Bone Conduction Lock

ECE 445 Design Document — Spring 2018

Alex Lee, Brandon Powers, Ramón Zarate
Team 3
TA: Jacob Bryan
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1 Introduction

1.1 Objective

The ability to quickly enter a locked door without fumbling for keys is an issue the car industry has recognized and worked to eliminate with features like keyless entry. Home and building locks on the other hand, have lagged behind in this field. Even so-called ‘smart locks’ on the market today often require consumers to fumble through their belongings to find a phone and interact with an app [1]—assuming they have remembered to budget enough battery power to keep their phone alive, that is—all the while exposing themselves to cold, rain, or potentially dangerous persons they would rather have on the other side of a locked door. If not dependent on a smartphone, alternate mechanisms are either expensive or vulnerable. Keypads are simple to crack with the aid of fingerprinting dust or an infrared camera [2]. Fingerprint locks can be fooled by pictures of secretly-gathered prints [3]. Iris scanners are impractically expensive for the average household. Facial recognition poses the risk of allowing those who use it to be identified in a crowd without their consent if the data is ever compromised or sold to advertisers [4]. Card-swipe or RFID proximity card locks suffer from the same fumbling problem as keys, and a lost or stolen wallet can render the locks as good as shut.

The Bone Conduction Lock System (BCLS) provides an efficient way to lock/unlock a door while laying the groundwork for further investigation of cheap and secure biometric authentication in the future. The BCLS consists of two parts: a wearable wristband (hereafter, band)—far more resistant to loss than wallet—and a door-mounted lock. When the user wants to unlock a BCLS-secured door, they press a button on the band and touch their finger[1] to the lock. A haptic motor inside the band will then use the bones in the user’s hand as a channel to transmit vibrations to the lock. An amplitude-modulated signal at a carrier frequency signal capable of being conducted through bone will carry a vibration signal to the receiver in the lock. The signal itself will also be perturbed by the channel: the user’s hand. If the signal received at the lock is correct, the lock opens. While not a requirement of the project, this method lays the groundwork to investigate using the specific perturbations imparted by the user’s hand as a form of biometric identification.

1.2 Background

Smartphone dependence of existing smart locks is an issue due to minority populations. The National Federation of the Blind reports there are 1.3 million [5] legally blind Americans. While there are accessibility features for the vision impaired available on smartphones, a system that is entirely haptic such as the BCLS would be more accessible to those populations. It will also be more convenient for the sighted, who will not have to fumble through their pockets for their keys or phone to unlock their doors. Additionally, the elderly or those making too little to afford

[1] The specific finger is arbitrary. It need only be the same finger each time.

smartphones could also gain access to the ease and security of smart locks without being required to purchase a phone or take the time to learn to use one. Unlike smartphones, the BCLS band would not have to perform all the battery-draining features of a phone, and would be less prone to running out of battery when it may be needed to enter a locked door.

There has been some initial exploration of human bone as a viable communication channel for vibration signals by Professor Choudhury's Systems Networking Research Group (SyNRG, http://synrg.csl.illinois.edu/index.php) here at the University of Illinois at Urbana-Champaign.

Previous research also indicates there is enough difference in skeletal structure to potentially warrant unique identification via bone conduction. German researchers undertook a Google Glass based project called Skullconduct, which used vibrations conducted through the skull to correctly identify users with a 97% success rate [6]. The BCLS lays the groundwork for similar applications based on users' hands. Another potentially fruitful area to investigate is whether the channel distortion is affected by hand or finger position. If so, users being forced to replicate hand or finger positioning could be another layer of the 'password' when entering a BCLS-secured door.

1.3 High-level Requirements List

- The only communication channel from band to lock must be vibrations conducted through the user's hand.
- When the correct "key" is transmitted from the band to the lock, BCLS must operate with no more than 10% of attempts leading to false negatives.
- We must be able to lock/unlock the BCLS in 10 seconds or less.

2 Design

The BCLS is lock/unlocked using vibrations conducted through the user's hand. BCLS is composed of two independent modules: the band and the lock. The user wears a band on their wrist connected to a ring containing a haptic motor worn on their finger. When the band is powered on, the user presses a button on the band and the haptic motor in the ring generates a vibration signal that acts as the "key" to the lock. The haptic motor is a linear resonant actuator (LRA) motor. The LRA motor generates a vibration by using AC power to move a mass back and forth along an axis. When the user presses their finger to the lock, the vibration signal is conducted through the user's hand to their fingertip and is received at the lock. If the lock receives the correct "key", it locks/unlocks depending on its current state. Status LEDs on the lock indicate the state of the lock and whether an attempt to lock/unlock the lock was successful or unsuccessful. When the lock is in its locked state, the red LED is on. When the lock is in its unlocked state, the green LED is on. If an attempt to lock/unlock the lock is successful, the green LED will blink. If an attempt to lock/unlock the lock is unsuccessful, the red LED will blink. The lock also keeps a log of all the attempts to lock/unlock it.

