add Controller
And | And | 1

Actuators ✓ Sel ✓ Act ✓ Link ✓ State
Index Finger | Add Actuator
Motion | Motion
Motion Type: Simple Motion
Loc: X: 0.00 | Y: 0.00 | Z: 0.00 | L
Rot: X: 0° | Y: 10° | Z: 0° | L

Figure 69: Scripting For Finger Rotation

With this script we can command the index finger to rotate with an ‘L’ press. Now we’ll be able to incorporate the glove and change the script to change the angle by whichever means we feel necessary using the glove’s input.

14: Bringing it all together

Now that we have the key features, let’s add a few things in that will make our demo ready for our device. Keep in mind that the main things we need to demonstrate are: Motion, haptic feedback (vibrations), and temperature change (Peltier devices). For this, we added a few more objects to the desk.

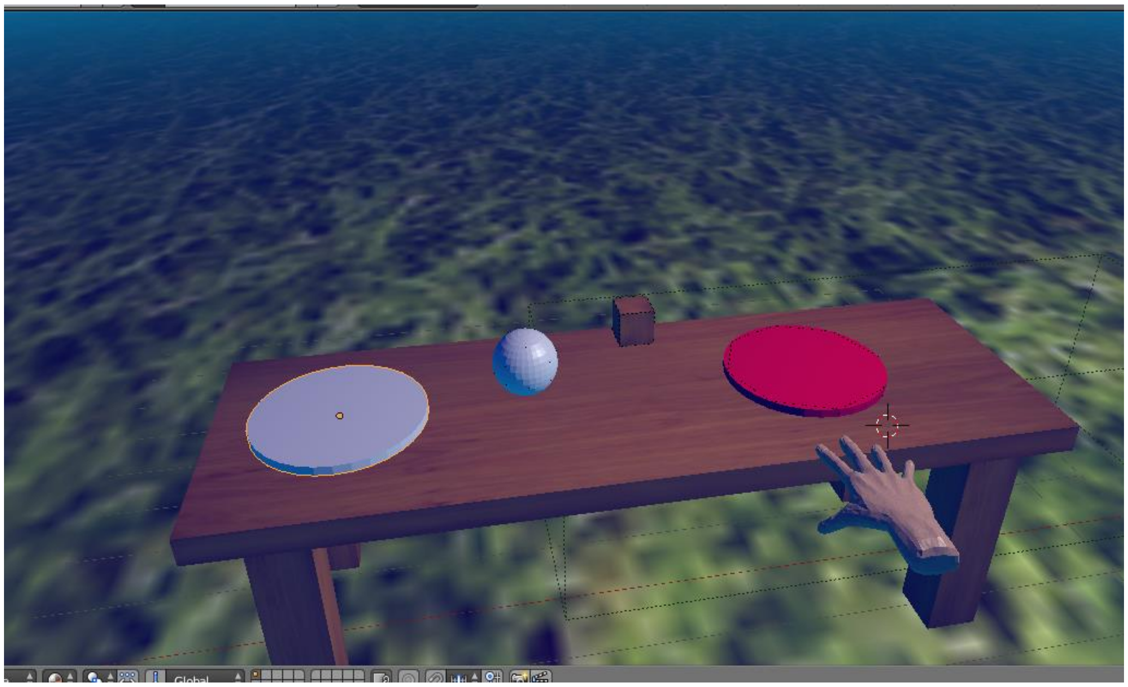


Figure 70: More objects added to desk

The first of which is a sphere, which is added for two reasons. The first one is to be able to demonstrate the haptic feedback of the glove more thoroughly. The glove is designed to give haptic feedback at multiple “intensities,” so the sphere can simulate a “soft” material while the block can simulate a “hard” material. The glove’s haptic feedback will vibrate more intensely when coming in contact with the block than coming in contact with the sphere.

The second reason is to demonstrate the positional aspect of the haptic feedback. A sphere will be in contact at different points in your hand than a block when holding it. These different points will vibrate to more simulate the “feeling” part of the project in a more immersive way.

This will be done by adding an attribute to the objects that will be named “Mass” to each object in the demo. This value will be used as a coefficient for the frequency of the haptic feedback in the glove, which will also consider the velocity at which the glove collides with the object. In physics, momentum transfer is based off of mass and velocity, so we’ll have a function that takes the velocity of the hand coming into contact with the object and multiplies it with the mass value of the object it comes into contact with. This can be attributed to the object with the game properties tool as so.

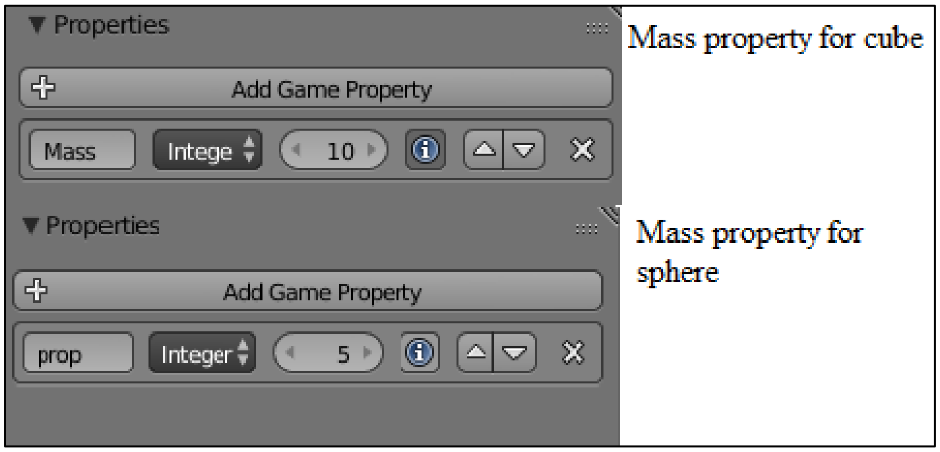


Figure 71: Mass properties for sphere and cube

The other two objects added are thin cylinders on either side of the desk, one colored blue and one colored red. This is a simple way to make "stove tops" that can be used to test the Peltier portion of the glove's functionality. The cylinders will be given a field of range, extending upward but not out to the side. When the hand enters these fields, the Peltier will heat or cool according to the color cylinder the hand is hovering above.
This can be accomplished by adding invisible, transparent, and taller cylinders on top of the ones we have. This will be the "field" of the stovetops, and we can script a function to begin when the hand comes into the space of these taller cylinders. This function will instruct the glove to start heating up or cooling down the Peltier sensors, depending on which cylinder the hand has entered.
Since we don't want the Peltier devices to reach over certain temperatures, we'll also script it to check the current temperature of the glove on top of detection collision with the invisible cylinders. This way the Peltier devices won't overheat or get too cold.

15: Device Driver & Input

In order for the device to communicate with the PC, a driver will be used. This driver is what will interpret the signals that comes from the glove via the Bluetooth signal that will be implemented. Blender will communicate with the driver to interact with the glove.

The device itself works in a differential system. Once the device is calibrated, the device will send data on how it's position changes over time. Because of this, the easiest way to implement the device into Blender is to have it detect the driver as a game controller and send inputs as the glove changes. Blender will take these inputs and adjust the in-game hand accordingly.

For the finger movement, Blender will take 'Axis' inputs, where each segment of each finger will have an 'Axis' event that the logic editor can keep track of. The axis will update based on the inputs from the driver, and the finger poses will adjust accordingly, allowing them to match the glove's hand formation.

For the hand tracking, two 'Axis' inputs can be used. Each input from the driver will be a different direction on the axis and based on that input the position of the hand will change accordingly. The two axes will be used to separately control the hand on the XY plane and the XZ plane, for full 3D movement.

Two more axes will be used for wrist tracking. The first axis will work similarly to the finger, where it will change the angle the hand is at based on the user's wrist angle. The second axis will be used for wrist rotation, which will allow the user to turn their entire hand on its side or upside down.

The Blender demo will also have to send data back to the driver for the haptic feedback and Peltier device. Blender will send an ID for which vibrator or Peltier device on the glove is being affected, and another value for the severity level. For the Peltier device the severity value will tell the device if it needs to cool or heat up and how quickly it should heat up. For the vibration, it'll give a frequency for each device to resonate at.

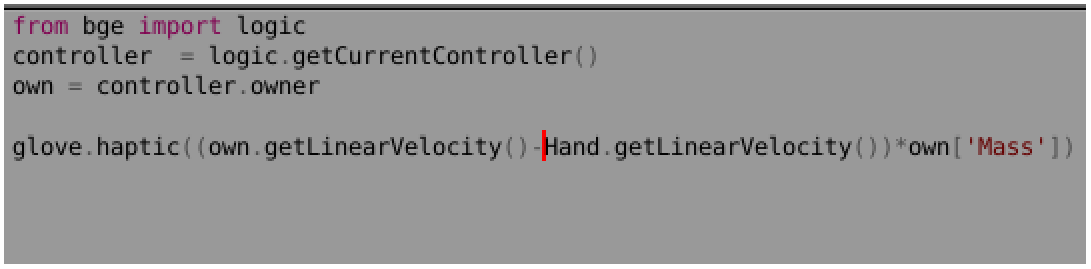
For the axis sensors, Blender already has built in axis sensors and controller detectors, making implementation for the hand movement easy to do. For the Peltier and haptic feedback devices, the actuator in the logic section will invoke a python script to invoke their effects.

Altogether the driver will be able to command the hand to move and adjust in the same fashion that the glove does, and Blender will be able to command the driver to have the glove Peltier devices change temperature and the haptic feedback devices vibrate at the rate as scripted.

16: Python Scripting

Blender allows for python scripting for more control on how the program works. This is done through its python API which contains a large library of functions capable of math, geometry, game logic, GPU functions, Audio Systems and more. [25] This is necessary for how we want to implement the Peltier and haptic feedback devices on the glove.

The following code is attached as a controller to a Collision sensor on the object. When the hand comes into collision with the object, it will use the getLinearVelocity() function from the logic API and multiply it with the 'Mass' property applied to the object.



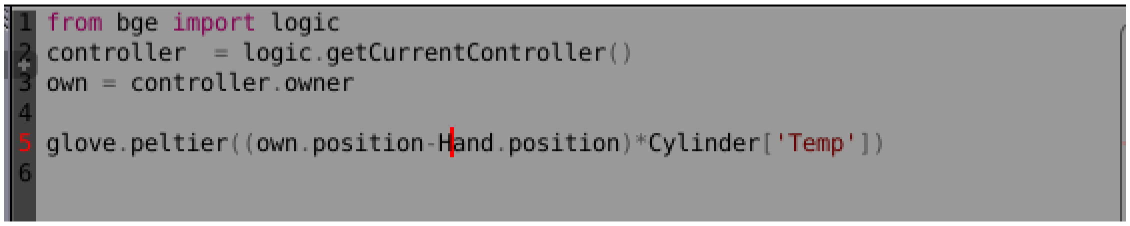
```
from bge import logic
controller  = logic.getCurrentController()
own = controller.owner

glove.haptic((own.getLinearVelocity()-Hand.getLinearVelocity())*own['Mass'])
```

Figure 72 Python Haptic Feedback Code

This script will activate when the hand comes into collision with the object, then it will calculate the difference between the hand's velocity and the object velocity, multiply it by the 'Mass' property, and pass it through the "glove.haptic" function.

The "glove.haptic" function is a function that will take a number and have the hand vibrate by a frequency based on the number that passes through it. This function will be made to interact with the driver to perform this functionality.

The Peltier function can be implemented in a very similar way using a collision detection in the invisible cylinders on the table that serve as the "field" in which the glove will heat up. Instead, it'll use a function to calculate distance from the object and a base value for the heat.



```
from bge import logic
controller  = logic.getCurrentController()
own = controller.owner

glove.peltier((own.position-Hand.position)*Cylinder['Temp'])

```

Figure 73 Python Script for Peltier Device

The distance is calculated by subtracting the hand position from the object position. This distance is multiplied by the 'Temp' property associated with the cylinder and passed through the function. The 'Temp' property on the red cylinder will be positive, and on the blue cylinder will be negative, which the driver will interpret into instructions to warm or cool the peltier device.

17: Configuration Utility

The Configuration Utility provides a configurable interface between the hardware glove and the 3D environment rendering software. The utility consists of two primary functions, data passing and configuration management. Data passing handles data transmission between the glove and the 3D environment. The glove passes the user's hand motion to the utility which forwards the data, so the 3D environment can update the position of the corresponding virtual hand. The 3D environment passes touch and temperature data through the utility which forwards the data to the glove to update the haptic and thermal feedback experienced by the user. Configuration management allows for multiple connected gloves to be mapped to their corresponding virtual counterparts. Each connected glove is individually configurable to allow for customizing both the haptic and thermal feedback intensity, along with pairing to identify which gloves represent the hands of which user.

17.1: Development Overview

The configuration utility will be developed utilizing Microsoft's Visual Studio Community 2015 [26]. Visual Studio is Microsoft's primary integrated development environment which provides platforms such as the Windows API and Windows Forms. Team and code management is supported along with full featured debugging. Visual Studio supports a variety of programming languages including, but not limited to, C, C++, Visual Basic, C#, Python, and JavaScript. The Community edition is a free version of Visual Studio with a license that restricts use to individual or team development of open source projects. The configuration utility was developed using the C# programming language and following Microsoft's C# and .NET coding standards.