2.1 Block Diagram

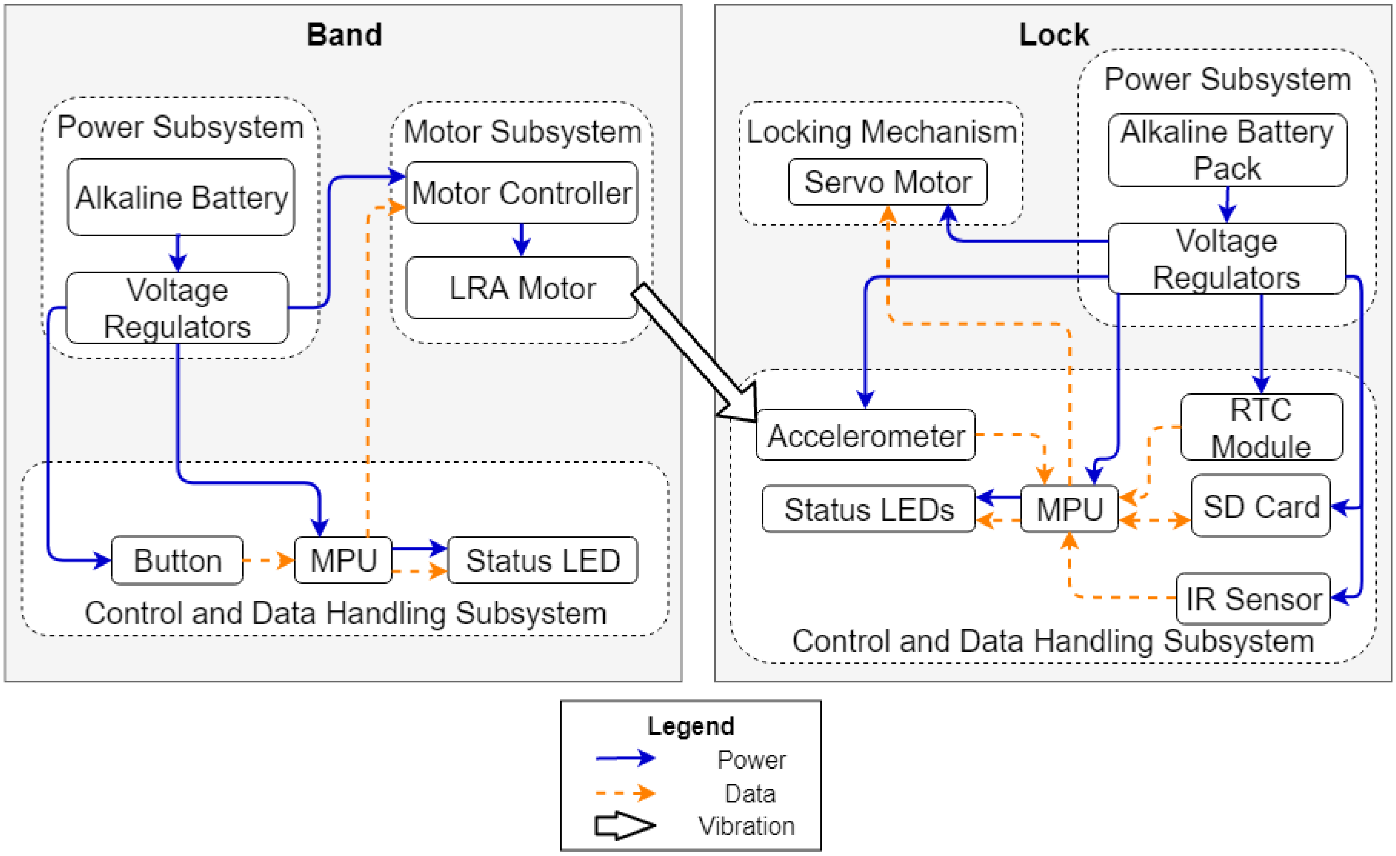

Figure 1: BCLS Block Diagram

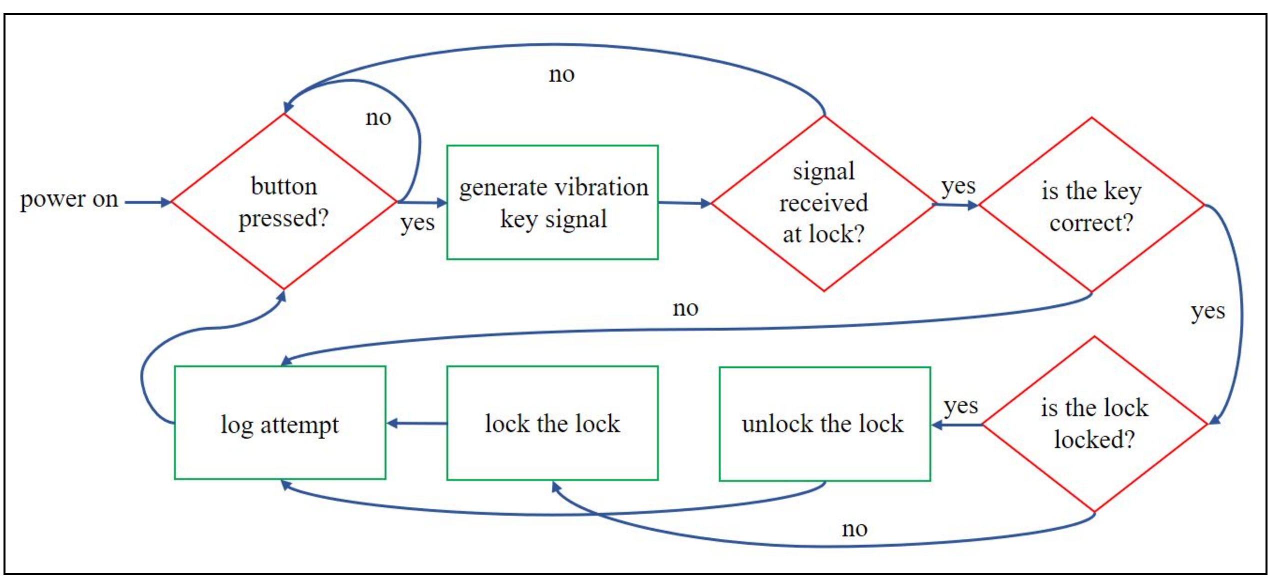

Figure 2: BCLS operation flow chart

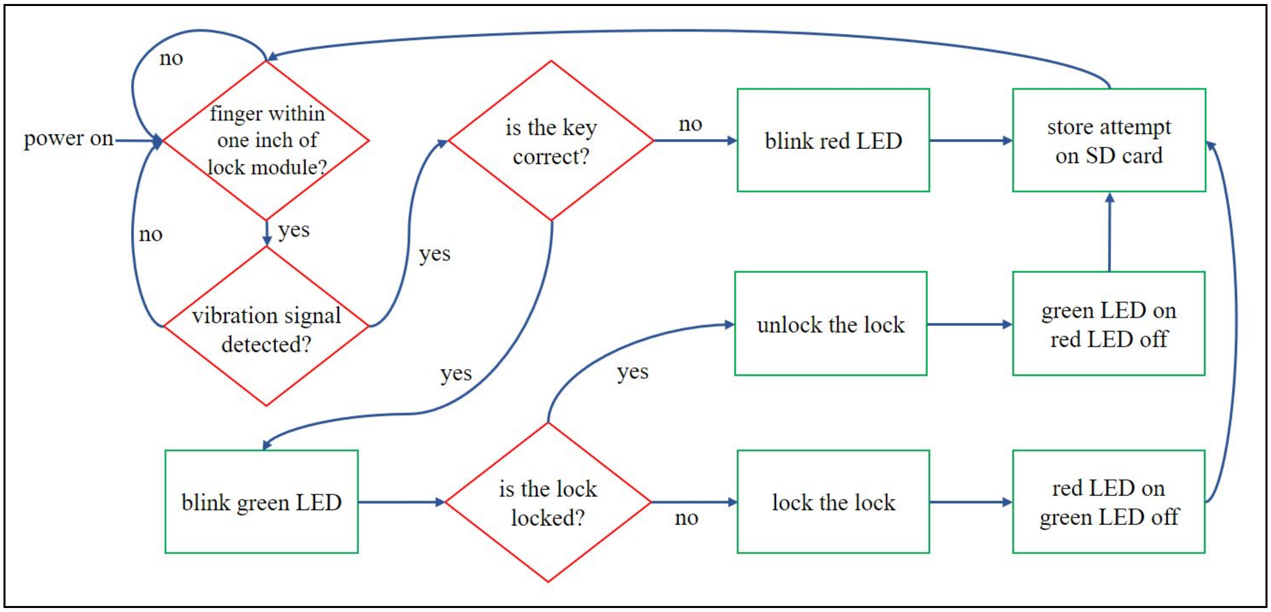

Figure 3: Lock module operation flow chart

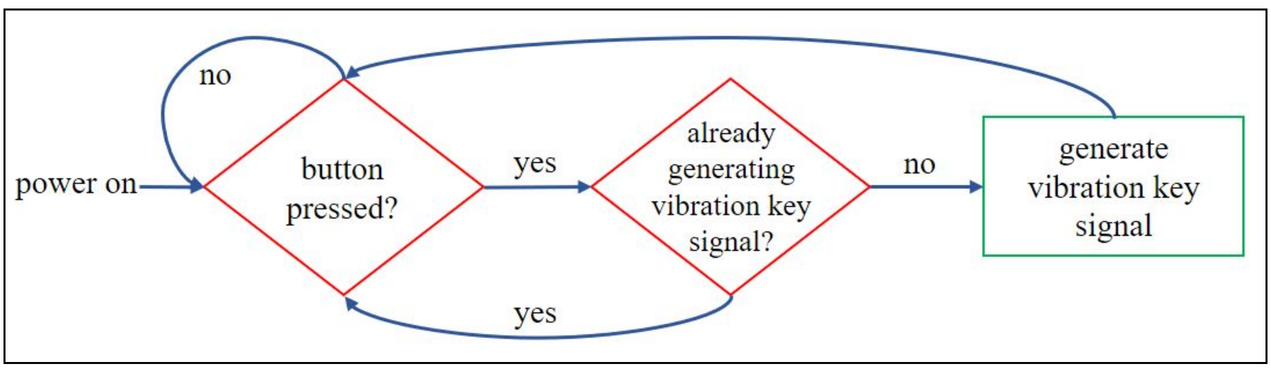

Figure 4: Band module operation flow chart

2.2 Physical Design

2.2.1 Door Lock Module

For the physical design of the lock module, we want to mimic the HID module on the doors in UIUC's Electrical and Computer Engineering Building (ECEB). The HID module is the black rectangle located above the door handle as seen in Figure 5. To operate the door lock, a student id card is placed in close proximity (1- 3 cm) allowing the HID module to read the identification number associated with the I-card. If the identification number is approved, the lock unlocks.

Our lock module will be a close approximation of the HID module in appearance. However, unlike the HID module which uses a wireless communication protocol, we will be using a physical vibration signal protocol. Our lock module is comprised of four main components: the control unit, locking mechanism, status LEDs, and battery.

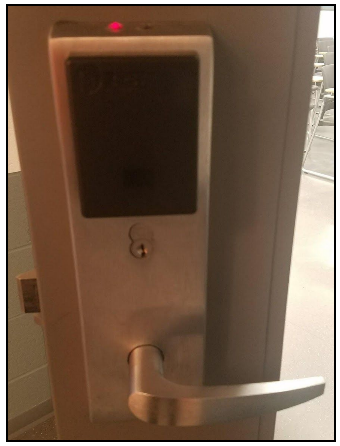

Figure 5: HID Unit at ECEB

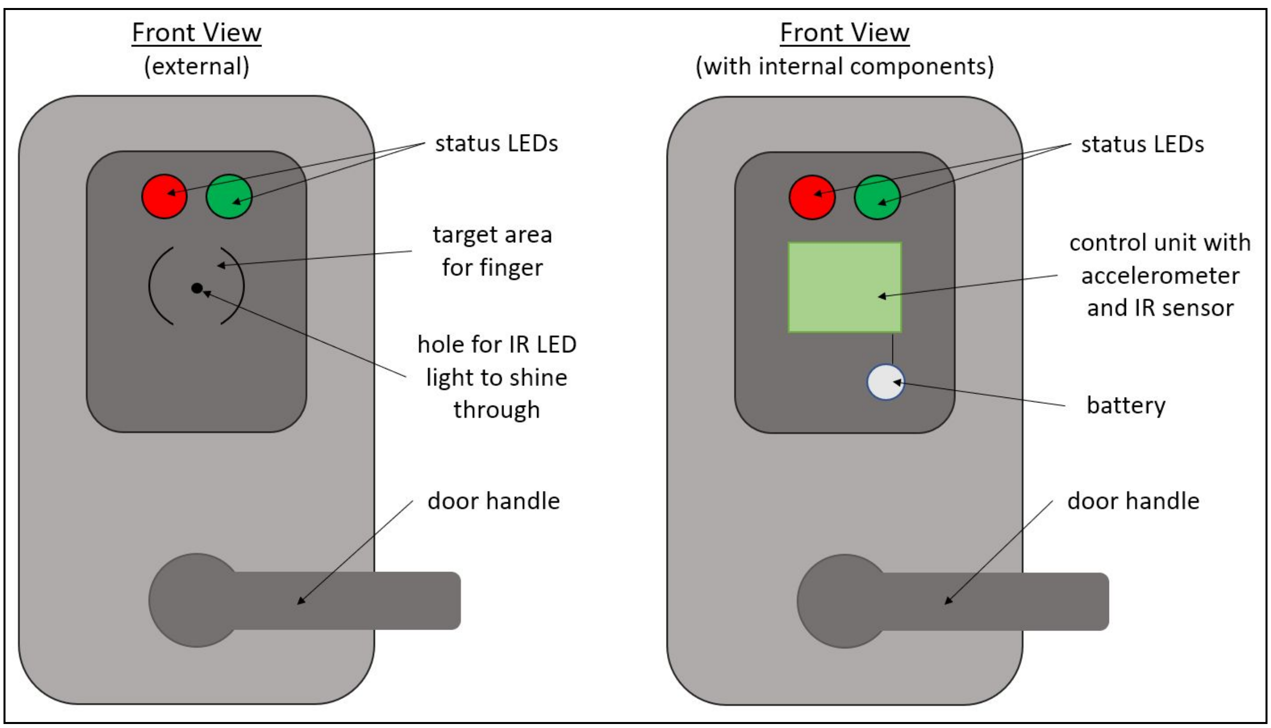

Figure 6: Physical Design of Lock Module
(physical locking mechanism not in figure)

As seen in Figure 6, all the components are housed in a rectangular module located above the handle. Looking at the module, the only exposed components are the status LEDs. The rest of the components will be hidden inside the casing of the module. Since an accelerometer is a microelectromechanical system, to get the best signal to noise ratio, it is crucial to minimize the distance between the accelerometer and the point of contact where the finger touches the module. Because the accelerometer will be surface mounted on the PCB, the PCB will need to be located as close to the point of contact with the finger as possible. A marking on the outside of the casing will indicate the optimal place for the user to touch their finger to ensure the strongest signal possible. There will also be a small hole in the center if the circular marking on the casing of the lock module. This hole allows the light from an IR sensor to shine through. With the IR sensor, we can determine if a finger is being pressed against the lock module. This will help determine whether output from the accelerometer is due to a transmitted vibration signal or just random vibrations from the environment.

2.2.2 Band Module

The band module is responsible for generating the vibration signal. The band will have a similar form factor to a smartwatch. The difference is that the band module is made of two connected parts: the main band and the ring. This form factor can be seen in Figure 7. Preliminary tests showed the signal amplitude from the LRA motor mounted on a ring was far greater than when the motor was mounted on a wristband. The components of the band are the PCB, push button, LRA motor, status LED, and battery. The components are housed in the portion of the band located on the top side of the wrist. This connects via cable to a ring housing the motor. All components will be contained entirely inside the band's housing with the exception of the push button and status LED, which will protrude out of the casing. The user will be able to push the button to generate the vibration signal. When the battery is low, the status LED will indicate this, prompting the user to change the battery.

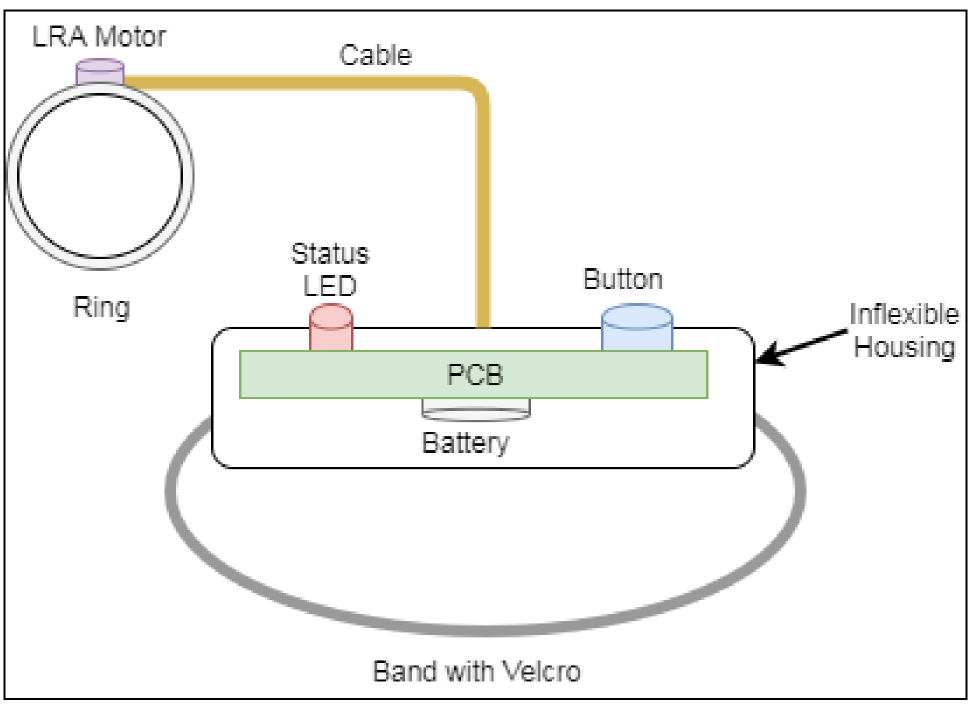

Figure 7: Physical Design of Band Module

2.3 Block Design

2.3.1 Lock Module

2.3.1.1 Power supply subsystem

The lock module's power subsystem drives the control unit subsystem and locking mechanism. Specifically, it supplies power to the microprocessor, accelerometer, SD card reader, and servo motor. The power subsystem is comprised of a 7.5 V Alkaline battery pack and two voltage regulators. The lock module is battery powered so the lock can be independent from the door it's securing. This makes installation of the lock module easier and ensures the lock will continue to work in the event of a power outage. The regulators output 5 V and 3.3 V respectively.

(a) Alkaline Battery Pack

The alkaline battery pack provides power to the other components in the lock module. The battery pack has a 7.5 V rating, as opposed to a higher voltage, to limit the dropout voltage of the linear regulator. The dropout voltage is the voltage the regulator needs to dissipate in order to step down the voltage from the input voltage to the regulated voltage. Therefore, the voltage of the alkaline battery pack (input voltage) must always be higher than each regulated voltage (In this case, 5 V and 3.3 V). Preliminary data on the lock module's total load current estimates 100 mA max current draw when the servo motor is operating. The battery pack has a capacity of 15.25 Ah. This results in a total battery life of ~150 hours. However, this total battery life estimate is shorter than the expected battery life since the servo is the most power-hungry component in the module, and it will not be running most of the time.

(b) Voltage Regulators

The 3.3 V regulator drives the accelerometer. Meanwhile, the 5 V regulator supplies power to the microprocessor, IR sensor, RTC module, SD card reader, and servo motor. The voltage regulators are linear regulators. A linear regulator is a system use to maintain a steady voltage. The voltage regulator acts like a variable resistor, constantly adjusting a voltage divider network to maintain a constant output voltage and continually dissipating the difference between the input and regulated voltage as waste heat.

Requirements	Verification
1. Must output 3.3 V ± 5% with a current load of up to 150 mA	a. Measure the output voltage using a multimeter. b. Vary the load current by changing load

	resistance. c. Show on multimeter that voltage stays in its tolerance range as current is varied up to 150 mA.
2. Must output 5 V ± 5% with a current load of up to 150 mA	a. Measure the output voltage using a multimeter. b. Vary the load current by changing load resistance. c. Show on multimeter that voltage stays in its tolerance range as current is varied up to 150 mA.
3. Maintain a temperature below 120°C	a. Use an IR thermometer or IR camera when the IC is in operation to show that the temperature stays below 120°C.

Table 1: RV Table for the Lock Module's Power Subsystem

2.3.1.2 Control unit subsystem

The control unit is tasked with detecting/verifying the vibration signal transmitted from the band and determining what action to take: lock/unlock the lock or do nothing. The control unit also keeps a log of all the attempts to lock/unlock the lock. The control unit is powered by the power supply subsystem and is comprised of the MPU, accelerometer, IR sensor, status LEDs, RTC module and SD card reader.

(a) Microcontroller

The microcontroller is connected to all the components in the lock module. The microcontroller processes the output from the accelerometer and IR sensor to determine what the other components of the lock module should be doing. The microcontroller only reads the accelerometer output when the user's finger is detected within one inch of target area on the lock module. The lock module uses the ATmega2560, a high-performance picoPower 8-bit AVR RISC-based microcontroller. The ATmega2560 has 256 KB ISP flash memory, 8 KB SRAM, and 4 KB EEPROM. The microcontroller is capable of both digital (UART, SPI, I^2C) and analog communication.

(b) Accelerometer

The accelerometer constantly outputs data to the microcontroller corresponding to the vibration it experiences. The lock module uses the MMA8452Q, a micro-machined 3-axis accelerometer with 12 bits of resolution. It supports ± 2g, 4g, or 8g full-scale range at up to 800 Hz and communicates with the microcontroller over an I^2C interface.

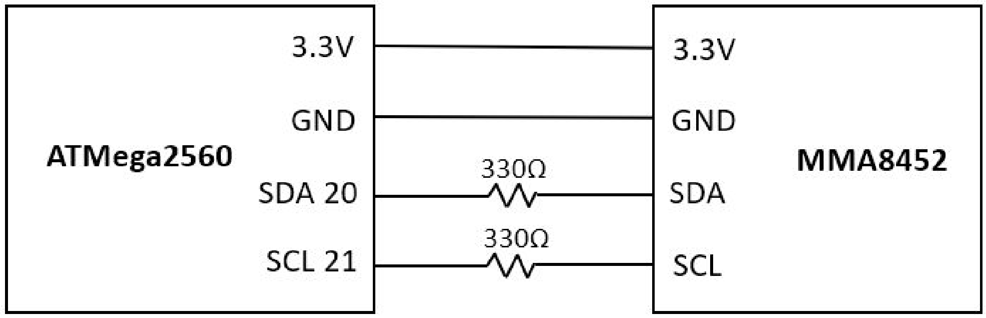

Figure 8: Accelerometer block diagram

(c) IR sensor

The IR sensor detects if a finger is within a one inch proximity of the lock module. The IR sensor works by shining and IR LED and seeing how much light bounces back using a photoresistor. The lock module uses the QRE1113. The analog output from the IR sensor is read in by the microcontroller. A 10kΩ resistor is used to pull the IR sensor output pin high. When the light from the IR LED is reflected back onto the photoresistor, the output will get lower. The more IR light sensed by the photoresistor, the lower the output voltage read by the microcontroller.

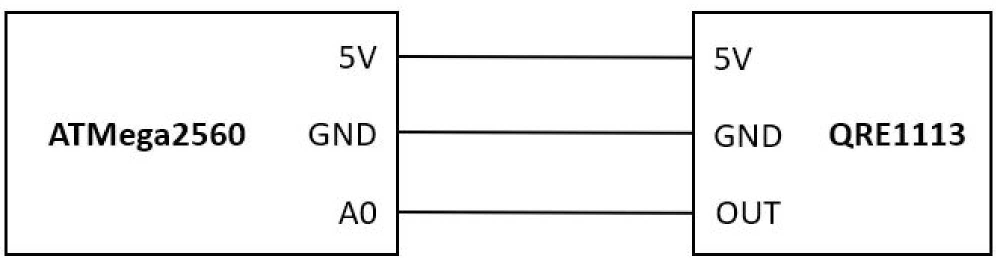

Figure 9: IR sensor block diagram

(d) Status LEDs

The status LEDs serve as a visual representation of the state the lock is in. When the lock is unlocked, the green LED is on. When the lock is locked, the red LED is on. When a correct “key” is received at the lock, the green LED blinks. When an incorrect key is received at the lock, the red LED blinks.

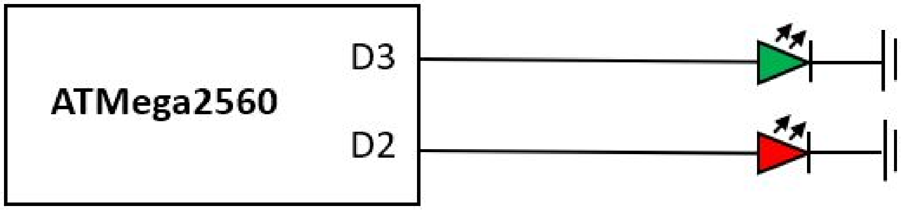

Figure 10: Status LEDs block diagram

(e) RTC module

Since the microcontroller only has an internal system clock, the RTC module is responsible for maintaining an external real-time clock. The RTC module timestamps all the lock activity the microcontroller logs on the SD card. The lock module uses the DS1307 real-time clock. The microcontroller communicates with the RTC module via I^2C protocol and can get the time in *hour:minute:second* | *day_of_week* - *month/day/year* format.

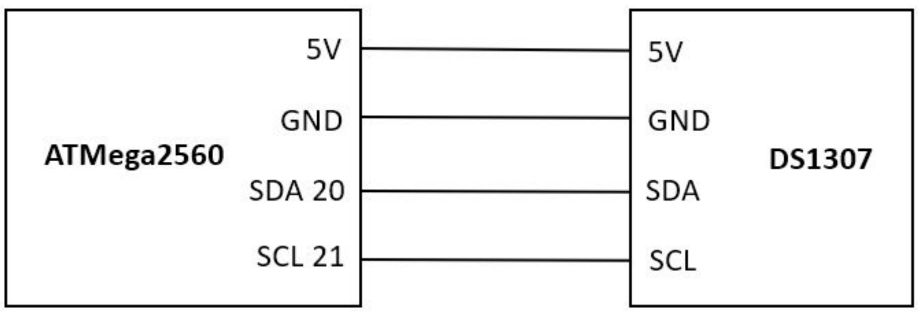

Figure 11: RTC module block diagram

(f) SD card reader

The SD card reader is connected to the microcontroller and stores the activity of the lock. It logs when a "key" was received at the lock, if the "key" was correct or not, and if the lock was locked or unlocked.