17.2: Use Case

Use case diagrams also known as behavior diagrams are used to describe a set of actions or use cases that some system or systems should or can perform in collaboration with one or more external users. Each use case provides an observable and valuable result that is product of the action or actions taken by the user. When used to describe software, use case diagrams can specify, external requirements of a system, functionally of a system that is offered to a user, and the effect the system has on the environment.

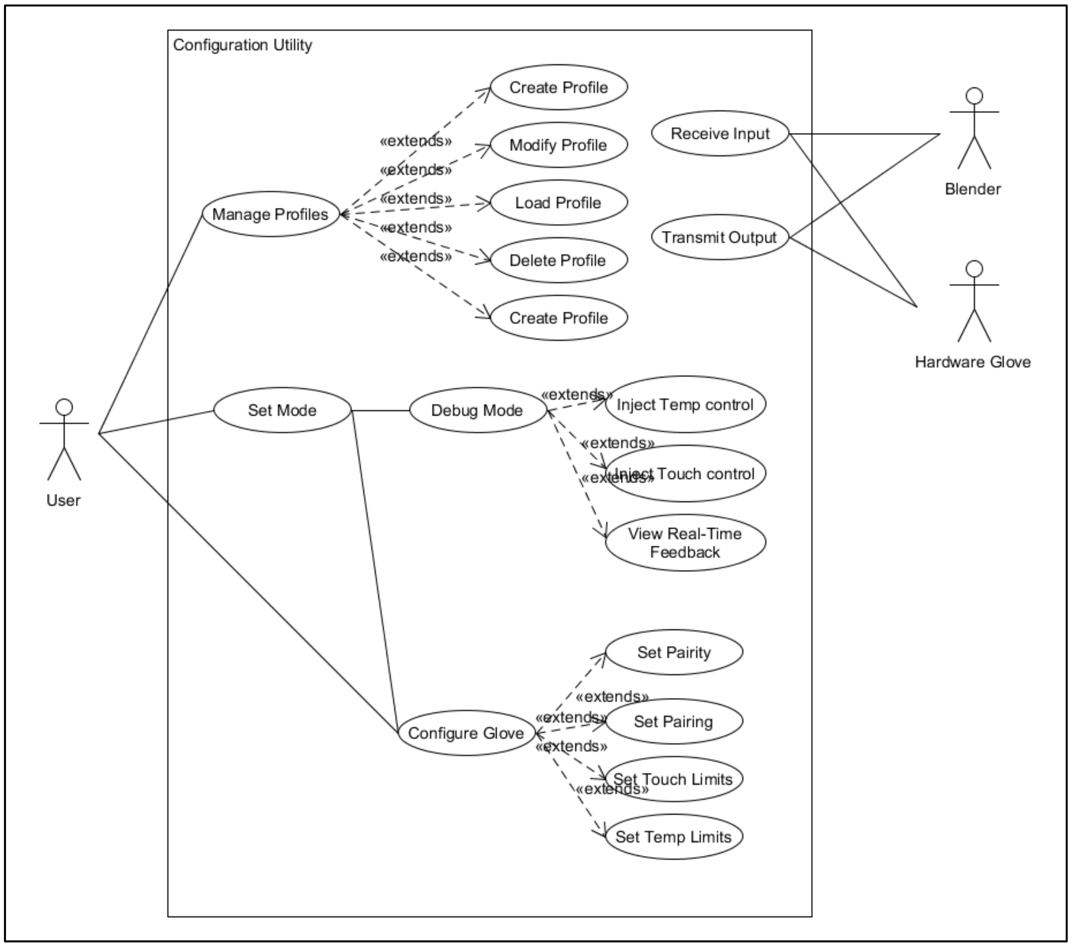


Figure 74: Utility use case diagram

The use case diagram for the configuration utility is shown in the figure above. There are three actors that interact with the utility. They are the user, the blender 3d software, and the hardware glove. The diagram shows that from the glove and blender's perspective, the utility exits only as a gateway for transmitting and receiving data between them. This has the effect of isolating the hardware glove and 3d software from each other allowing for independent development and maintenance of each component. The primacy actor that interacts with eh configuration utility is the user. From the use case diagram, the user uses the utility to perform three major tasks each of which is supported by minor tasks. The major tasks for the utility are managing profile, setting the mode of the utility, and configuring connected glove devices.
Managing Profile is supported by the actions of creating, modifying, loading, and deleting profiles. These actions are how the user manages the memory of the utility. Configurations and profiles are stored in the utility directory using an xml scheme. When loaded, the profiles preserve settings, so the user does not have to go through the process of configuring the same glove every time the utility is started.

Setting the utility mode is how the user toggles a selected glove profile between regular and debug modes. While in debug mode, this action is supported by three additional actions that are only available while in debug mode. Real-Time view of feedback allows the user to real-time updating charts of the outputs and inputs to all of the major electrical sensors and actuations in the hardware system. The commanded and actual value of the vibration motors and Peltier devices will be displayed. The real-time positional displacements of the accelerometers will be displayed. Injecting of temperature and touch data allows the user to send and observe signals to the vibration and Peltier devices. The debug mode aids the user in assessing the functionality of the hardware and isolating potential faulty devices. When the utility is in normal mode, the user can undertake profile management and individual glove configuration. Synced gloves can have their parity set, be paired together, and have the hardware limits for touch and temperature set. While in normal mode, the utility will act as the data relay and transformer between the glove and the 3d software.

17.3: System Architecture

The structure of the configuration utility consists of a graphical user interface layered on top of data packager that converts a serial connection interface from a Bluetooth device into a windows process interface connected to a 3D rendering software. In between the user interface and the connection logic sits the profile manager, linear interpolator, debugger, and the configuration storage. The Layout of the utility is shown in the figure below.

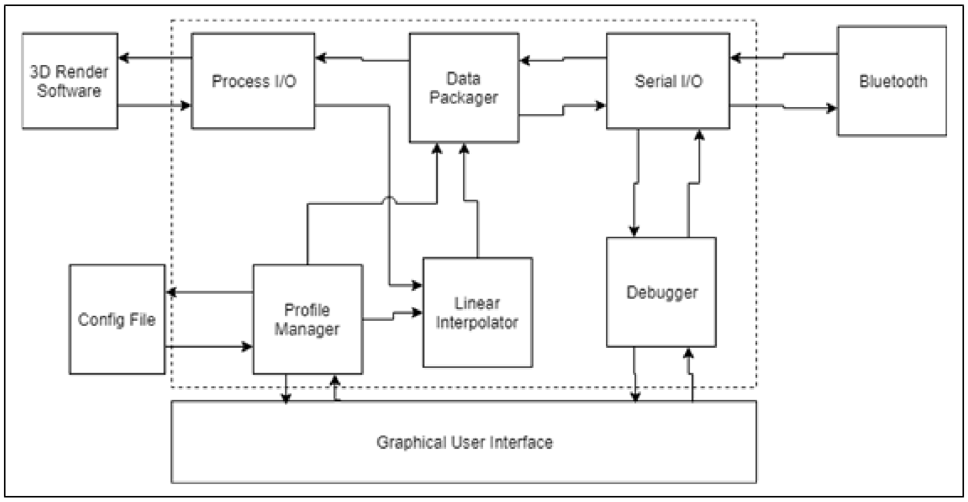


Figure 75: Utility Architecture Diagram

The profile manager is the main component of the utility. It handles the creating and storage of profiles, routing of data through the utility, responds to the user interface, and provides the linear interpolator with the user specified limits for generating feedback signals in the glove device.

The debugger is the primary means for accessing operational issues with a connected glove device. The debugger sits directly between the user interface and the serial connection. This configuration allows for isolating a glove device from the remain system. Through the debugger, the user can monitor real-time feedback of glove motion, and the current commanded vibration and temperature feedback. The debugger also provides the user with an interface for injected feedback signals directly to individual feedback devices on the glove, so the response can be monitored.

The role of the linear interpolator is to transform the touch and temperature values from the virtual environment, into the corresponding feedback values using the limits set by the configuration utility. Linear interpolation is the method of curve fitting using linear polynomials to construct new data points within the range of a set of known data points. Setting the high and low range for the touch and temperature feedback, allows the user to scale the intensity of the feedback response as well as to ensure that the glove operates within the limits imposed by the hardware.

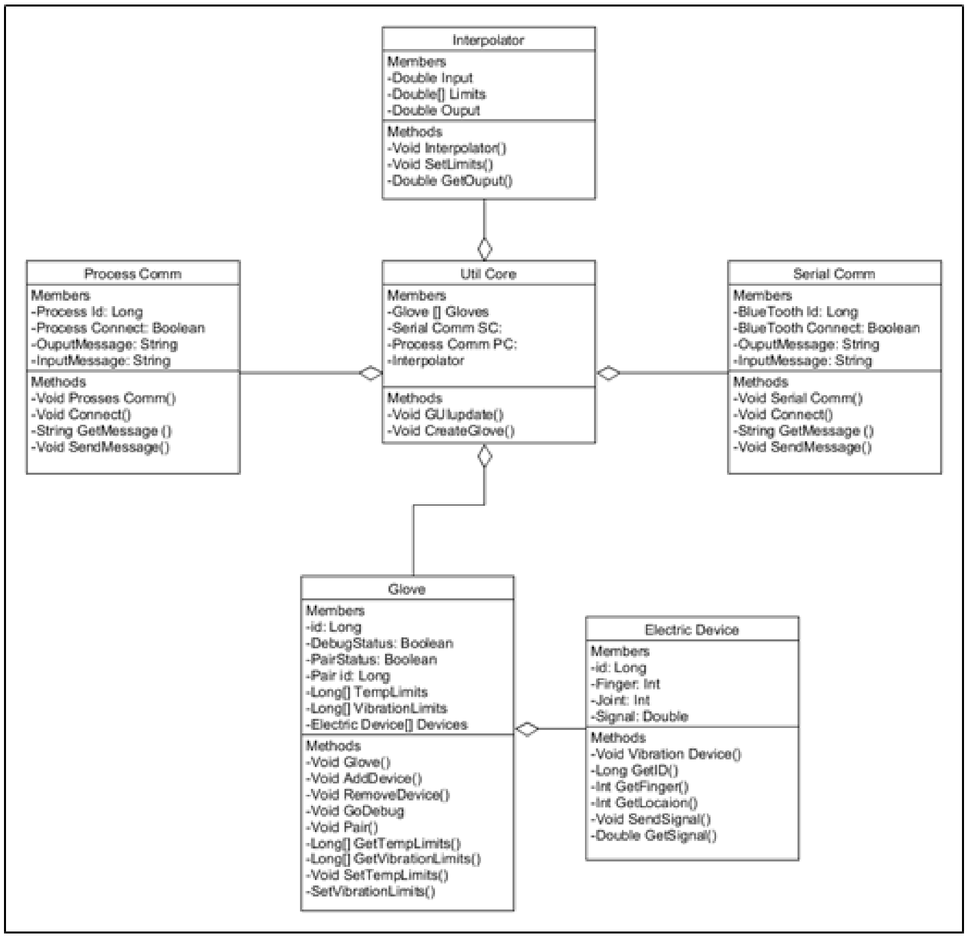


Figure 76: Utility Class diagram

The class diagram above shows the preliminary design of the configuration utility software. The configuration utility is broken down into several class. Each class provides a specific service to the software. The use of the object-oriented design methodology allows for software development that is streamlined, highly modular, and easy to update and maintain such that additional future features can be readily implemented.

The heart of the software is the Util Core. The core provides the logical brain of the software and is composed of other classes. The brain is responsible for updating the graphical user interface, handling of software state, controlling inbound and outbound communication, managing connected glove components, and controlling the interpolation routines. The Utili Core is composed of four direct classes; process Comm, Interpolator, Serial Comm, and Glove.

The glove class organizes and provides and interface for the configuration utility to manipulate and interact with a connect glove. Each connected glove is represented internally by an instance of the glove class. The glove class provides the methods needed to manipulate the debug mode, pairing between gloves, as well as creating and removing the glove. Each glove is composed of multiple electronic devices. Each of these devices is represented by the Electric device class. Each class provides an interface for reading and writing to the device. The physical location the electric device on the glove is also set so that the virtual hand can be mapped one-to-one with the hardware glove.

17.4: Inter-Process Communication

The Process Comm handles the data communication between the configuration utility software, and the 3D environment software. The process comm establishes manages and maintains the communication connection. To facilitate this, the process comm will use an inter-process communication available on a windows system.

Inter-process communication refers specifically to the mechanisms an operating system provides to allow the process to manage shard data. Typically, applications can use IPC in a client-server scheme where the client request data and the server responds to clients. IPC is divided into categories which vary based on software requirements, such as performance and modularity requirements, and system circumstances, such as network bandwidth and latency. There are several inter process communication schemes available on a windows system. [27]

17.4.1: File

A file is a storage structure on a digital medium. A major portion of an operating system is the file server which allows process to create, delete, modify, read, and write files. Process can leverage this mechanism to provide rudimentary communication by reading and writing to the same file. File communication is available on most operating systems.

17.4.2: Socket

Data sent over a network interface, either to a different process on the same computer or to another computer on the network. Leverages the power of TCP and UDP protocols to provide inter process communication and is available on most operating systems.

17.4.3: Unix domain socket

Similar to an internet socket but all communication occurs within the kernel. Domain sockets use the file system as their address space. Processes reference a domain socket and multiple processes can communicate with one socket. Available on windows with windows 10.