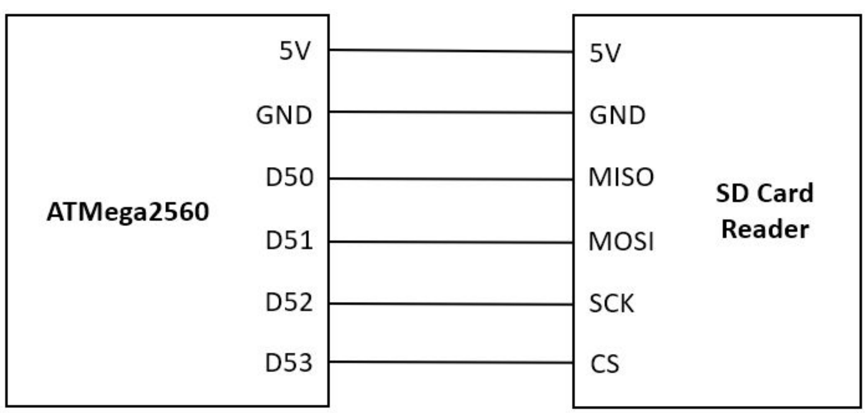

Figure 12: SD card reader block diagram

Requirements	Verification
1. Accelerometer output has full-scale range of ± 2 g with minimum sampling rate of 800 Hz to be read by microcontroller	a. Sweep frequency range using function generator to capture frequency response. b. Show that frequency response does not get clipped at 2 g on the serial monitor.
2. Accelerometer output has 0.01 g precision and maximum noise floor of 1.02 g	a. Send accelerometer output to microcontroller. b. Show the output has 0.01 g precision on serial monitor. c. Show accelerometer has maximum noise floor of 1.02 g on the serial monitor.
3. IR sensor detects finger when within one inch of the lock module target area	a. Send IR sensor output to microcontroller. b. Display sensor output on the serial monitor. c. Show change in IR sensor output is a function of proximity of finger when within one inch of the lock module target area.
4. Keeps log of at least the last 50 attempts to lock/unlock the lock	a. Transmit correct "key" to the lock. Read the log on the SD card to show successful attempt to lock/unlock the lock. b. Transmit incorrect "key" to the lock. Read the log on the SD card to show unsuccessful attempt to lock/unlock the lock.
5. Status LEDs show state of the lock	a. When lock is in locked state (0°), the red LED is on. b. When lock is in unlocked state (90°), the green LED is on.

6. Status LEDs give visual feedback on attempts to lock/unlock the lock	a. When correct "key" is received at the lock, green LED blinks. b. When incorrect "key" is received at the lock, red LED blinks.

Table 2: RV Table for the Lock Module's Control Subsystem

2.3.1.3 Locking Mechanism

(a) Servo

The servo receives its rotational position from the microcontroller and is responsible for locking and unlocking the physical lock mechanism. The servo receives positions information from microcontroller PWM peripheral.

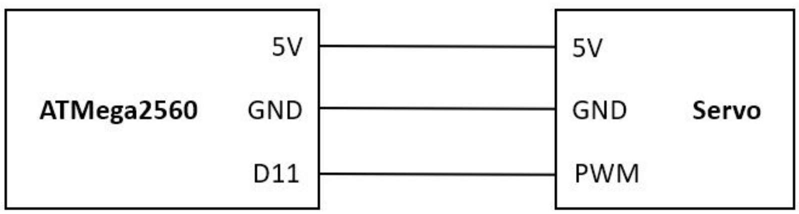

Figure 13: Servo block diagram

Requirements	Verification
1. Lock has two clear states: locked and unlocked	a. Perform sweep of designated servo motor range. Show the range allows the lock to be in two distinct positions. - locked state (servo is in its initialized position of 0°). - unlocked state (servo has position of 90°).
2. Status LEDs correctly correspond to the state of the lock	a. When lock is in locked state (0°), red LED is on. b. When lock is in unlocked state (90°), green LED is on.

Table 3: RV Table for the Lock Module's Physical Locking Mechanism

2.3.2 Band Module

2.3.2.1 Power Subsystem

The band module's power subsystem is responsible for powering the control unit subsystem and motor subsystem. Specifically, it supplies power to the MPU, push button, and motor driver. The power subsystem is comprised of a 6 V Alkaline battery and two voltage regulators. The band module is battery powered so it can be worn on the user without discomfort. The regulators output 5V and 3.3 V respectively. The status LED will indicate to the user when the battery is low.

(a) Alkaline Battery

The alkaline battery provides power to the other subsystems of the band module. The band module uses a 6 V alkaline battery for low power dissipation and reasonable battery life given its size. Preliminary data estimates a max current of 30 mA of current for the band module to drive the LRA motor. The battery has a capacity of 170 mAh, giving the band module an estimated battery life of ~5.7 hours. However, in the idle state, the power consumption of the band module is much lower, resulting in a longer battery life than the given estimate. Given the estimated battery life, the band module will be able to generate ~4,500 vibration signals.

(b) Voltage Regulators

The band module contains two voltage regulators. The 3.3V regulator drives the motor drive. The 5 V regulator supplies power to the microprocessor and push button. The voltage regulators in the band module are linear regulators. A linear regulator is a system use to maintain a steady voltage. The voltage regulator acts like a variable resistor, constantly adjusting a voltage divider network to maintain a constant output voltage and continually dissipating the difference between the input and regulated voltage as waste heat.

Requirements	**Verification**
1. Must output 3.3V ± 5% to with a current load of up to 100 mA	a. Measure the output voltage using a multimeter. b. Vary the load current by changing load resistance. c. Show on multimeter that voltage stays in its tolerance range as current is varied up to 100 mA.
2. Must output 5V ± 5% to with a current load of up to 100 mA	a. Measure the output voltage using a multimeter.

	b. Vary the load current by changing load resistance. c. Show on multimeter that voltage stays in its tolerance range as current is varied up to 100 mA.
3. Maintain a temperature below 120°C	a. Use an IR thermometer or IR camera when the IC is in operation to show that the temperature stays below 120°C.

Table 4: RV Table for the Band Module's Power Subsystem

2.3.2.2 Control Unit Subsystem

The control unit takes user input from the push button and determines when to generate the vibration signal. Control unit also notifies use when battery life of the band module is running low. The control unit contains the microcontroller, push button, and status LED.

(a) Microcontroller

The microcontroller is the specific component tasked with handling the user input and initiating subsequent tasks. It gets its power from the battery and is connected to the push button, status LED, and the motor driver. When the button is pressed, the microcontroller sends a signal to the motor driver to generate a vibration signal. When the battery on the band module is running low, the microcontroller turns on the status LED to notify the user. The lock module uses the ATmega328, a high-performance picoPower 8-bit AVR RISC-based microcontroller. The ATmega328 has 32 KB ISP flash memory, 2 KB SRAM, and 1 KB EEPROM. The microcontroller is capable of both digital (UART, SPI, I^2C) and analog communication.

(b) Push button

The push button is the method the user will use to communicate with the band. The push button is connected to the microcontroller. When pressed, the push button will send a signal to the microcontroller to initiate the vibration signal. The push button in the band module is a momentary switch. When the button is pressed, a circuit is completed. The newly established circuit sends a signal to the microcontroller, indicating the button has been pressed.

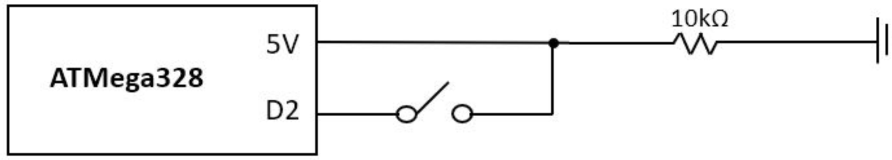

Figure 14: Push button block diagram

(c) Status LED

The status LED acts as a visual representation of the battery level of the wristband. The microcontroller turns the status LED to indicate to the user when the battery is running low.

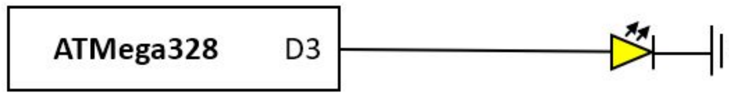

Figure 15: Status LED block diagram

Requirements	Verification
1. Signal from push button is momentary	a. Display output from push button on serial monitor b. Show the microcontroller only receives signal when button is pushed.
2. Pushing the button results in one complete transmission of the "key"	a. Wait five seconds without pressing the button and show that the motor does not generate a signal. b. Push the button and observe the motor generate a complete signal on the serial monitor. c. Push the button while the motor is generating a signal and show that it does not affect the completion of the current signal on the serial monitor.
3. Must be able to generate and transmit multiple complete "keys"	a. Transmit two consecutive signals by pressing the button once, wait for the first signal to transmit completely, then press the button again to transmit the second complete signal. b. Show two complete signals were transmitted on serial monitor.

Table 5: RV Table for the Band Module's Control Subsystem

2.3.2.3 Motor Subsystem

The motor subsystem is responsible for generating the vibration signal. It contains the motor driver and the LRA motor.

(a) Motor driver

The motor driver drives the LRA motor. The motor driver is connected to the microcontroller and the LRA motor. When a vibration signal needs to be generated, the motor driver receives a signal from the microcontroller that tells the motor driver what frequency the motor needs to run at. With this information, the motor driver drives the LRA motor appropriately. The motor driver used in the band module is the DRV2605L haptic motor driver. The DRV2605L takes input from the microcontroller by I^2C and supplies AC power to the LRA motor to drive it with the appropriate haptic effect at the desired frequency.

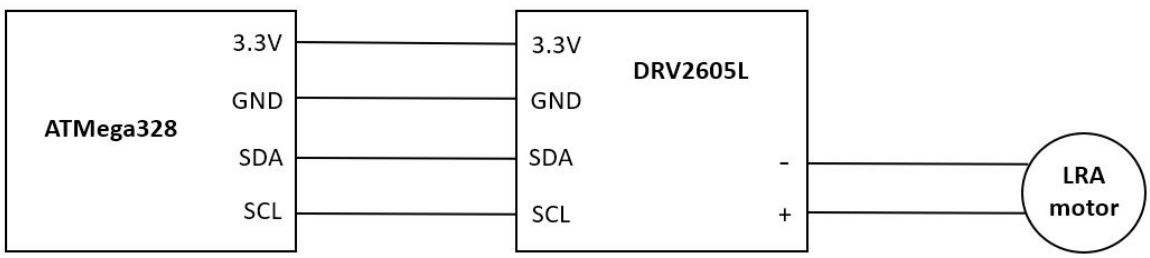

Figure 16: Motor driver and LRA motor block diagram

(b) LRA motor

The LRA motor is the actual mechanism that produces the vibration signal. The LRA motor receives AC power from the motor driver. The frequency the motor runs at is dependent on the waveform of the AC power it receives. The LRA motor used in the band module is the DMJBRN0832AF. It has a resonance frequency of 200 ± 5 Hz.

Requirements	**Verification**
1. Motor has resonant frequency in the range of 150-300 Hz (intersection of human bone conduction range and typical LRA motor resonance frequency range)	a. Conduct frequency sweep from 150-300 Hz. Show amplitude of vibration signal on the serial monitor. b. The peak of the frequency response is the motor's resonance frequency. Show that the resonance frequency lies within the required range by using an accelerometer to show the change in vibrational signal amplitude during the frequency sweep in real time and

	display it on the serial monitor.
2. Vibration signal generated by the LRA motor conduct through the hand to the fingertip has an amplitude that exceeds 1.02 g (accelerometer noise floor)	a. Generate a vibration signal from the motor. b. Conduct the signal through the hand to the fingertip, show the received signal on the serial monitor. c. Use accelerometer to show the vibration signal being received from the fingertip on the serial monitor. Vibration signal's amplitude is greater than the accelerometer noise floor if the change in the accelerometer output is a function of the vibrations of the motor.

Table 6: RV Table for the Band Module's Motor Subsystem

2.4 Tolerance Analysis

DMJBRN0832AF LRA Motor and MMA8452Q 3-DOF Accelerometer

The bone conduction lock system depends on the ability to conduct a vibration signal through the user's hand through the fingertip and receive it at the lock module. This being the case, one of the two most important components of the project are the motor that generates the vibration signal and the receiver which picks up the signal.

There are two types of haptic motors: eccentric rotating mass (ERM) and linear resonant actuator (LRA) vibration motors. Initially, we opted to use an ERM motor due to its low cost and ability to be driven with DC power. However, during our initial testing, the ERM motor was unable to generate a clean vibration signal. This was due to the underlying technology powering the ERM motor. ERM motors use a small unbalanced mass mounted on a DC motor. When the motor rotates, the motion of the unbalanced weight causes vibrations. This mechanism can be seen in Figure 17. While the magnitude of the vibration is easily controlled, control of the frequency and direction of the vibrations is not.

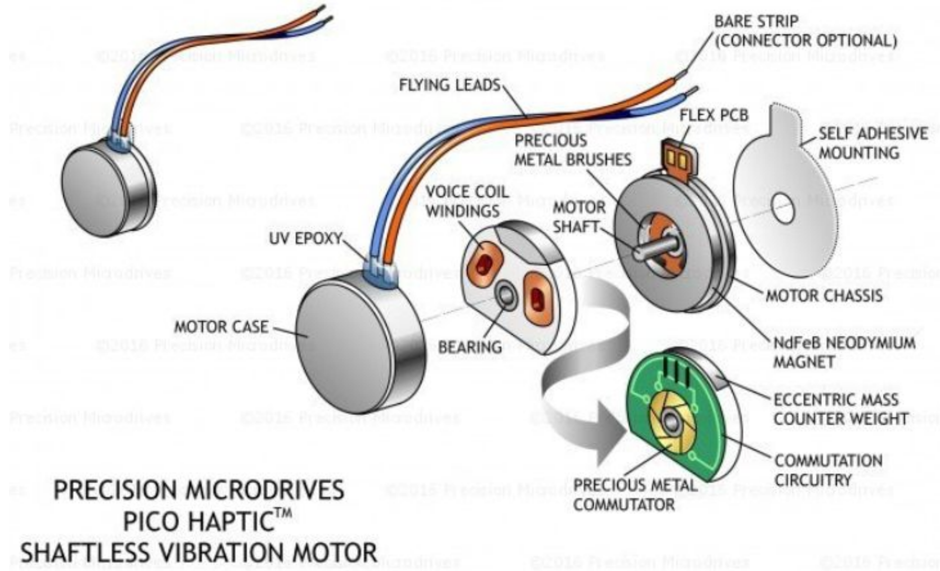

Figure 17: ERM motor mechanical design

An LRA motor generates vibrations with a different mechanism. LRA motors contain a small internal mass attached to a spring. The mass oscillates when driven with AC power. This mechanism can be seen in Figure 18. An LRA motor gives us a more precise control over the frequency the motor is running at. However, they are less common, and therefore more expensive than ERM motors. For our project, the benefit of frequency control justifies the price of the LRA motor.

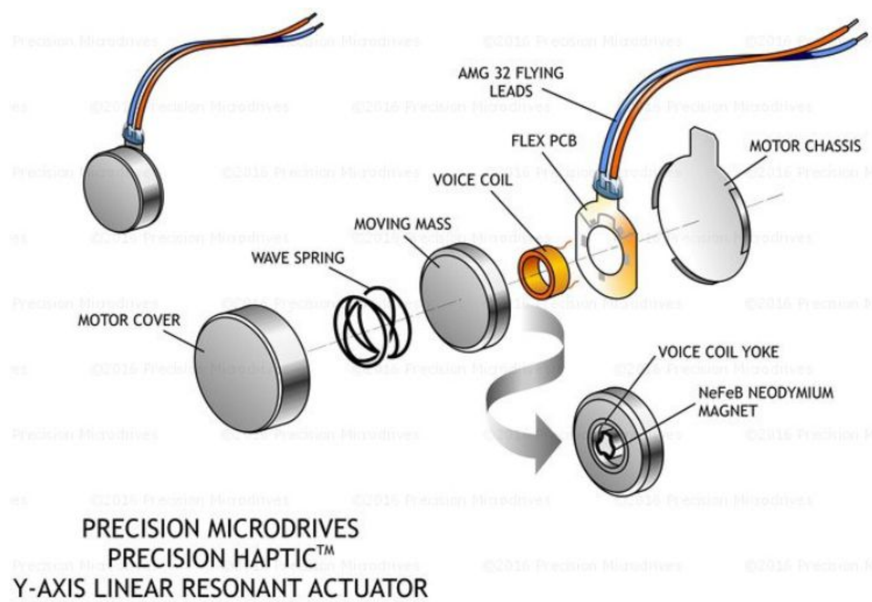

Figure 18: LRA motor mechanical design

To find the resonance frequency of the LRA motor, we conducted a frequency sweep from 180 Hz to 220 Hz. The results can be seen in Figure 19. From the results of the experiment, the resonance frequency of the LRA motor was 200 Hz ± 5 Hz.

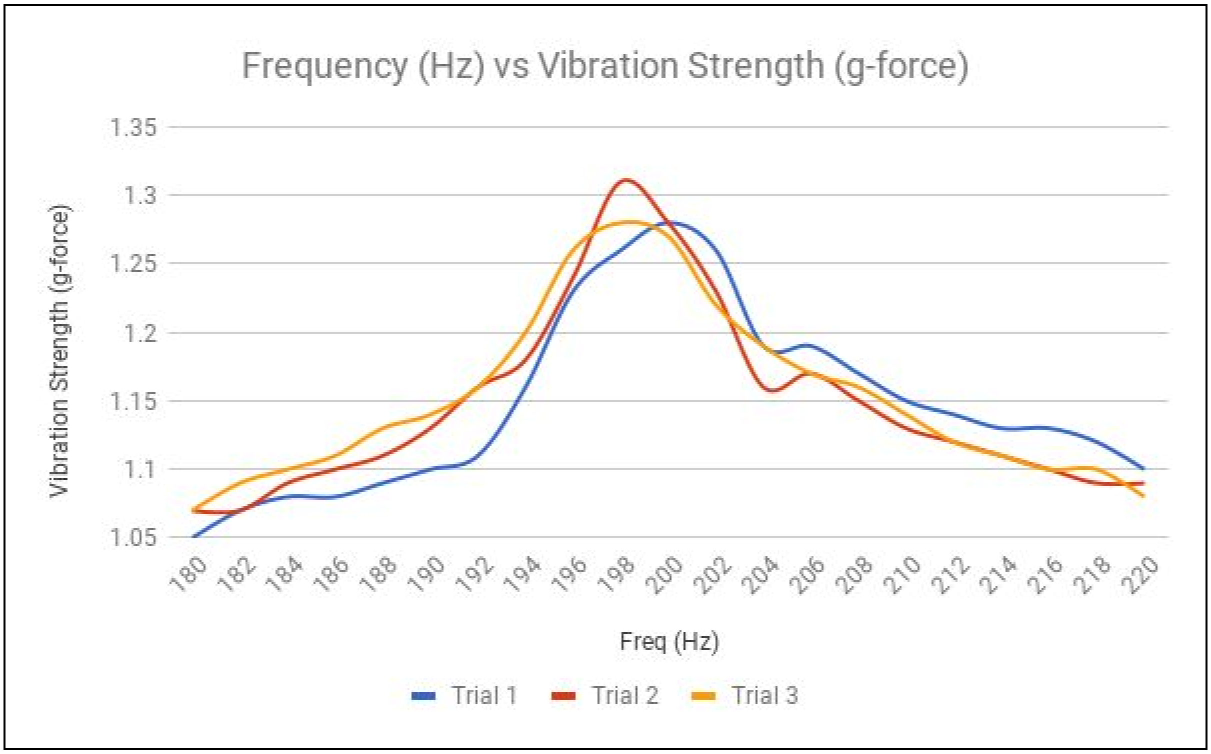

Figure 19: Preliminary test results for LRA motor resonant frequency

Since the resonance frequency of the LRA motor is known, the limiting factor when choosing the accelerometer is the sampling frequency. To determine the appropriate sampling frequency, we use the Nyquist-Shannon sampling theorem. The Nyquist-Shannon sampling theorem is a fundamental bridge between continuous-time signals (analog signals) and discrete-time signals (digital signals). It states that the accelerometer needs to have a sampling rate at least twice as fast as the vibration frequency of the LRA motor. Since the material that the LRA motor is secured to can affect the resonance frequency, we decided to have a sampling frequency of at least 440 Hz, which is twice as fast as the highest frequency (220 Hz) that we observed to produced a noticeable vibration.