17.4.4: Message queue
Data stream similar to a socket but all communication occurs within the kernel. Domain sockets use the file system as their address pace. Processes reference a domain socket and multiple processes communicate with one socket. Available on windows.

17.4.5: Pipe
A unidirectional data channel. Data written to the write end of pipe is buffered by the operating system until it is read from the red end of the pipe. Two-way data streams between process can be achieved by creating two pipes utilizing standard input and output. Available on windows.

17.4.6: Named pipe
Combination of File and Pipes, allows multiple process to communicate. Available on windows.

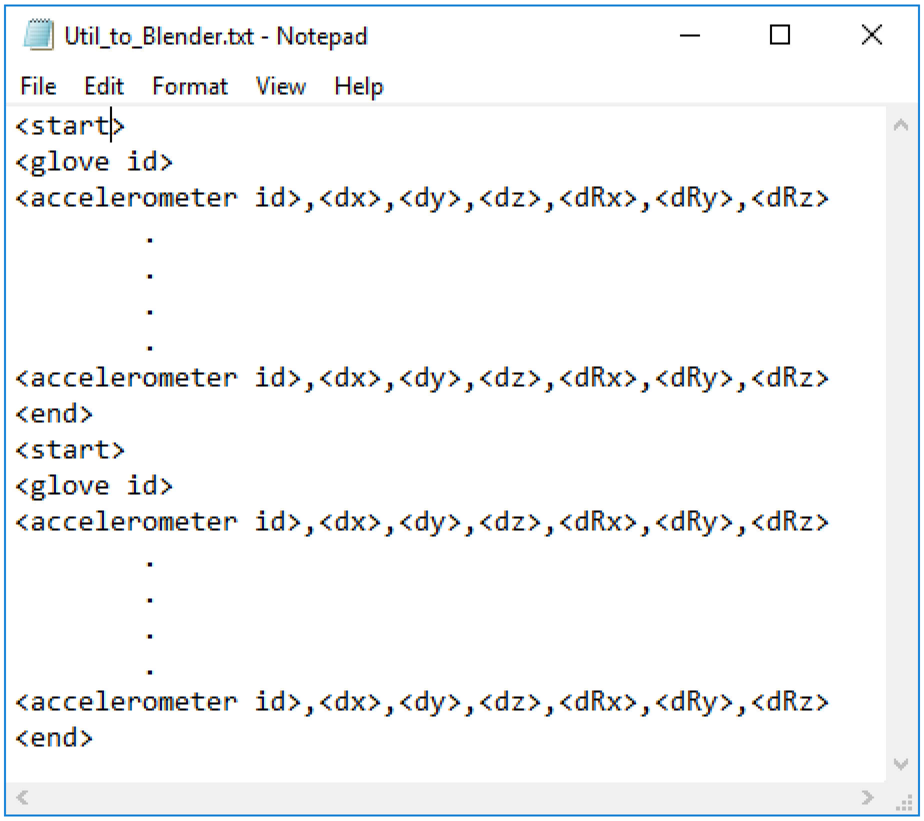
17.4.7: Shared Memory
Multiple processes are given access to the same block of memory which creates a shared buffer for the processes to communicate with eat other. Available on windows.

17.4.8: Message Passing
Allows multiple programs to communicate using message queues and/or non-OS managed channels. Not OS dependent.

17.4.9: Memory-mapped file
A file mapped to RAM and can be modified by changing memory addresses directly instead of outputting to a stream. Similar to the File method. Available on windows.

17.4.10: Selected Inter-Process Communication Scheme
The Process Comm will use the file communication method due to its simplicity of implementation. The basic operations that can be performed on a file are; create, change permissions, open, read, write, and close. In addition, files can be moved, modified, grown, and shrunk. Process comm and the 3D environment software will communicate using two predetermined files on the windows operating system. The files will be created at the startup of the configuration utility and deleted when the utility is determined.

The first file is designated as the communication point for passing positional data that utility received from the hardware glove to the 3D environment software in order to update the position of the virtual hand. Blender will continuously monitor the file to determine if new positional data is available. When available data is detected, Blender will retrieve the next complete set of input data from the file. The configuration utility will receive updated positional data from the hardware glove. After receiving the data, the utility maps, formats, and writes the data to the file for Blender to retrieve. The file will be designated as a plain text file and be named. “Util_to_Blender.txt”. The following figure shows the delineation of the data written to and read from the file.

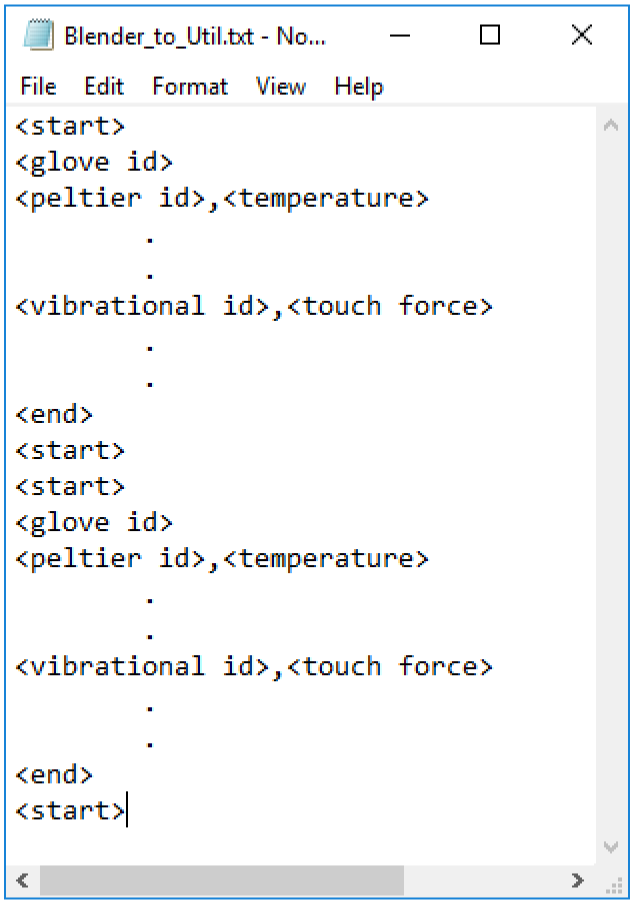


```
<start>
<glove id>
<accelerometer id>,<dx>,<dy>,<dz>,<dRx>,<dRy>,<dRz>
         .
         .
         .
         .
<accelerometer id>,<dx>,<dy>,<dz>,<dRx>,<dRy>,<dRz>
<end>
<start>
<glove id>
<accelerometer id>,<dx>,<dy>,<dz>,<dRx>,<dRy>,<dRz>
         .
         .
         .
         .
<accelerometer id>,<dx>,<dy>,<dz>,<dRx>,<dRy>,<dRz>
<end>
```

Figure 77: Util_to_Blender.txt

Each data set is framed by a start and end indicator. Next the glove id is given so that the updated positional data can be applied to the correct virtual hand when multiple hardware gloves are in use. The majority of the data set consists of the accelerometer data itself. This data is calculated by the processor on the glove itself. Each line begins by identify the accelerometer so that the data can be applied to the correct joint on the virtual hand. The data on each line consists of the changes in all 6 degrees of freedom present in a three-dimensional system. These are the changes in the three translational directions x, y, and z, along with the changes in the three rotational directions, x-axis, y-axis, and z-axis. As each data set is read by Blender, the data block is removed. As new data is received from the glove, a new data block is added. This effect results in the transfer file continuously growing and shrinking as both Blender and the configuration utility communicate.

The second file is designated as the communication point for passing touch and temperature data from Blender to the configuration utility where it is processed and sent to the hardware glove to drive the vibration and Peltier devices to produce the feedback response. The configuration utility will continuously monitor the file to determine if new feedback data is available. When available data is detected, the utility will retrieve the next complete set of input data from the file. Blender will generate updated feedback data as a result of updated positional data. After generating the data, Blender maps, formats, and writes the data to the file for the utility to retrieve. The file will be designated as a plain text fiel and be named “Blender_to_Util.txt”. The following figure shows the delineation of the data written to and read from the file.



```
<start>
<glove id>
<peltier id>,<temperature>
        .
        .
<vibrational id>,<touch force>
        .
        .
<end>
<start>
<start>
<glove id>
<peltier id>,<temperature>
        .
        .
<vibrational id>,<touch force>
        .
        .
<end>
<start>
```

Figure 78: Blender_to_Util.txt

Each data set is framed by a start and end indicator. Next the glove id is given so that the updated feedback data can be applied to the correct virtual hand when multiple hardware gloves are in use. The majority of the data set consists of the feedback data itself. This data is produced by Blender as a result of the updated position of the virtual hand within the 3D environment. The data section of each frame is split into two parts. The first part consists of a line of data for each of the Peltier devices on the hardware glove and corresponds to a temperature measurement point on the virtual hand. Each line begins by identifying the temperature measurement point so that the data can be applied to the correct Peltier device on the hardware glove. The data on each line consists of the currently measured temperature of that point in the 3D environment. The second part of the data section consists of a line of data for each of the vibrational motors on the hardware glove and corresponds to touch force measurement point on the virtual hand. Each line begins by identifying the touch force measurement point so that the data can be applied to the correct vibrational motor on the hardware glove. The data on each line consist of the currently measured force applied to that point in the 3D environment. As each data set is read by the configuration utility, the data block is removed. As new data is generated by Blender, a new data block is added. This effect results in the transfer file continuously growing and shrinking as both Blender and the configuration utility communicate.

17.5: Bluetooth communication

The serial comm class, handles the communication between the utility software and the glove itself. The communication protocol that will be used is Bluetooth. Bluetooth is an industry-standard protocol that enables wireless connectivity for a multitude of devices. The key features that make Bluetooth the go to protocol from a software perspective, are its presence in virtually all modern PCs, its support in modern operating systems, it is a standardized technology with a multitude of resources, and it is a well-defined and familiar programming interface that allows for quick development.

Bluetooth on windows provides functionality with similarity to TCP. [28] Using Bluetooth in a standard networking implementation, results in Bluetooth connectivity and data transfers being programmed through windows sockets function calls. This approach combines common windows sockets programming techniques and principles with specific Bluetooth extensions. In addition, Bluetooth provides features such as discovery and notifications which a necessary for any communication scheme operating in a wireless environment. Support for Bluetooth on Windows Operating Systems began with Windows XP Service Pack 1 and includes all subsequent releases of the Windows Operating System. Microsoft provides two approaches for programming and using Bluetooth on Windows devices; Using the Windows Sockets interface [29] or Managing devices directly by using non-socket Bluetooth interfaces.

17.5.1: Selected Windows Bluetooth Method

[30]The serial comm will leverage windows provide Bluetooth APIs to establish a serial UART connection. The serial comm provides methods to access the serial connection and read the input message from the hardware glove and provide an output message to the hardware glove. The selected Bluetooth programming approach is the Windows Sockets interface. As stated, this method extends the windows sockets API with Bluetooth standard features. Windows Sockets enables programmers to create applications that transmit data across the wire in a manner that is independent of the network protocol being used. The Winsock API provides access to advanced networking features such as multicast and Quality of Service.

Bluetooth is a serial communication protocol that operates using packets that consist of headers and administrative fields surrounding a payload of data. The nature of the configuration utility will leverage the structure of the connection to utilize the headers and administrative information to identify both the source and recipient of transmitted data. The payload can then be reserved for the actual data being transmitted. The configuration utility uses Bluetooth for communication in two directions.

The first direction is receiving data from the hardware glove. When communicating in this direction, the utility will receive updated positional data from the hardware glove. This data consists of the changes in all 6 degrees of freedom present in a three-dimensional system. These are the changes in the three translational directions x, y, and z, along with the changes in the three rotational directions, x-axis, y-axis, and z-axis. Each set of 6 degree of freedom changes also contains the identity of the generating accelerometer When receiving the data. The utility identifies the source glove and then maps and formats the data so that the updated positional information can be transmitted to Blender using the file inter-process communication scheme.

The second direction of communication is sending data from the utility to the hardware glove. First the utility processes the feedback data received from Blender. Interpolation is used to both scale and determine the driving signals necessary for the feedback devices. These signals are then sent using Bluetooth to the hardware glove. The Bluetooth module on the glove itself, identifies the data meant for it form the header and administrative information in the Bluetooth packet. The payload of the packet contains the device driving signal, along with Identifies for which Peltier or vibrational device that signal is for.

17.6: Interpolation

The interpolator class contains the mathematical logic for converting the blender environment response into the signal values needed to drive the electrical devices on the hardware glove. The first action the interpolator does is scale the signal value so that it falls in-between the associated limits for the glove. Each Peltier and vibrational device contain documented values that correlate input signal value to output value. If an output signal value that is not provide is need, then interpolation must be used to construct the necessary output signal value. Interpolation is a method of constructing new data points within the range of a discrete set of known data points. There are a variety of interpolation methods. [31]

17.6.1: Piecewise constant interpolation

This is the simplest method of interpolation. If a need data point falls between two known points, the value of the of the closest known point is chosen and assigned to the data point. This method is fast and simple to implement.

17.6.2: Linear interpolation

This method treats the space between known data points as lines. If a need data point falls in-between two known points, the value is determined by a liner equation and governed by the two known points on either side if the needed point. Like piecewise interpolation, linear interpolation is fast and simple to implement while providing increased accuracy.