The accelerometer we are using is the MMA8452Q. This accelerometer is a micro-machined 3-axis accelerometer with 12 bits of resolution. It supports ± 2g, 4g, or 8g full-scale range at up to 800 Hz and communicates with the microcontroller over an I^2C interface. To test the viability of the MMA8452Q as the vibration signal receiver, we secured the LRA motor to the same surface as the accelerometer. Then we generated a continuous bit sequence represented by the regular expression $(01)^*$ with the LRA motor by modulating to two waves: a sine wave (200 Hz, 5 Vpp) and a square wave (2 Hz, 5 Vpp). Figure 20 shows the signal detected by the accelerometer.

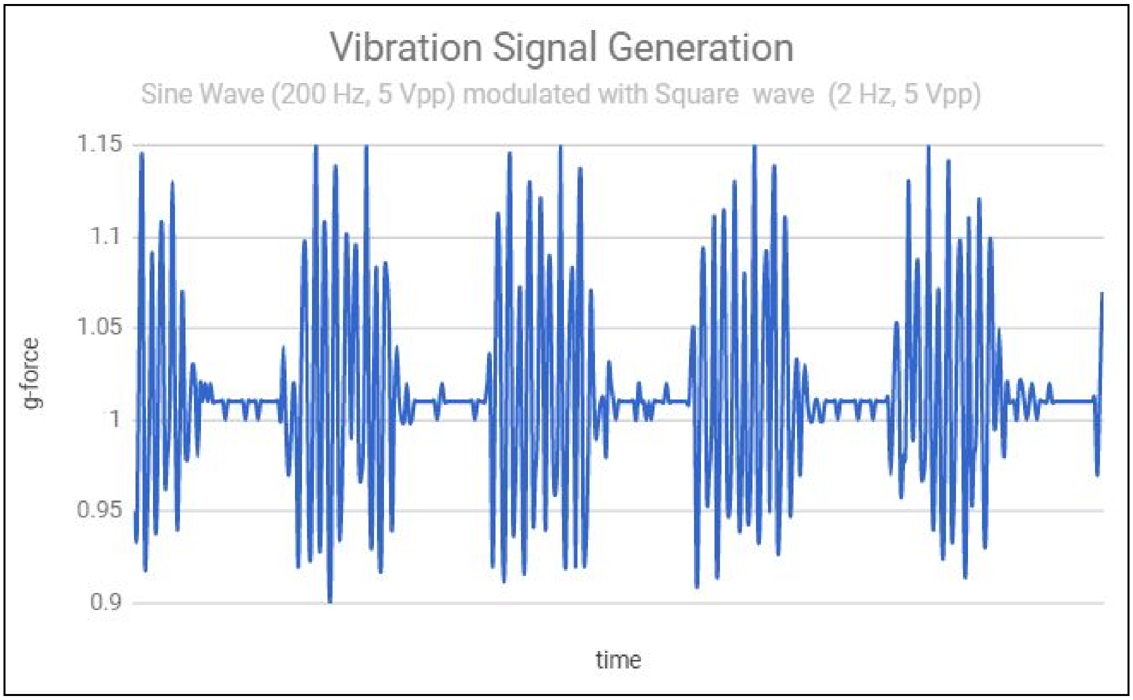

Figure 20: Vibration signal measured by the accelerometer

The signal received by the accelerometer was clean enough to detect a bit sequence and is lossless because we adhered to the Nyquist-Shannon sampling theorem. To detect a bit sequence in the signal received by the accelerometer, we used the following procedure:

1. *Rectify the signal.* With the signal centered on the y-axis at 1 Hz, we made all the negative going measurements (below 1 Hz) positive going (above 1 Hz).

2. *Determine bit values in signal.* We determined the number of discrete signal samples per bit. Then found the average value for each bit. If the average value was greater than a preset threshold, the bit has a value of one. If the average value was less than a preset threshold, the bit has a value of zero.

We were able to use the accelerometer to detect and verify the bit sequence generated by the LRA motor, justifying our choice to use the MMA8452Q 3-DOF accelerometer and DMJBRN0832AF LRA motor.

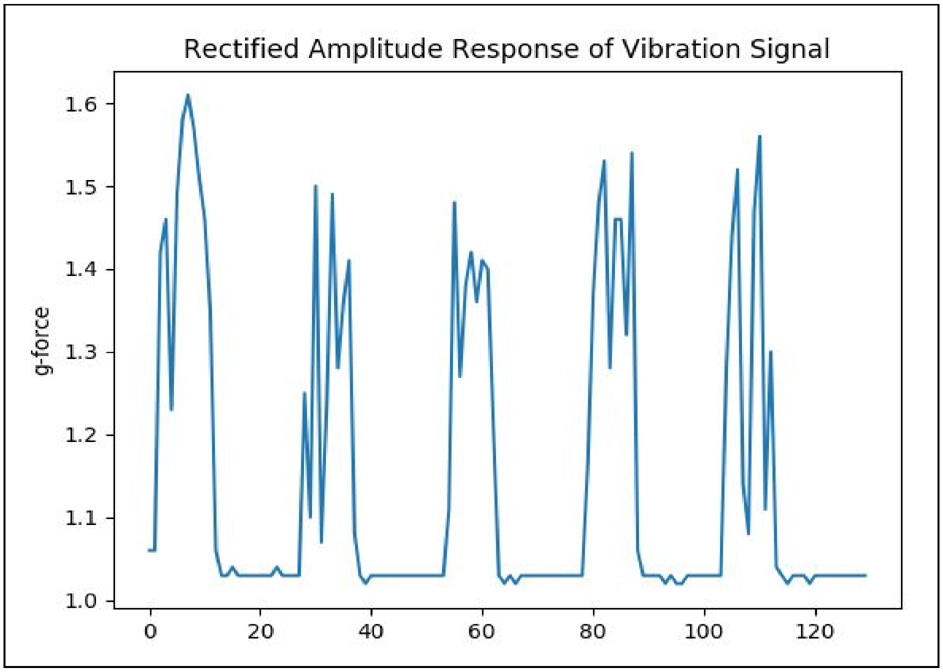

Figure 21: Rectified signal

Figure 21 shows the signal after it has been rectified. Since this signal was generated from the motor being directly pressed against the breadboard the accelerometer is pinned to, the signal-to-noise ratio (SNR) is good and there is a clear differentiation when the motor is vibrating, and when the motor is not vibrating. However, when the vibration signal is conducted through the the finger to the breadboard that the accelerometer is pinned to, the SNR is reduced by an average of 18.5%. Figure 22 below shows the rectified signal conducted through the finger.

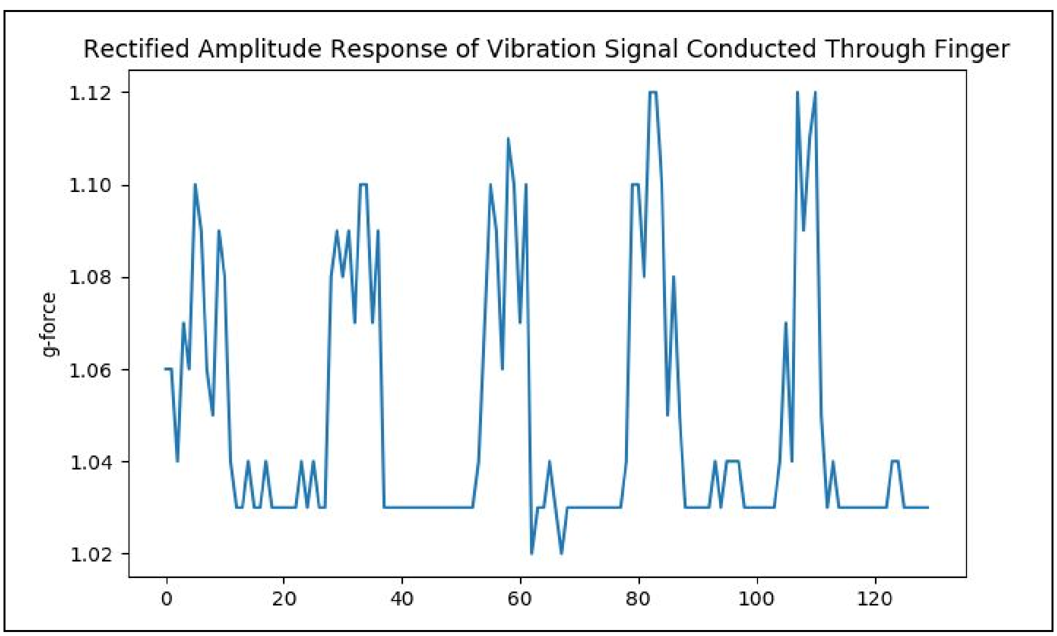

Figure 22: Rectified signal conducted through finger

2.5 Schematics

For those who may have trouble reading them, larger versions of these schematics are located in Appendix A.

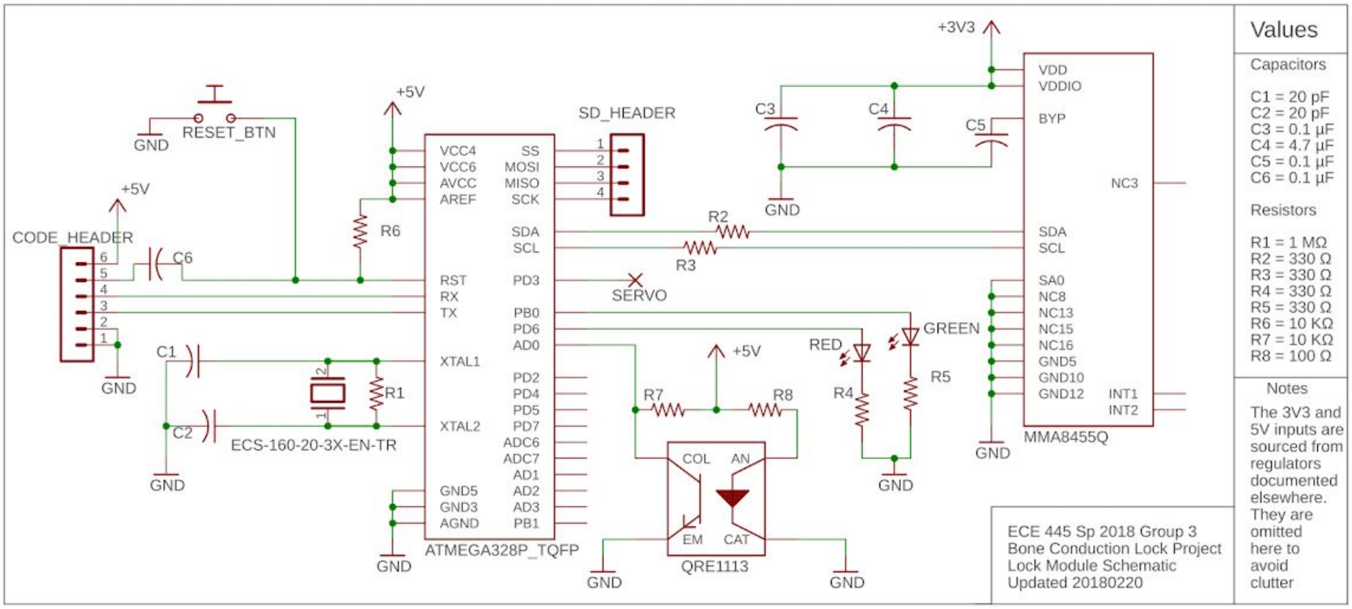

Figure 23: Lock module circuit schematic

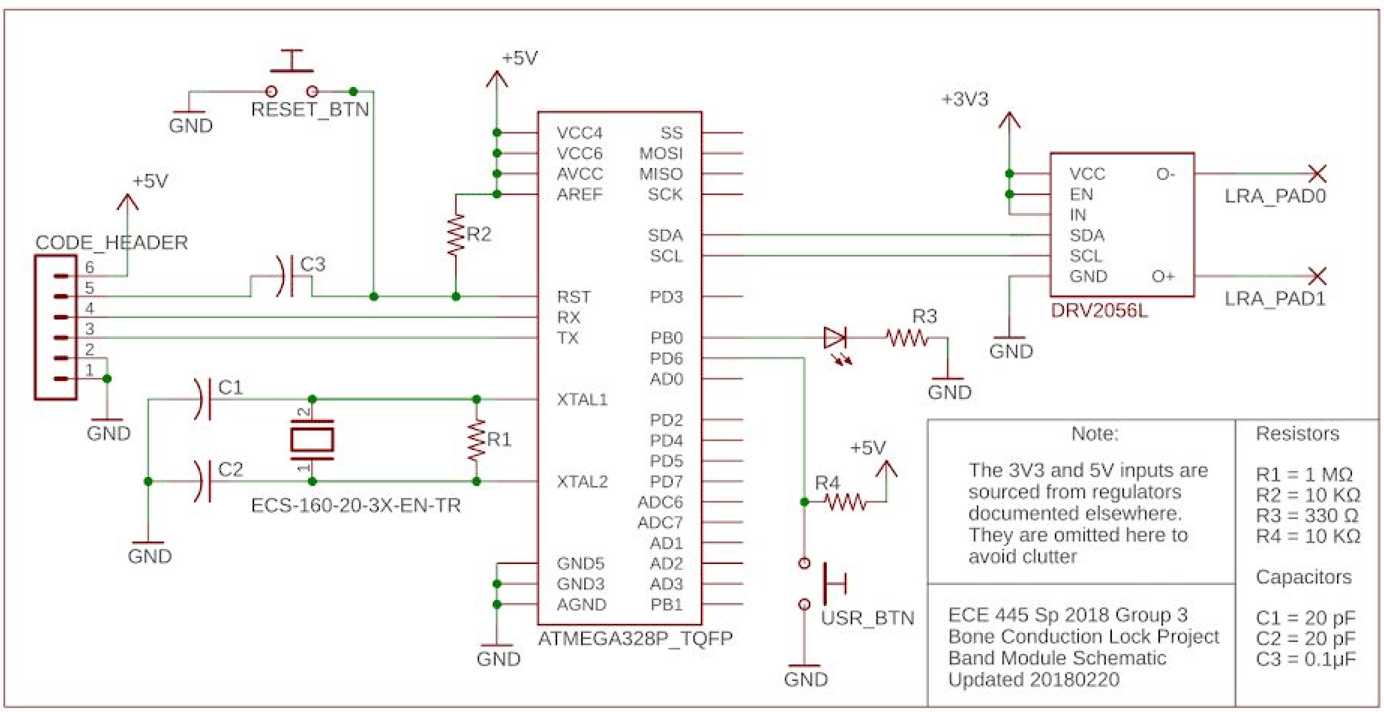

Figure 24: Band module circuit schematic

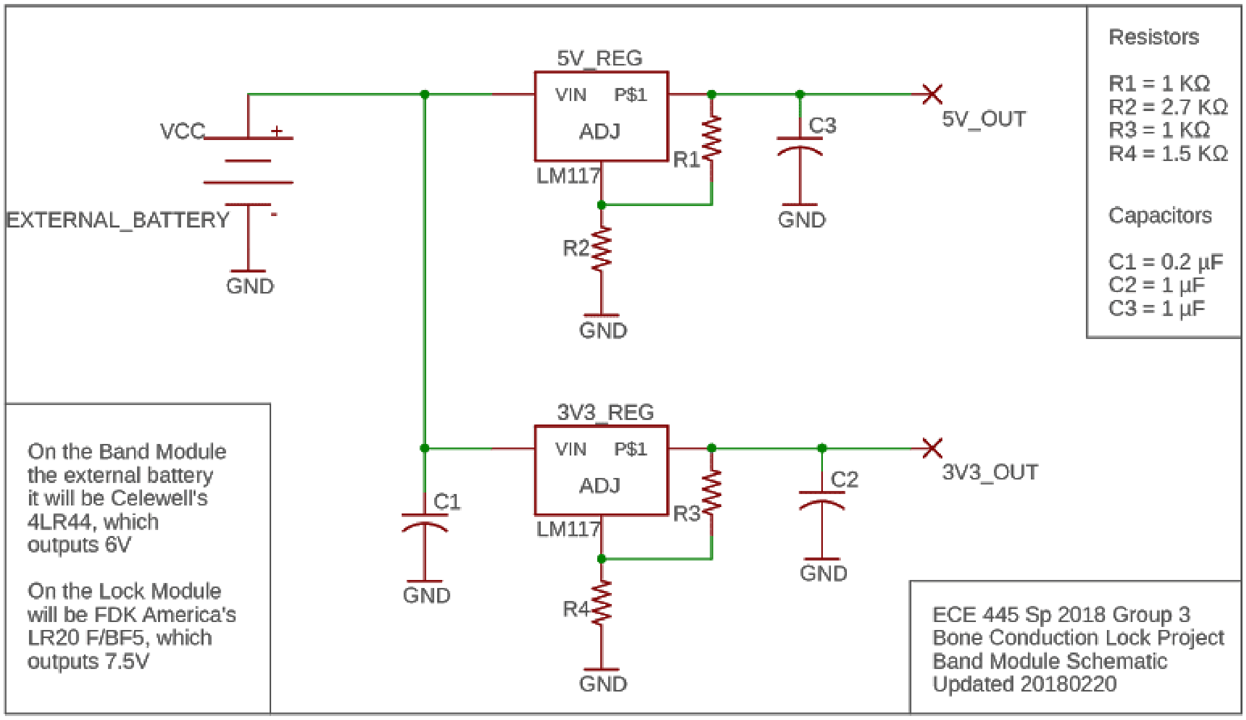

Figure 25: Power supply circuit schematic

3 Cost Analysis

3.1 Labor

For hourly labor costs, we decided that even though the group consists of two computer engineers and one electrical engineer, we're all getting the same hypothetical salary for our time. This will avoid breeding hypothetical resentment. In 2016 the average UIUC CompE graduate made $81,748 a year, and the average EE graduate made $68,392[8]. We weighted each of those salaries proportionally by number of group members, making the average yearly cost of one of our group member's labor $77,296. Assuming a 52 week year and 40 hour work week, that comes out to $37.16/hr for a group member's labor. Using the rule of thumb for college studying that each course warrants two hours of out-of-class studying for every hour of in-class time, and assuming we spend the extra four hours a week freed up by a lack of lecture on more work for this class, that comes out to 12 hours per person per week on this class. The class is sixteen weeks long. At 36 person-hours of work per week for sixteen weeks at $37.16/hr, that comes to a total labor cost of $21,405.05. This is by far the majority of our cost.

3.2 Parts

Description	Part Number	Manufacturer	Quantity	Total Cost
Microprocessor	ATMega2560-16AU	Microchip	1	$12.56

Accelerometer	MMA8452Q	NXP	1	$1.89
IR Sensor	QRE1113	ON Semiconductor	1	$1.01
Battery Pack	LR20 F/BF5	FDK America	1	$11.53
Regulator	LM117	Texas Instruments	2	$2.28
Servo Motor	SG90 9g Micro Servo	Longruner	1	$1.99
SD Card	8 GB	SanDisk	1	$7.95
SD Card Reader	Slot Socket Reader	SunFounder	1	$5.99
Crystal Oscillator	ECS-160-20-3X-EN	ECS	1	$0.46
RTC Module	DS1307	Maxim Integrated	1	$3.27
Status LEDs	HLMP-1301	Broadcom Limited	3	$1.23
Reset Button	KS-01Q-01	E-Switch	1	$0.53
4.7 µF Capacitor	10SVP4R7M	Panasonic	1	$1.08
100 µF Capacitor	EEF-CX0J101R	Panasonic	2	$2.90
10 uF Capacitor	EEF-CD0J100R	Panasonic	1	$1.33
0.1 µF Capacitor	865230640001	Wurth Electronics	3	$0.51
20 pF Capacitor	06031A200JAT2A	AVX Corporation	2	$0.50
1 MΩ Resistor	ERA-6AEB105V	Panasonic	1	$0.36
10 kΩ Resistor	ERA-2AED103X	Panasonic	2	$0.44
2.7 kΩ Resistor	ERA-2AED272X	Panasonic	1	$0.22
2 kΩ Resistor	ERA-2AED202X	Panasonic	1	$0.22
1.5 kΩ Resistor	ERA-2AED152X	Panasonic	1	$0.22
1 kΩ Resistor	ERA-2AED102X	Panasonic	3	$0.66
330 Ω Resistor	ERA-2AED331X	Panasonic	4	$0.88
100 Ω Resistor	ERA-2AED101X	Panasonic	1	$0.22