17.6.3: Polynomial interpolation

This method is an extension of liner interpolation. While linear interpolation is of degree one, polynomial interpolation can take the form of any degree greater than one. It is guaranteed that a polynomial can be found that contains the known data points however, the region between that data points may not be an accurate representation of the needed behavior characteristic of the device. This method is slower than the previous two and much more difficult to implement as the degree of the polynomial increases.

17.6.4: Spline interpolation

This method is a variation of linear interpolation. Instead of connecting the known data points with straight lines, individual low degree polynomials are used such that a smooth curve that passes through the known data points is produced. Spline interpolation can produce more accurate results than other methods but is much more difficult to implement.

17.6.5: Selected Interpolation Method

Linear interpolation is the method that will be used by the interpolator class. The electric devices operate on small signal ranges. It is the noticeability of an output difference rather than the precise accurate value of the output that is most important to the design. The figure below shows how linear interpolation will be used to drive the output signal for the electrical feedback devices.

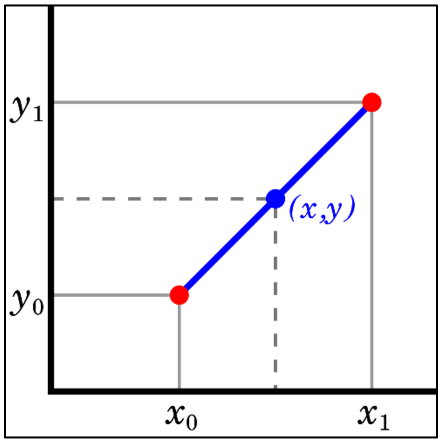


Figure 79: Linear interpolation example [32]

In the figure, the x axis represents the commanded feedback value, touch or temperature, from the 3D environment. The y axis represents the output signal needed to drive the corresponding feedback device to the required value. The points (x1, y1) and (x0, y0) represent the set configuration limit for the feedback signal. The value x is the current value commanded by the 3D environment. First the value is scaled to fall in-between the configuration limits. Next the equation below is used to linearly interpolate and find the output signal value y. This is the signal that is passed to the hardware to drive the corresponding electrical device to produce the desired feedback experience.

$$\boxed{y = y_0 + (x - x_0)\frac{y_1 - y_0}{x_1 - x_0} = \frac{y_0(x_1 - x) + y_1(x - x_0)}{x_1 - x_0}}$$

Equation 3: Liner Interpolation [33]

17.7: System Deployment

The configuration utility will be developed for and deployed on a Windows 10 machine. The Windows Operation system was chosen because it is the most common and most utilized computer operating system in use today. It is also designed to be user friendly and the visual studio development environment is specifically designed to work on and interact with the Windows operation system. The configuration tool system foot-print and deployment plan are shown in the figure below.

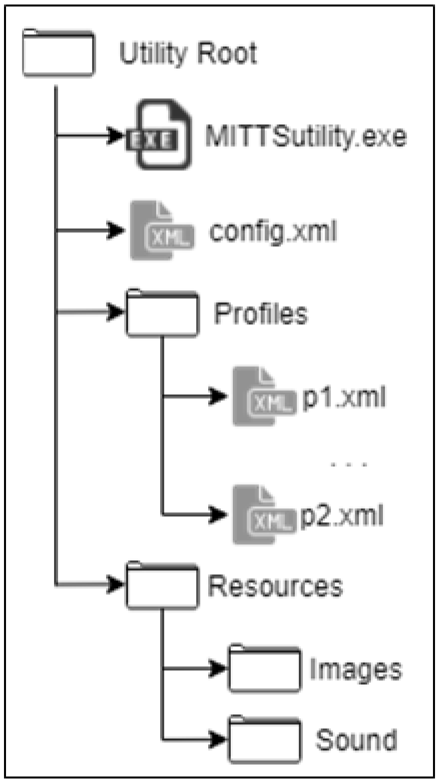


Figure 80: Utility Deployment

The root directory will contain the compiled utility executable along with a configuration xml file and subdirectories for profiles and system resources. The resources directory will contain subdirectors for images and sounds. These images and sounds are those utilized by the utility itself i.e. the splash screen, button sounds etc.

The profiles directory contains the stored profiles in xml form. Each profile contains the configuration settings for one or more glove devices. These settings consist of Bluetooth I.D. for the glove, parity of the glove (left or right hand), pairing of gloves to represent a single user, and the interpolation limits for temperature and touch feedback.

17.8: Data Design

The data design of the System consists of three parts. The input/output design details how data enters and leaves the configuration utility. The internal design details how data is manipulated and routed within the utility. The storage design details how persistent data is stored and accessed by the utility.

The input/output data design is centered around serial-based message passing. Serial messaging is characterized by individual 8bit characters transmitted 1-bit at a time between two components. Serial messaging is simple, relatively easy to implement and is the standard scheme use by many commercial devices such as USB and Bluetooth.

The internal data design consists of how data is manipulated inside the utility. The utility will be develop using the object-oriented programming paradigm. In object-oriented programming, data is associated with objects. Objects contain the data and provide methods so that other objects can manipulated the data. The utility, data is associated with a particular glove object. Input signals from the glove is mapped to the corresponding glove instance in the utility. The utility the packages the data so that blender can associate a set of data with the corresponding virtual representation of the manipulated hand.

The storage data design determines how persistent data is maintained between uses of the utility. To accomplish this, the XML data structure will be used. XML, Extensible Markup Language, is a markup language that defines a set of rules for encoding documents in a format that is both human-readable and machine-readable. The design goals of XML emphasize simplicity, generality, and usability. XML is defined through the use of a Schema. The schema detals what a valid entry into the XML must contain, along with what a valid entry can contain. Using XML, system configuration settings and glove profile can make use of individual defined schema to create, modify, and store their states in XML format in the utility directory. XML is stored the form of a file, and as a file, it is subject to all the standard operations available to file manipulation.

17.9: User Interface Design

The user Interface utilizes the Windows Forms API to present a simple user-friendly environment for accessing all the features of the configuration utility. The UI layout is broken down into several distinct components detailed in the following sections.

- Splash Screen
    - Initial utility loading graphic
- Home Screen
    - Load, Create, Modify profiles
    - Add, Remove, Modify glove devices
- Configuration View
    - Modify feedback parameters for selected glove
    - Select left or right parity
    - Pair Gloves together
- Debug Screen
    - Display data received from the selected glove
    - Pass data to selected glove

17.9.1: Splash Screen

The Splash Screen is the initial entry point of the configuration utility. It serves to display the Project Logo along with addition relevant information. The splash screen is shown in the figure below.

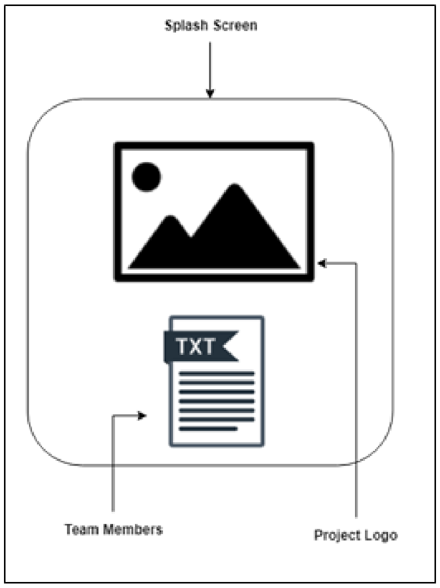


Figure 81: Splash Screen

Some of the information displayed are for example; the project members, configuration utility version, and copyrights. The functional use of the Splash Screen is to show that configuration utility has successfully loaded and is starting up. A successful startup transitions the configuration utility to the Home Screen.

17.9.2: Home Screen

The Home Screen is the primary user view for the utility and consists of three sections; Menu Bar, Main Display, and Selection Tabs.

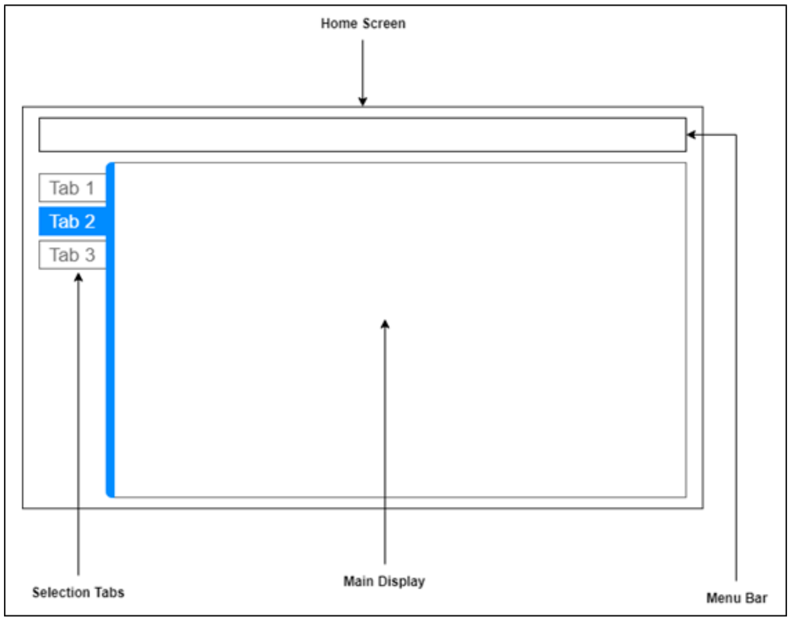


Figure 82: Home Screen

The menu bar is the primary administrative interface for the user and is where the high-level functions of the utility are accessed. The actions provided by the menu bar are; minimize, maximize, exit, create profile, load profile, close profile, and delete profile. Each of the actions are detailed in the table below.

Action	Description
Create Profile	Creates a new profile for storing a set of glove configurations
Close Profile	Closes the currently loaded configuration profile
Delete Profile	Permanently deletes a configuration profile
Load Profile	Loads a saved configuration profile
Minimize	Standard windows action, collapses configuration utility to the taskbar.
Maximize	Standard windows action, fills display with the configuration utility
Exit	Standard windows action, safely terminates the configuration utility

Table 21: Menu Bar commands

The selection tabs are populated whenever a selected profile has saved configuration data for a glove device. Each tab represents the data for a single glove that is associated with that profile. Selecting a tab, updates the main display to show the configuration interface for that glove. Closing a tab removes that glove from the display and erases the corresponding configuration data from the saved profile.

17.9.3: Configuration View

Selecting a configuration tab from the home screen, loads the configuration view for that glove device. The figure below shows the layout of the configuration view.

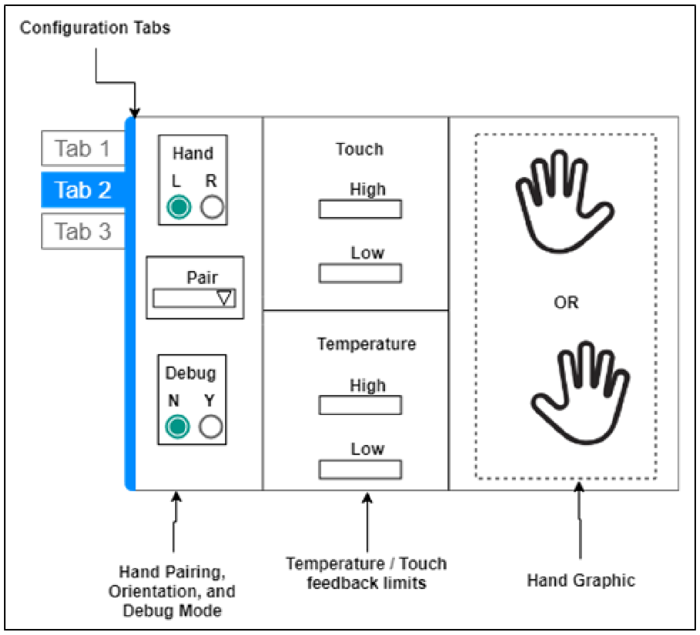


Figure 83: Configuration Tab

The configuration view is where glove devices are modified. The parameters available are; hand parity, glove pairing, and the touch and temperature high low limits. Hand parity designates whether the glove is left or right handed. This is used for interfacing with the 3D environment software, and for pairing of gloves. Selecting a parity is accomplished by selecting the corresponding radio button. Glove pairing is the action of assigning two gloves to represent both hands of a single user. Like parity, this is used for interfacing with the 3D environment. It also allows for configuration settings to be mirrored across both gloves. To pair two gloves, open the dropdown list in the entry field. The list will be automatically populated with gloves that are part of the currently loaded profile, are of opposite parity, and that are not currently paired.

The touch and temperature high and low limits are used to set the values used by the linear interpolator when converting 3D environment values into glove signals. Setting these values allows the user to tune the intensity of the feedback responses, as well as ensure that hardware limits are not exceeded.

The displayed hand graphic will reflect the selected parity of the glove, the connection I.D. of the glove, as well as display the number and location of sensors and feedback devices the glove provides.

The debug option places the utility and glove into debug mode and loads the debug screen for the selected glove. Debug mode allows for direct monitoring of glove state and interaction with glove feedback devices.

17.9.4: Debug Screen

Debug mode is the primary method for assessing issues with the glove connection and/or the glove itself. It is also used to test feedback response to aid in determining the best touch and temperature limit settings for the user. Selecting yes on the debug menu on the configuration view transitions the main display into the debug view shown in the figure below.

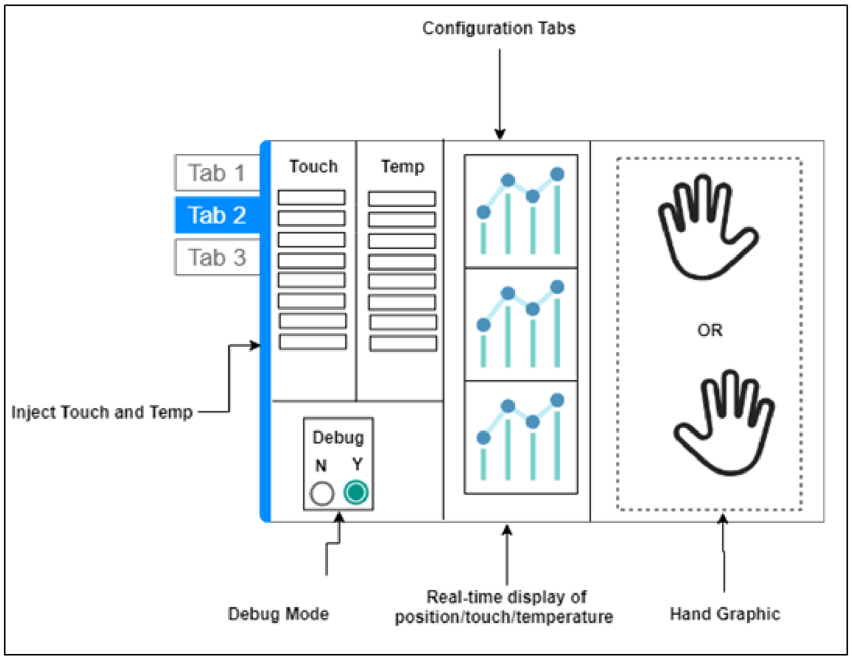


Figure 84: Debut View

While in debug mode, the glove is disconnected from the 3D environment software. A direct connection is established between the configuration utility and the glove hardware providing access to the individual devices of the glove itself. The debug view provides two features to the user, real-time display, and signal injection.

The primary feature of the debug view is the real-time display. Three charts that monitor the accelerometer, touch, and temperature signals are displayed and updated in real-time. Each of the charts displays data for every device of the corresponding type that the glove provides.

The second feature of the debug view is the ability to inject touch and temperature feedback signals directly to the glove. This is done one device at a time, and when used in conjunction with the real-time display, provides a rapid interface for assessing technical problems with the glove and identify potentially flawed or failed devices.

To exit the debug view, select the corresponding radio button on the debug menu. This returns the user to the configuration view for that glove and resumes normal operation of the glove.

18: Testing

Testing of the system will be conducted in three phases. Phase I consists of unit testing. Each component will be tested in a standalone capacity. Phase II consists of integration testing. Each components interface will be tested with the components it interacts with. Phase III consists of a system testing. A fully integrated system consisting of all the components will be tested to verify the completed system.

To facilitate early testing; stubs and drivers will be developed to simulate critical software components, while breadboards and Arduino micro controllers will be used to test individual hardware components. Stubs and drivers are pieces of code used to stand in for some other functionality and act to simulate the behavior of an existing component or a yet-to-be developed component. A driver will be developed to simulate the interaction between the configuration utility and the 3D environment software. The driver will be capable of receiving positional data from the utility and transmitting touch and temperature data back to the utility. A stub will be developed and used to simulate the interaction between the configuration utility and the hardware glove. The stub will transmit positional data to the utility and receive touch and temperature data back from the utility. An Arduino micro controller allows for testing of the individual glove components while the processor circuity is still under development. Breadboards allow for connecting and testing hardware components while the final PCB design is being refined, manufactured and delivered.

18.1: Phase I

Phase I consists of unit testing [34]. Each individual component and device will be tested in a standalone environment. A full test of the individual component functionality will be executed. A stub and driver will be used to simulate the interaction between the configuration utility and the hardware glove and 3D environment software. An Arduino micro controller and breadboard circuit will allow for the testing of the individual touch and thermal sensors, vibration motors, and accelerometers. Testing will cover all aspects of the system and is broken down into two categories; software testing and hardware testing. Software testing evaluates the software components functionality. A Stub will be used to simulate the presence of a glove, and a driver will be used to simulate the 3D environment software. Hardware testing evaluates the hardware components functionality. An Arduino microcontroller and breadboard will be used to test individual hardware components.

18.2: Phase II

Phase II consists of integration testing [35]. The interface between sub components of the system will be tested in a bottom up approach. Bottom-up testing is an approach where the lowest level components are tested first. As components are test, they are used to facilitate the testing of higher components. This is repeated until the upper most component in the system hierarchy is tested. At each stage of the testing, software stubs and drivers, and Arduino microcontrollers will be used to provide functionality for missing components. Testing focused on the interface and data transmission between the components.

18.3: Phase III

Phase III consists of system testing [36]. The completed system will be tested both software and hardware components. Testing focused on full function the complete interface and data transmission chain proceeding from glove to utility to 3D software, and the reverse. The tests demonstrated continuity between all components of the completed system. Testing will be performed and verified against the documented requirements specifications in order to determine the final pass or fail status of the system.

18.4: Testing Management

[37]Testing management outline and document the tests that are needed to demonstrate compliance with the requirements specifications. The tests represent testing conducted during all three phases of the testing process. Test management consists of two parts. The First is test tracking. Testing is tracked through a Testing Traceability Matrix show in the table below. A traceability matrix is a data structure used to assist in determining the completeness of a relationship by correlating any two baselined documents using a many-to-many relationship comparison. The testing matrix Identifies what test was performed, when it was performed, who is responsible for performing the test, and the outcome of the test.

Test ID	Test Name	Tester	Test Result (Pass/Fail)	Test Date
1	Peltier	Chris	Fail	7/24/18
2	Vibration Motor	Chris	Pass	7/24/18
3	IC Sequencer	Chris		
4	Accelerometer	Chris		
5	Power Regulator	Chris		
6	Thermistor	Chris		
7	Digital Potentiometer	Chris		
8	Battery Charger	Chris		
9	H-Bridge	Chris		
10	Peltier Controller	Chris		
11	Motor Controller	Chris		
12	Configuration Utility	Francisco		
13	Windows Function	Francisco		
14	Profile Manipulation	Francisco		
15	Configuration Manipulation	Francisco		
16	Data receive	Francisco		
17	Data Transmit	Francisco		
18	Debugger	Francisco		
19	SWD	David		
20	LED Function	David		
21	Data Format	David		
22	I2C Read	David		
23	Boot-Up Process	David		
24	Blender Collision & Physics	Hunter		
25	Blender-Driver Communication	Hunter		
26	Hand Tracking Script	Hunter		

Table 22: Testing Traceability Matrix

18.5: Testing Procedures

The second part of test management are the testing procedures. Each test outlined in the traceability matrix has an associated testing procedure. Testing procedures detail how a test is to be performed. Elements of a testing procedure indicate the test to be performed, who is to perform the test, the procedure for performing and the equipment needed to perform the test, and the pass/fail conditions for the test.

1: Peltier Test

- **Description:** Peltier devices must change temperature with respect to an applied current.
- **Procedure:** The Peltier devices will be individually connected to a current supply. The current will be manually varied, and the produced temperature measured with a digital thermometer. The current and the temperature shall be recorded along with any insights into how the operation of the Peltier will interact with human skin and perception. Note must be taken of the range of currents that the human hand, in the location designated for the Peltier, is capable of sensing before the temperature becomes uncomfortable for the user.
- **Pass/Fail:** To pass this test each, Peltier deice must demonstrate a heating and cooling range of 40 degrees Celsius to 10 degrees Celsius.
- **Who:** Test will be performed by Chris.

2: Vibration Motor Test

- **Description:** Vibration motor devices must vary vibration frequency with respect to an applied voltage.
- **Procedure:** The vibration motors will be individually connected to a voltage source. The voltage will be manually varied, and the produced vibrational frequency will be measured. The voltage and relative vibrational intensity shall be recorded along with any insights into how the operation of the motor will interact with human fingertips and perception. Note must be taken of the range of voltages where the human hand can perceive the vibration magnitude and frequency of the motor.
- **Pass/Fail:** To pass this test, each vibration motor must demonstrate a vibration range that can be perceived by the human hand as having a distinct difference from in vibrational magnitude from the lowest setting to the highest setting.
- **Who:** Test will be performed by Chris.

3: IC Sequencer Test

- **Description:** IC sequencer devices must deliver a voltage after a specified time delay.
- **Procedure:** The IC sequencers will be connected to a digital multi meter. A timer will be used, and the voltage output observed while varying the controlling capacitor. The capacitor will be chosen such that the timer will give a multi second delay. This long delay will only be used for testing purposes since the test technician is incapable of perceiving micro second time differences.
- **Pass/Fail:** To pass this test, each IC sequencer device must demonstrate a delay in voltage delivery with respect to controlling capacitor.
- **Who:** Test will be performed by Chris.

4: Accelerometer Test

• **Description:** Accelerometer devices must respond to changes in orientation and position with respect to a normalized start point.

• **Procedure:** The accelerometers will be tested by connecting them to an Arduino board through an I2C connection. The accelerometer will then be oriented, and the output data passed to the Arduino which must be able to calculate the distance traveled by the device from the acceleration data.

• **Pass/Fail:** To pass this test, each accelerometer must demonstrate and discriminate between three degrees of freedom at a resolution of 14 bits.

• **Who:** Test will be performed by Chris.

5: Power Regulator

• **Description:** The power regulator must produce 3.3 volts using the schematic referenced in the Power Regulator section.

Procedure: The power regulator must be prototyped on a breadboard, prototype board, a custom PCB, or a combination of the three. After prototyping the input of the circuit will be hooked to a bench top voltage source set to between 4.2 and 3.7 volts. The load of the power regulator will initially be a 1 MΩ resistor to simulate a low current environment. The voltage across this resistor will be checked with a digital multimeter. The load will then be lowered to 1.1 Ω to simulate a high current environment. The voltage will be checked with a digital multimeter.

• **Pass/Fail:** To pass this test the circuit must be able to maintain voltage on a load ranging 1 MΩ to 1.1 Ω. The 1.1 Ω resistor must be a high watt model.

• **Who:** Test will be performed by Chris.

6: Thermistor

• **Description:** The thermistor must vary its resistance in accordance to the equation and design referenced in the Thermistor section.

• **Procedure:** The voltage divider will be implemented and the voltage at various thermistor temperatures will be read with a multimeter.

• **Pass/Fail:** To pass this test the circuit must be able to vary its voltage with the temperature on the thermistor.

• **Who:** Test will be performed by Chris.

7: Digital Potentiometer

• **Description:** The digital potentiometer must respond to I2C commands to change its resistance.

• **Procedure:** The digital potentiometer will be connected to a voltage divider. The voltage divider will be powered by a benchtop voltage supply. The circuit will be prototyped on breadboard, prototype board, or a custom PCB. The digital potentiometer's resistance will be varied using the I2C controls on the I2C line. The output of the voltage divider will be measured with a digital multimeter.

• **Pass/Fail:** To pass this test the circuit must be able to vary the voltage measured by the digital multimeter in a fashion that can be controlled via I2C.

• **Who:** Test will be performed by Chris.

8: Battery Charger

• **Description:** The battery charger will be purchased from a supplier and must be verified for quality before being used on the main PCB board. This is to ensure that the battery charger does not over charge the lithium ion batteries or damage them from over current.

• **Procedure:** The charger will be plugged in and a digital multimeter will be used to check the voltage across the leads. This must be less than 4.2 volts. The maximum current of the charger must be checked using a digital multimeter. This current cannot exceed the stated maximum current listed in the data sheet.

• **Pass/Fail:** To pass this test the battery charger must be able to charge the batteries to 4 volts and not exceed its posted current limit.

• **Who:** Test will be performed by Chris.

9: H-Bridge

• **Description:** The H-bridge must respond to the Enable/Phase design referenced in the H-bridge section. It must be able to produce variable voltage based on the analog voltage applied to the input terminals and change the polarity of the output voltage based on the phase activation.

• **Procedure:** The circuit must be build using breadboard, prototype board, a custom PCB, or a combination of the three. Power will be supplied with a benchtop voltage supply. The input voltage and phase activation will be supplied by a voltage source while the output will be measured by a multimeter.

• **Pass/Fail:** To pass this test the circuit must be able to generate varied voltages based upon the input voltage and the phase of the voltage must be able to be changed upon activation of the phase control circuitry.

• **Who:** Test will be performed by Chris.

10: Peltier Controller

• **Description:** The Peltier controller circuitry must be able to apply properly controlled voltage across the Peltier device to generate the proper current that will drive the Peltier device to the proper temperature. Since this is an integration test the circuit must contain the H-bridge circuitry as well as the circuitry for the I2C controlled digital potentiometer circuitry.

• **Procedure:** The Peltier controller test will implement the Peltier controller schematic referenced in the Peltier Controller section. It will include the H-bridge circuity. The circuit must be build using breadboard, prototype board, a custom PCB, or a combination of the three. Power will be supplied with a benchtop voltage supply. This circuit must implement a digital potentiometer which should be controlled via I2C. Temperature must be measured using a digital thermometer such as the built in one on many digital multimeters.

• **Pass/Fail:** To pass this test the Peltier controller must be able to vary temperature in both the positive and negative direction. It must be I2C and GPIO controlled with the I2C controlling the magnitude of the temperature change and the GPIO pin controlling the direction.

• **Who:** Test will be performed by Chris.

11: Motor Controller

• **Description:** The motor controller circuitry must be able to apply properly controlled voltage across the motor to generate the proper vibrational frequency and magnitude. Since this is an integration test the circuitry must incorporate an I2C controlled digital potentiometer circuitry.

• **Procedure:** The motor controller test will implement the Motor Controller schematic referenced in the Motor Controller section. The circuit must be build using breadboard, prototype board, a custom PCB, or a combination of the three. Power will be supplied with a benchtop voltage supply. Vibrations of the motor should be varied by application of I2C controls.

• **Pass/Fail:** To pass this test the circuit must be able to vary the frequency of vibration in the vibrational motors. It must be controlled by I2C with the I2C potentiometer controlling the frequency of vibration.

• **Who:** Test will be performed by Chris.

12: Configuration Utility

• **Description:** The Configuration Utility must be able to be installed and initiated on the operating machine.

• **Procedure:** The configuration utility is placed onto the operating machine as detailed in the system deployment section of this document. The machine must be using the Windows 10 operating system. The configuration Utility is initiated by double clicking the “MITTSutility.exe” executable in the root directory.

• **Pass/Fail:** The splash screen should appear followed by the Home screen. The utility must not freeze or crash.

• **Who:** Test will be performed by Francisco.

13: Windows Function:

• **Description:** The standard windows application functions of minimize, maximize, and close are tested.

• **Procedure:** The configuration Utility is first initiated by double clicking the “MITTSutility.exe” executable in the root directory. The minimize windows button is selected from the top right corner of the utility home screen. The utility is collapsed to the task bar. The minimized utility is selected on the taskbar and restored to its original state. The maximize button is selected from the top right corner of the utility home screen. The utility fills the display. The maximize button is selected from the top right corner of the utility home screen. The Utility returns to its original state. The close button is selected from the top right corner of the utility home screen. The utility process is terminated, and the utility is closed.

• **Pass/Fail:** The minimize, maximize, and close buttons should correctly function with respect to a standard windows application. The windows functions must not crash the utility or alter any of its parameters.

• **Who:** Test will be performed by Francisco.

14: Profile manipulation

- **Description:** The profile manipulation operations of the configuration utility are tested.
- **Procedure:** The configuration Utility is first initiated by double clicking the "MITTSutility.exe". The create profile option is selected from the menu on the home screen. A name is given to the new profile, the profile is saved, the home screen displays the active profile. The profiles directory will now contain a new xml file with the specified name. Close profile is selected from the home screen menu. The current profile is unloaded, the home screen displays its default view. Load profile is selected from the menu on the home screen. A profile xml file is chosen from the standard windows open/save dialog box. The home screen updates to reflect the chosen profile as being active.
- **Pass/Fail:** Creating, Loading, Closing, and Removing of profiles should correctly display in the utility, and update the corresponding storage file.
- **Who:** Test will be performed by Francisco.

15: Configuration Manipulation

- **Description:** The ability of the utility to set and modify the configuration of a single connected glove is tested.
- **Procedure:** The configuration Utility is first initiated by double clicking the "MITTSutility.exe". Load profile is selected from the menu on the home screen. A profile xml file is chosen from the standard windows open/save dialog box. The home screen updates to reflect the chosen profile as being active. From the active profile, the configuration tab for the glove that is to be manipulated is selected. The configuration view for that glove is displayed as the active view. Paring, Parity, and the touch and temperature limits are set for the glove. The configuration entry in the profile xml file is updated.
- **Pass/Fail:** Parity, Paring, and modification of touch and temperature limits for a selected glove should function correctly, display in the utility, and update the corresponding storage file. The parameters must be accurate and translate accurately to the glove.
- **Who:** Test will be performed by Francisco.

16: Data receive

- **Description:** The ability of the configuration utility to receive data is tested
- **Procedure:** The configuration Utility is first initiated by double clicking the "MITTSutility.exe". Load profile is selected from the menu on the home screen. A profile xml file is chosen from the standard windows open/save dialog box. The home screen updates to reflect the chosen profile as being active. Blender is initiated, and the test virtual environment loaded.
- **Pass/Fail:** Utility should correctly receive positional data from the glove, and touch and temperature data from the 3D environment. The utility must be able to access the Blender API.
- **Who:** Test will be performed by Francisco.

17: Data transmit

- **Description:** The ability of the configuration utility to transmit data is tested
- **Procedure:** The configuration Utility is first initiated by double clicking the "MITTSutility.exe". Load profile is selected from the menu on the home screen. A profile xml file is chosen from the standard windows open/save dialog box. The home screen updates to reflect the chosen profile as being active. Blender is initiated, and the test virtual environment loaded.
- **Pass/Fail:** Utility should correctly transmit touch and temperature data to the Glove, and positional data to the 3D environment software. The utility must be able to access the blender API.
- **Who:** Test will be performed by Francisco.

18: Debugger

- **Description:** The ability of the configuration utility to utilize the debugging mode is tested.
- **Procedure:** The configuration Utility is first initiated by double clicking the "MITTSutility.exe". Load profile is selected from the menu on the home screen. A profile xml file is chosen from the standard windows open/save dialog box. The home screen updates to reflect the chosen profile as being active. From the active profile, the configuration tab for the glove that is to be set to debug mode is selected. The configuration view for that glove is displayed as the active view. On the configuration view, the debug radio button is selected. The view changes to the debug view for that glove. Electrical device charts begin displaying data in real-time. Manual signals for touch and temperature are injected and the device charts reflect the changes in real-time.
- **Pass/Fail:** Utility debug functionality should be able to interact directly with the Glove. The debug function must be able to display raw data reads from the glove.

Who: Test will be performed by Francisco.

19: SWD

- **Description:** With the SWD (single-wire debug), the STM32 will be flashed. For this to occur, we need to utilize some type of connection from the computer to the chip, which as described in the research, the ST-Link V2 may come in handy. Flashing the chip is essential in the hardware working.
- **Procedure:** Using the STM32 Flasher program as well as the ST-Link V2, we will flash the chip and verify that the chip is working by changing which colored LED turns on when the chip is flash. If one flash is red and the other time we flash, it's green, then we know the procedure worked.
- **Pass/Fail:** The test passes if the PCB design starts flashing red when flashed with the red LED program and also flashes green when flashed with the green LED program. It fails if either LEDs do not flash during their correlating program.
- **Who:** Test will be performed by David.

20: LED Function

- **Description:** As mentioned in the boot-up procedure section, we need a couple of LEDs to signify different states of the board. One state is powered, another is that everything has been initialized and the accelerometers have zeroed out. These LEDs will signify at which step our board is processing.
- **Procedure:** When powering the board, we will perform a visual test of the red LED coming on first and followed by the green LED. We will have dummy functions in place of what procedures will be there and will test those individually.
- **Pass/Fail:** The test passes if the red LED is powered followed by the green LED being powered and both stay on during start-up procedure. The test fails if either of the LEDs do not turn on or come on in an incorrect order.
- **Who:** Test will be performed by David.

21: Data Format

- **Description:** Having the data formatted will be imperative to the project. As mentioned before, the data needs to be positional data and then needs to be formatted the correct way. There will be two parts of this test, one for ensuring that the data is reasonable and the other making sure the data coming in and out of the board is formatted correctly.
- **Procedure:** While debugging, initialization should zero out data. From here, we can verify that, by lifting the device, one of the axes should increase in value. From here, we can verify output format by checking the interface and whether our format follows the guidelines that we've set.
- **Pass/Fail:** This test passes if data output starts with x, y, and z data are zeroed out and can be verified through the interface or a debugger. The test also must also verify movement of PCB board causes changes in x, y, and z coordinates. The test fails if either x, y, or z coordinates do not start zeroed out or they do not change when movement occurs.
- **Who:** Test will be performed by David.

22: I2C Read

- **Description:** The data will need to be retrieved and sent to almost everything that the design incorporates. Every device has a set address.
- **Procedure:** This will be tested by monitoring the debugging software and ensuring that proper data is being read. We can further test by looking at the interface and ensuring that the data is both changing and accurate and that there is data coming into the interface in the first place.
- **Pass/Fail:** The test passes if each unique I2C device can send and receive data and will be verified through the debugger module. The test fails if any I2C device shows that it is neither sending nor receiving data.
- **Who:** Test will be performed by David.

23: Boot-up Process

- **Description:** In the system startup procedure, the design is specified as having a few steps that need to occur. This includes setting pins, I2C initialization, Bluetooth handshake, LEDs being turned on, and then reading and writing data.
- **Procedure:** To test this, we will monitor the debugging log and ensure by the visual cues of the LEDs as well as the output and input data of the interface has corrected values.

• **Pass/Fail:** The test passes if all the start-up steps are verified to have occurred, which includes pin setup, I2C initialization, Bluetooth communication, LEDs turning on in order, and reading and writing of data occurs. The test fails if any parameter fails.
• **Who:** Test will be performed by David.

24: Blender Collision & Physics
• **Description:** The Blender scenario must have working physics for the hand to be able to interact properly with the environment.
• **Procedure:** To test this, the physics settings will be configured, and the collision logic will be implemented. Once the game engine starts, gravity and collision should be working as intended.
• **Pass/Fail:** To pass the test, the objects in the engine should fall and collide with each other. If objects don't fall our pass through each other the test will fail
• **Who:** Test will be performed by Hunter.

25: Blender-Driver Communication
• **Description:** Blender must be able to communicate consistently with the driver in order to be able to demonstrate the device
• **Procedure:** To test this, a test script will be written into Blender's logic editor that displays the driver inputs in the Blender console window. When the game starts, the correct inputs should appear in console.
• **Pass/Fail:** To pass the test, the console must display the correct inputs that are being sent by the driver. If the console display is not correct, the test will fail.
• **Who:** Test will be performed by Hunter.

26: Hand Tracking Script
• **Description:** Blender must be able to move the in-game hand in accordance to the input from the driver. This includes both the position of the hand and formation of the fingers.
• **Procedure:** To test this, a test script will be written into Blender's logic editor that will change the hands position based off of the driver inputs. To make sure that the script is accurate, it'll also print the position of the hand and the inputs from the driver in the python console window so that data can be collected, and discrepancies will be noticed.
• **Pass/Fail:** If the hand moves correctly in the relative direction of the glove's motion, and there are no discrepancies in the console, the test will pass. If the hand doesn't move or moves incorrectly, the test will fail.
• **Who:** Test will be performed by Hunter.

18.6: Surface Mount Components

A surface mount component varies from the more traditional DIP style of packaging in that rather than having extended pins that fit through small holes in the PCB, surface mount components have small metal pads that rest on small metal pads on the PCB. The advantage of surface mount components over the through hole variety is that of size. Surface mount components are generally smaller in every dimension and weight quite a bit less than their bulkier cousins. It is not unusual to have an 8-pin chip by only a few millimeters in height, length, and width. The following figures show a 555 time in both DIP and SO-8 packages, courtesy of Texas Instruments and the 555 Timer Wikipedia page.

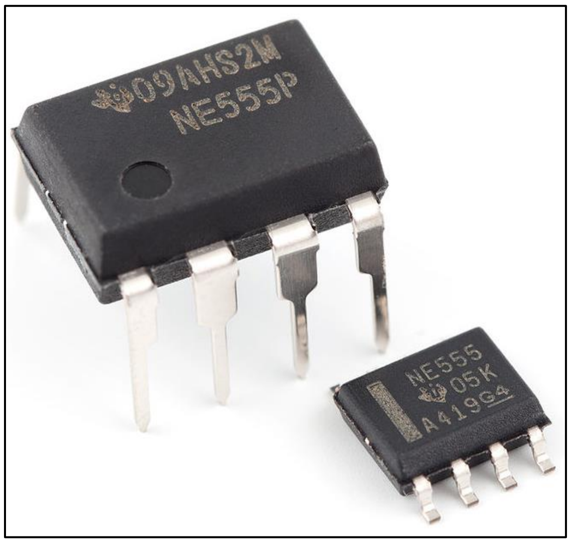


Figure 85: DIP 555 Timer and Surface Mount 555 Timer [38]

Note that the SO-8 package takes up less than half the volume for the same functionality as the DIP package. Since this project relies heavily on complex circuitry that must fit onto the back of a hand and even fingers in some cases then only surface mounted components will be used with very rare exceptions. This will save both mass and volume and more easily allow the project to meet its stated goal of remaining under 2 kilograms.
The following table shows the package and dimensions for each major surface mounted component used in this project.

Type	**Name**	**Package**	**Dimensions**
IC Sequencer	MAX6897	6 Thin SOT23	2.9 mm x 2.75 mm
Op Amp	TSV324	SO (14)	8.75 mm x 6.2 mm
Dual FET	NX3008C BKS	TSSOP (6)	2.2 mm x 2.2 mm
Dig Pot	AD5248	10 MSOP	3 mm x 5 mm
Power Reg	TPS62823	QFN (8)	2 mm x 1.5 mm
Accelerometer	MMA8451	QFN (16)	3 mm x 3 mm
I2C Mux	TCA954A	TSSOP (24)	7.8 mm x 4.4 mm
H-bridge	DRV8836	WSON (12)	2 mm x 3 mm

Table 23: **Package and Dimensions of all Major Surface Mounted Components**

As can be seen from this table all the major components used in this project are specified to be very small. As previously stated this is to minimize the size and mass of the final glove. Unfortunately, since many of these components do not come in DIP packages that are appropriate for bread boarding, adapters must be purchased or made. A large variety of adapters were purchased that should be able to account for all the parts. However, it these adapters do not then specific surface mount to dip adapters will be made by designing small custom PCBs and ordering them for the express purpose of breadboarding the various circuits described earlier in this paper.

19: Final Production Schematics

This section contains the final production schematics with all replication for this project. The only schematic not contained in this section is the battery and voltage regulator section since no changes to that design have been made. Note that some of the wiring discussion for the STM processor, the I2C bus, and the BL652 Bluetooth module are contained in this section.

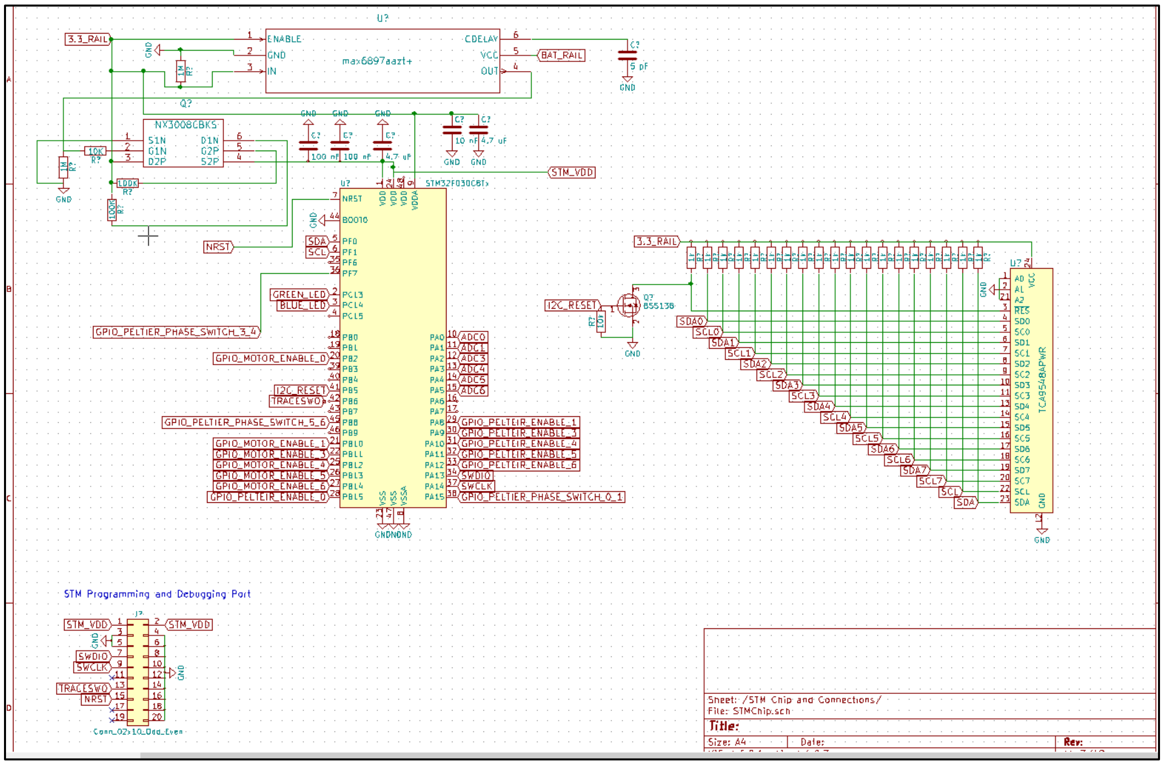


Figure 86: Final Schematic of STM Processor, I2C Bus, Timing Regulator, and STM Programming and Debugging Port

As seen in the figure above the STM32F030C8 has its final pin assignments. Note that the STM uses the SWDIO and SWCLK pins to program and debug in a 20-pin configuration as required from the STM datasheet. The I2C bus was established as per the TCA954A datasheet. Specifically, the 1 kΩ resistors were chosen to allow approximately 3 mA of current through as specified by the datasheet. This will minimize the bus capacitance which cannot exceed 400 pF. Any bus that exceeds 400 pF will not be able to switch voltage levels quickly enough to communicated with any degree of accuracy. Also note the Boot0 pin has been pulled to ground. This is to ensure that the STM boots from user flashed memory as opposed to the other options such as its onboard nonvolatile RAM. That can be accessed by setting the Boot0 pin high but is not desired for this specific project. The nRST is the STM's reset pin. It performs what is essentially a power down reset without actually having to power down the device. This pin has been linked to the programming/debug connector so that during programming the debug device can reset the STM in case of an error or to begin an operation from the beginning.

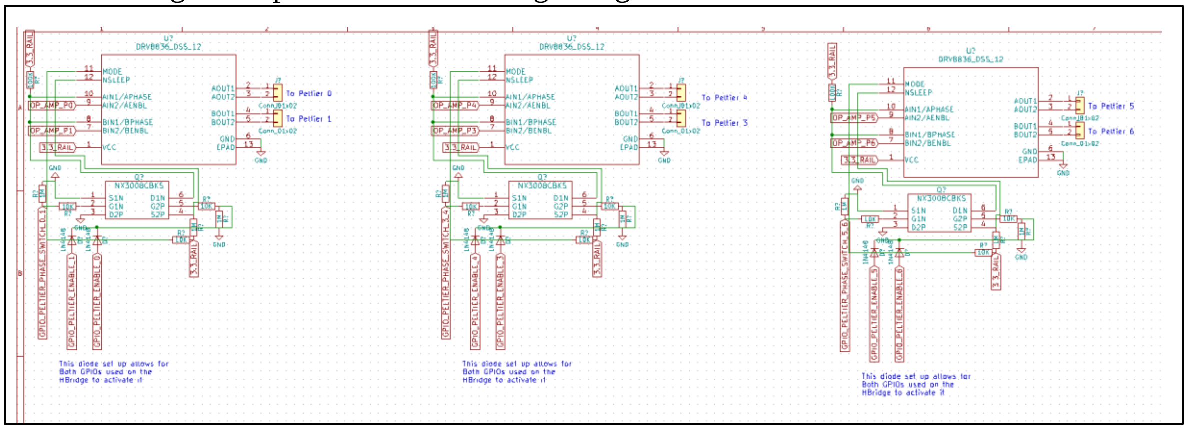


Figure 87: Final Schematic of H-Bridge Portion of Peltier Controllers with Replication

The figure above shows the final schematics of the H-Bridge portion of the Peltier controller. This schematic will be what will be used to establish traces for the final PCB layout.

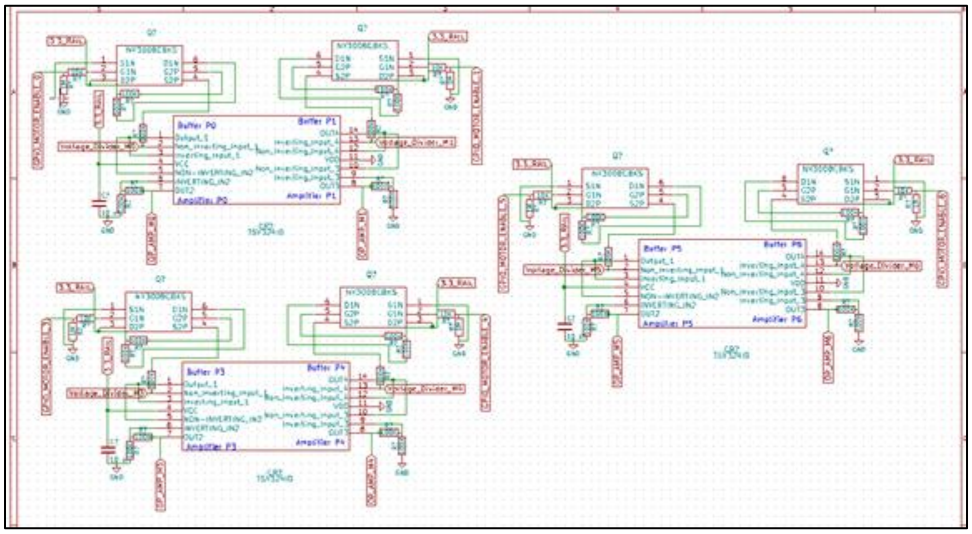


Figure 88: Final Schematic of the Operation Amplifier Portion of the Peltier Controller with Replication

This figure above shows the final schematics of the Operation Amplifier portion of the Peltier controller. This schematic will be what will be used to establish traces for the final PCB layout.

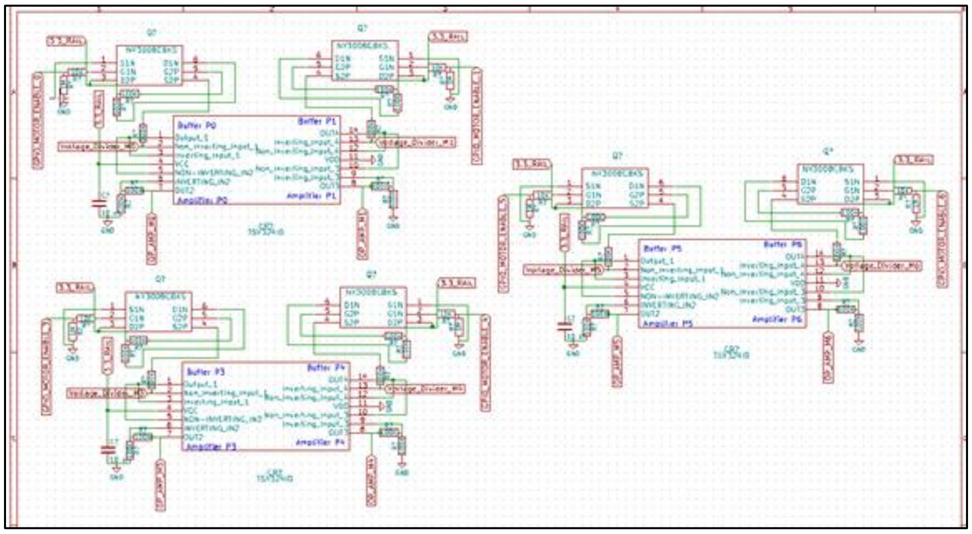


Figure 89: Final Schematic of the Operation Amplifier Portion of the Motor Controller with Replication

This figure above shows the final schematics of the Operation Amplifier portion of the motor controller. This schematic will be what will be used to establish traces for the final PCB layout.

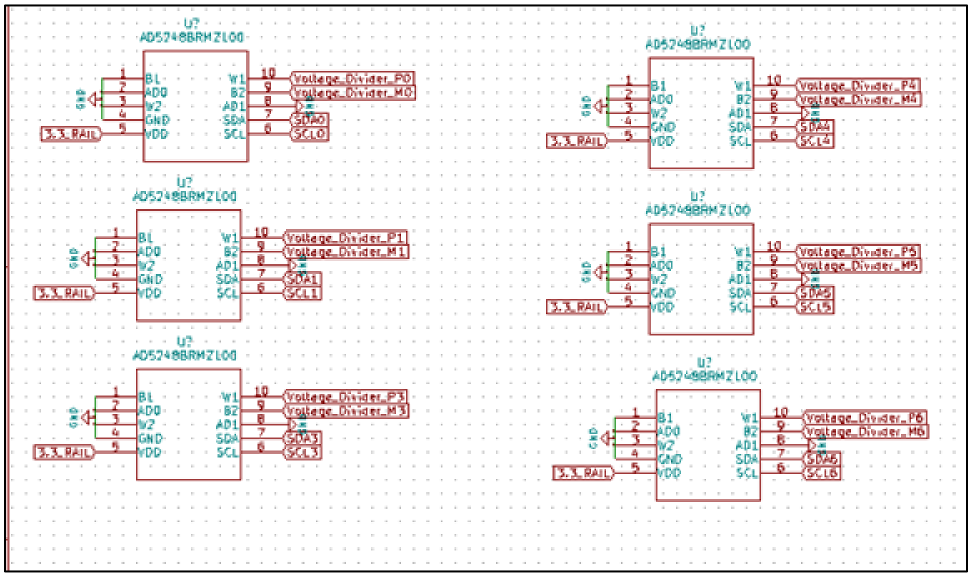


Figure 90: Final Schematic of Digital Potentiometers for all Controllers

The figure above shows the final schematic for the digital potentiometers for all controllers. This schematic will be what will be used to establish traces for the final PCB layout.

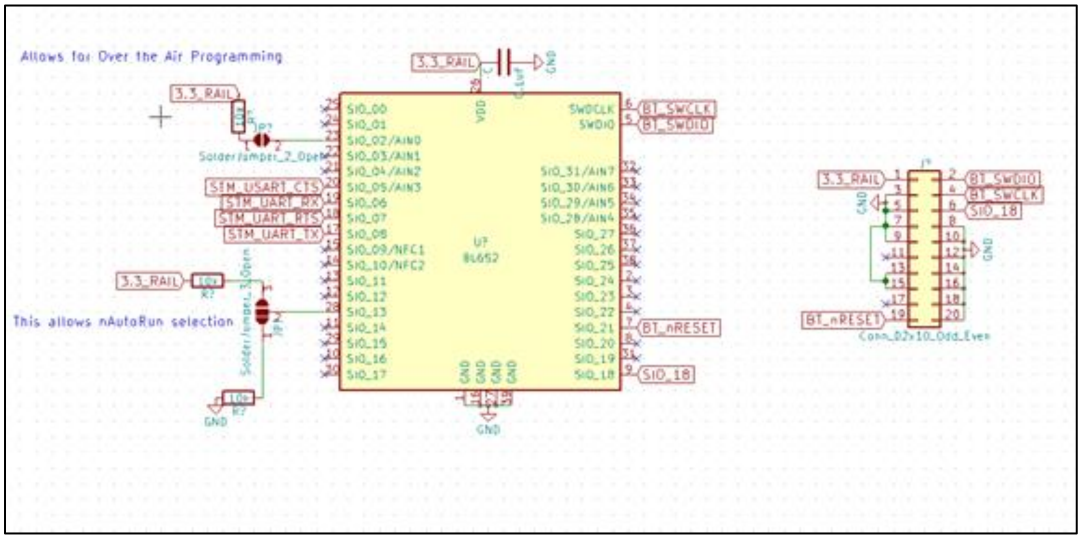


Figure 91: Final Schematic of the BL652 Bluetooth Module and Programming and Debugging Port

The figure above shows the final schematic for the BL652 Bluetooth module and accompanying programming and Debug port. This schematic will be what will be used to establish traces for the final PCB layout. Note that the USART TX and RX crosses have been accounted for in this schematic. Jumpers have been added to allow for the autoboot option to be implemented as can be seen on pin 28. Pin 22 has a jumper that will allow over the air programming if desired. These two features allow for an embedded code to run on the Bluetooth module's power up cycle or to program it though its RF functionality respectively. The BL652 has a built-in coding software that is similar to BASIC. However, this Bluetooth module is specified to simply send and receive UART packets, so the built-in programming language is more than likely not necessary. The same is true for the over the air programming capabilities. The design is not specified to have this capability, but having the option is nice. Therefore, jumpers were added for on the fly hardware modifications.

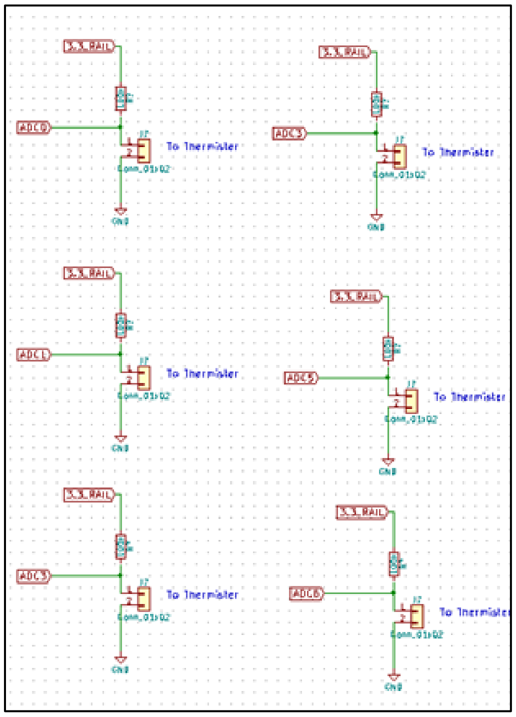


Figure 92: Final Schematic Thermistor Ports for all Peltier Controllers

The figure above shows the final schematic for the thermistor ports for all Peltier controllers. This schematic will be what will be used to establish traces for the final PCB layout. Note that each thermistor attaches to a unique ADC line that feeds directly into the STM processor while the actual thermistor attaches to the wire port. The thermistor will rest against the Peltier device.

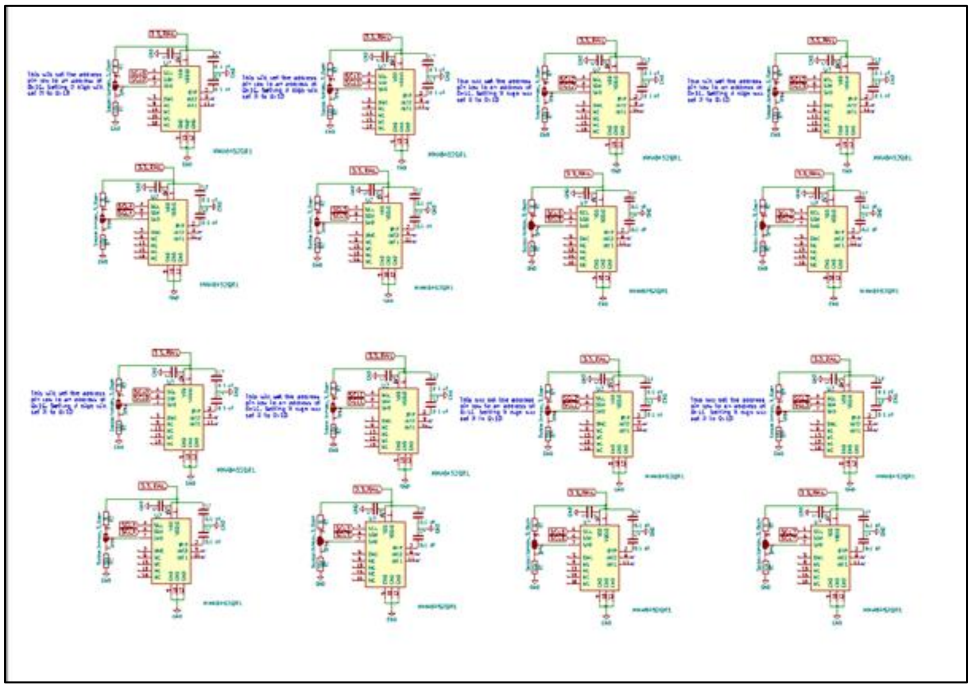


Figure 93: Final Schematic for the Accelerometers for all I2C busses

The figure above shows the final schematic for the thermistor ports for all Peltier controllers. This schematic will be what will be used to establish traces for the final PCB layout. Note that each of these accelerometers will be on its own separate PCB with attached ribbon cables. A jumper was added to allow for selectable addresses between the two possible addresses. This will allow for mass production of the accelerometer chips. Also note that each chip will be attached to each other along the fingers via ribbon cables which will also attach back to the main processor board.

20: Future Design Changes Based Upon Testing

20.1: Peltier Controller

The major design constraint of the Peltier device and its associated controllers, thermistors, PID feedback loops, and other associated circuitry was always what the human hand could sense and tolerate. For instance, if the device could accurately control temperatures from 100°C to 150°C it would be useless for the purposes of this project since it would scald any users. The degree of accuracy that it could be controlled with would be meaningless. To this end the Peltier device was tested in accordance with the testing procedure laid out in Section 18. Specifically, the Peltier was attached to a benchtop current supply and current was applied to the device and the temperature changes were measured. More importantly the impact of the temperature changes on human flesh was also examined. The great concern that was associated with the Peltier was that since an external heat sink was too bulk that device would not be able to efficiently vent or absorb. This proved to be true. The results of the test show that below 300 mA the heating of the Peltier device in ambient conditions was too small for the human hand to register while the temperatures that occurred at and above 350 mA were hot enough to be painful to flesh of the testing technician. The cooling of the device, being less efficient than the heating, were barely perceptible to the flesh of the testing technician. At 350 mA the cool side was analogous to a cool plastic surface that is slightly below ambient. Any more current would risk having the users walking around in virtual reality with what amounts to hot coals facing outwards on their hands. This obviously is a grave safety concern and cannot be tolerated. Since the cooling is barely perceptible at current ranges that make the offside of the device unsafe it was decide that cooling functionality would be removed.

These results mean that certain redesigns of the Peltier system must be done to adjust to the new information. Specifically, the Peltier will no longer have a variable temperature control. It will no longer have cooling functionality. It will simply be an on/off hot pad. This will also mean that the thermistors, and the feedback circuitry to control Peltier temperature are not necessary. The digital potentiometers are not necessary either. The Peltier controller circuitry will be simplified to two operational amplifies interaction with an H-Bridge. The H-Bridge will still be used since it is ideal for driving high current applications. This result also means that the need for high power batteries will be reduced, however it was decided that the current battery design will remain to extend the operating time of the device.

20.2: Motor Controller

The vibrational motor test results were much more successful than the Peltier device test results. They showed the ability to clearly control vibrational frequency and magnitude with applied voltage. Noticeable vibrations occurred at 1 volt and increased in intensity until 3 volts at which the test was deemed a success. It is to be determined if hardware should be changed so that GPIO activation of the motor controller results in an immediate application of 1 volt to the vibrational motors or if the design as it currently stands should simply set the voltage with the digital potentiometer.

21: Conclusion

Interacting with a virtual environment is both an academically interesting and technically challenging task that could produce dividends for the gaming and hobbyist communities. The addition of both haptic and temperature feedback could greatly expand the immersions of virtual worlds. By adding this design to the open source community, we expect to advance our careers and highlight our technical skills to prospective employers.

From PCB design to programming interfaces to working with Blender, this design has brought a unique experience to the group. PCB design is complicated and comes with a lot of trial and error. Creating an interface is a very valid real-world experience that will benefit us when alike tasks are assigned to us. The STM32 main PCB design has posed a risk of bottle-necking the project because of it being the main source for data retrieval and data transmission.

Overall, gathering this information has been very beneficial because of the knowledge of the potential risks and the comparisons between the parts that were a potential for the design.

22: Photo of Acquired Parts

Here is a detailed image of all the parts that the research suggests will satisfy the design. All surface mounts are small as the picture suggests; a quarter was placed in the image as a size comparison. All major components have been ordered, but there is a potential that the design may need package adapters to make the very small parts easier to work with.

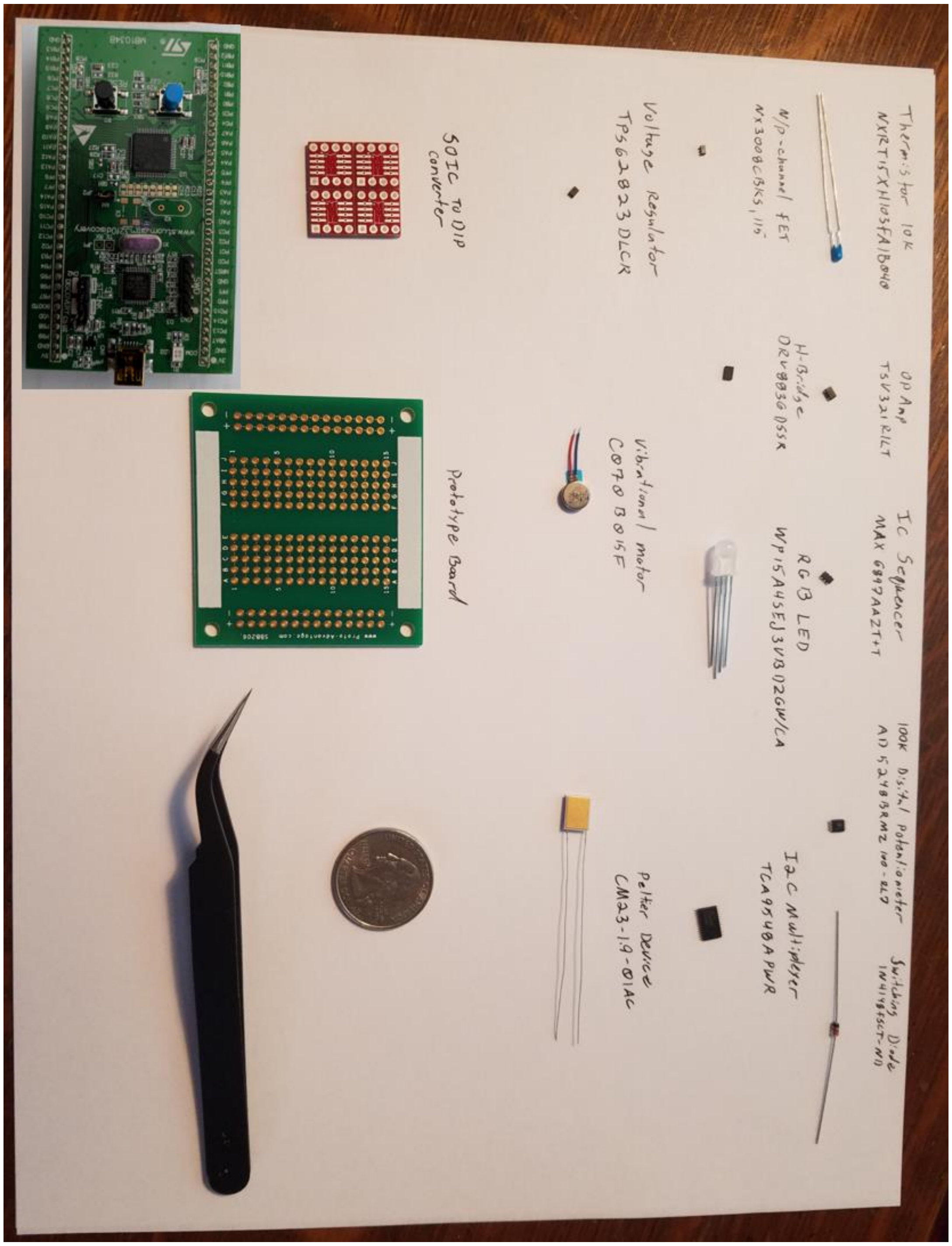


Figure 94: Purchased Parts with Quarter for Scale

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