Table 7: Lock PCB Parts Cost

Description	Part Number	Manufacturer	Quantity	Total Cost
Microprocessor	ATMega328P_TQFP	Microchip	1	$2.20
Motor Driver	DRV2605L	Texas Instruments	1	$3.60
LRA Motor	DMJBRN0832AF	Fyber Labs	1	$16.80
Regulator	LM117	Texas Instruments	2	$2.28
Battery	4LR44	Celewell	1	$0.90
Battery Holder	108	Keystone	1	$1.59
Crystal Oscillator	ECS-160-20-3X-EN-TR	ECS	1	$0.46
Status LED	HLMP-1301	Broadcom Limited	1	$0.41
Push Button	ESE-20D321	Panasonic	1	$1.24
Reset Button	KS-01Q-01	E-Switch	1	$0.53
100 µF Capacitor	EEF-CX0J101R	Panasonic	2	$2.90
10 uF Capacitor	EEF-CD0J100R	Panasonic	1	$1.33
0.1 µF Capacitor	865230640001	Wurth Electronics	3	$0.85
20 pF Capacitor	06031A200JAT2A	AVX Corporation	2	$0.50
1 MΩ Resistor	ERA-6AEB105V	Panasonic	1	$0.36
10 kΩ Resistor	ERA-2AED103X	Panasonic	2	$0.44
2.7 kΩ Resistor	ERA-2AED272X	Panasonic	1	$0.22
1.5 kΩ Resistor	ERA-2AED152X	Panasonic	1	$0.22
1 kΩ Resistor	ERA-2AED102X	Panasonic	2	$0.44
330 Ω Resistor	ERA-2AED331X	Panasonic	4	$0.22

Table 8: Band PCB Parts Cost

Description	Cost

Lock PCB Parts	$60.15
Band PCB Parts	$37.49
PCB Orders	$25
Physical Components	$5
Labor	$21,405.05
Total Parts Cost:	$127.64
Total:	$21,532.69

Table 9: Total Estimated Cost

4 Schedule

Week	Alex	Brandon	Ramon
2/12/18	Breadboard prototype of lock and band modules	Part verification	Parts list, power consumption, regulators
2/19/18	LRA motor tolerance analysis for design document, proofread design document	Accelerometer tolerance analysis for design document, proofread design document	Cost analysis for design document, proofread design document
2/26/18	Code for band operation (vibration signal generation)	Lock PCB Layout Order parts for lock	Band PCB Layout Order parts for band
3/5/18	Code for band operation (vibration signal generation)	Cross-check designs with each other. Swap constructive criticism and iterate on designs. Place order for band and lock PCBs.	
3/12/18	Code for lock operation (key detection/verification)	Test/debug lock PCB Group PCB order #1	Test/debug band PCB Group PCB order #1
3/19/18	Code for lock operation (key detection/verification)	Test/debug lock PCB	Test/debug band PCB
3/26/18	Modify code to lower power consumption	Test/debug lock PCB Group PCB order #2	Test/debug band PCB Group PCB order #2
4/2/18	Make sure code is running properly on PCBs and physical design	Implement physical design of lock module	Implement physical design of band module

4/9/18	Investigation of transmission of keys beyond simple bit sequences	Finish physical design of lock module	Finish physical design of band module
4/16/18	Ensure software side of demo is working	Ensure lock module is working	Ensure band module is working
4/23/18	Demo software	Demo lock module	Demo band module
4/30/18	Include all software updates in Final Report since Design Document	Include all hardware updates in Final Report since Design Document	Include the updated cost analysis in Final Report.

Table 10: Project Schedule

5 Ethics and Safety

Exposure to vibrations is known by the Occupational Hazards and Safety Administration [9] and the Canadian Centre of Occupational Health and Safety (CCOHS) to be a workplace hazard. According to the CCOHS, exposure of the hands and arms to vibrations can result in Hand-Arm Vibration Syndrome, a disorder affecting blood flow to the fingers and resulting in a loss of touch sensation [10] . A 2002 article in The Journal of Low Frequency Noise, Vibration, and Active Control titled *EU Directive on Physical Agents - Vibration* provides guidelines on the amount of safe hand-arm vibration exposure [11]. It is measured by the RMS magnitude of acceleration normalized by exposure time: a stronger vibration means a shorter exposure time before there is a risk of damage. The shortest time listed in the article was a half hour. Over this time period, the maximum acceleration deemed to be safe was 20 m/s^2 . Preliminary tests of haptic motors of similar size to those we plan to use showed a peak strength below that: 18.04 m/s^2. Additionally, since one goal of ours is to unlock the door in a timely manner, the time of vibration exposure will be on the order of seconds, not minutes or hours.

The operating frequency of the motors to be used in this project also make it unlikely that the vibrating band will cause damage to the user. In Shrawan Kumar's *Biomechanics in Ergonomics: Second Edition* [12], the author proposes damage may be more likely to occur at the resonant frequencies of certain internal organs and structures within the body. Their frequencies are listed in Table 11. Note that some organs and structures have ranges of resonant frequencies. Others have multiple discrete resonant frequencies. The former is notated by a hyphen, the latter with the word "and".

Internal Organ / Structure	**Resonant Frequency (Hz)**
Spine	5

Pelvis	5 and 9
Abdomen-thorax	3 and 5-8
Lower Intestine (while seated)	8
Heart	7
Head-Neck-Shoulder[2]	20-30
Eyeballs	60-90
Lower Jaw-Skull	100-200

Table 11: Resonant frequencies of various biological structures

These resonant frequencies are outside the range of ~200-250 Hz which our motors will be operating at. The lower jaw and skull, the biological structure whose resonant frequency is closest to our motor's operating frequency, is located at great distance from the source of the vibrations, making damage to those body parts an unlikely scenario.

Testing wearable technology comes with the risk of having dangerously hot or burning electrical components strapped to human testers in the event of a catastrophic failure. If a CO_2 fire extinguisher—the kind typically used on electrical fires—is used to put out a piece of technology being worn by a tester, they are liable to receive cold burns from the extinguisher as well as heat burns from the fire. To counteract this, as many tests as possible will be done without wearing the band while testing. Additionally, we will design the band and ring such that they can be easily removed in the event of an emergency. Using velcro as the band fastener was one proposed way to ensure this.

Ethically, the major issue which concerns this project is user data safety. If our project progresses rapidly enough to get to the biometric identification step, keeping users' biometric data secure becomes a concern. This issue can be handled by not storing the raw data[3]. The logs which will be written to an SD card inside of the lock do not store information about the signal received, only the time of attempt, bit sequence received, and indication of success or failure. The calibration data used to judge whether a particular user is authorized for entry will be stored in the memory of the microcontroller. Considering its position inside the physical lock itself, and the relative difficulty of offloading this data in comparison to say, taking an SD card, it is unlikely that this data will be compromised. Other ethical issues—namely those listed in the IEEE Code of Ethics[13]—are not made especially relevant by the nature of the work to be done. There are no

[2] The odd wording is courtesy of the original author. Whether this refers to all three body parts as separate or the system as a whole is unclear. Regardless, the implication that our motors operate well outside this frequency range is clear.

[3] At least not in the final product. In testing, gathering large amounts of raw signals to process later will be helpful when investigating biometrics, and the SD card provides an easy way to do that.

exceptional safety risks, conflicts of interest, potential for environmental damage, etc. outside of the risks bound to occur on any electrical engineering project

6 References

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Appendix A: Full-page Schematics

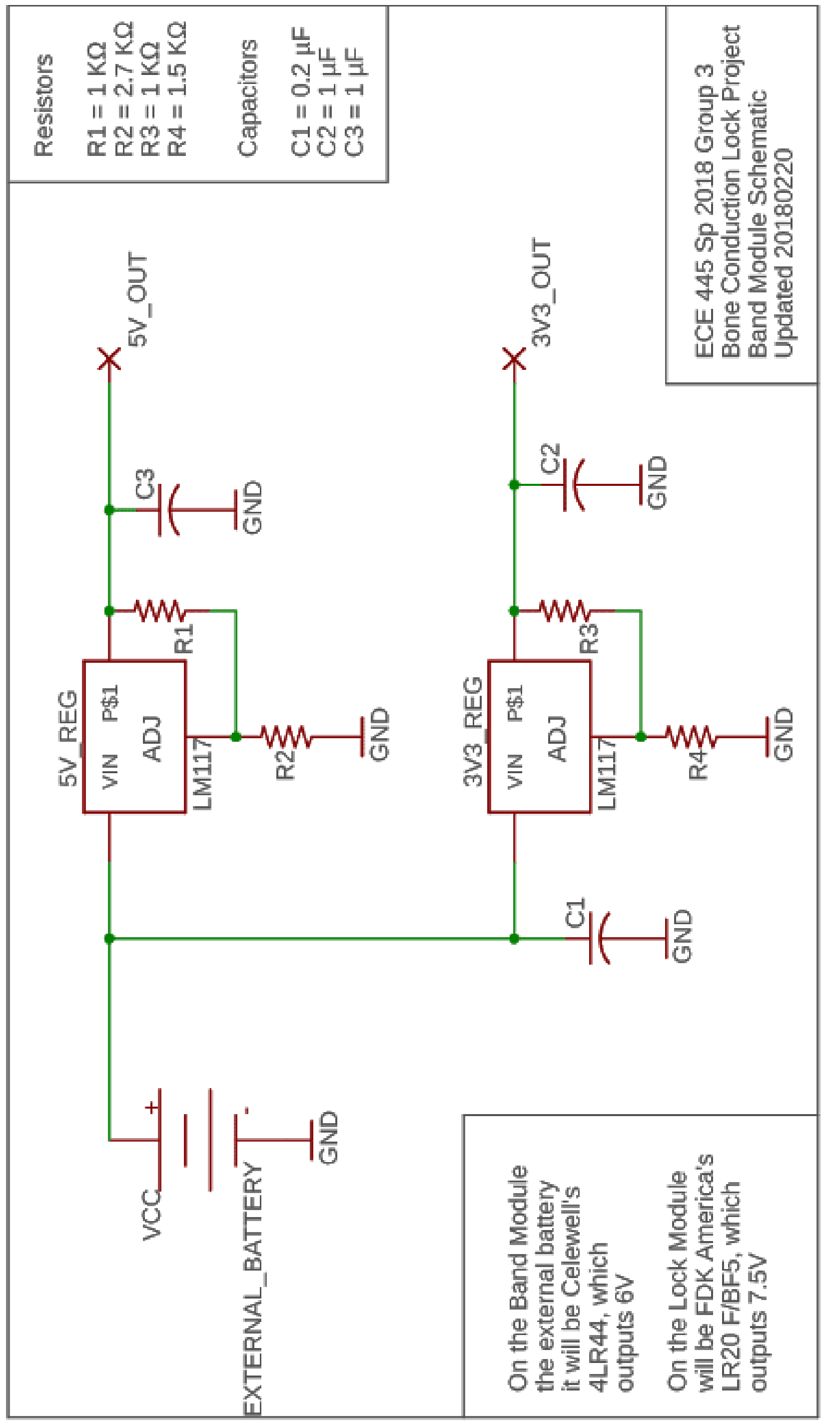

Figure 26: Voltage regulator schematic, large

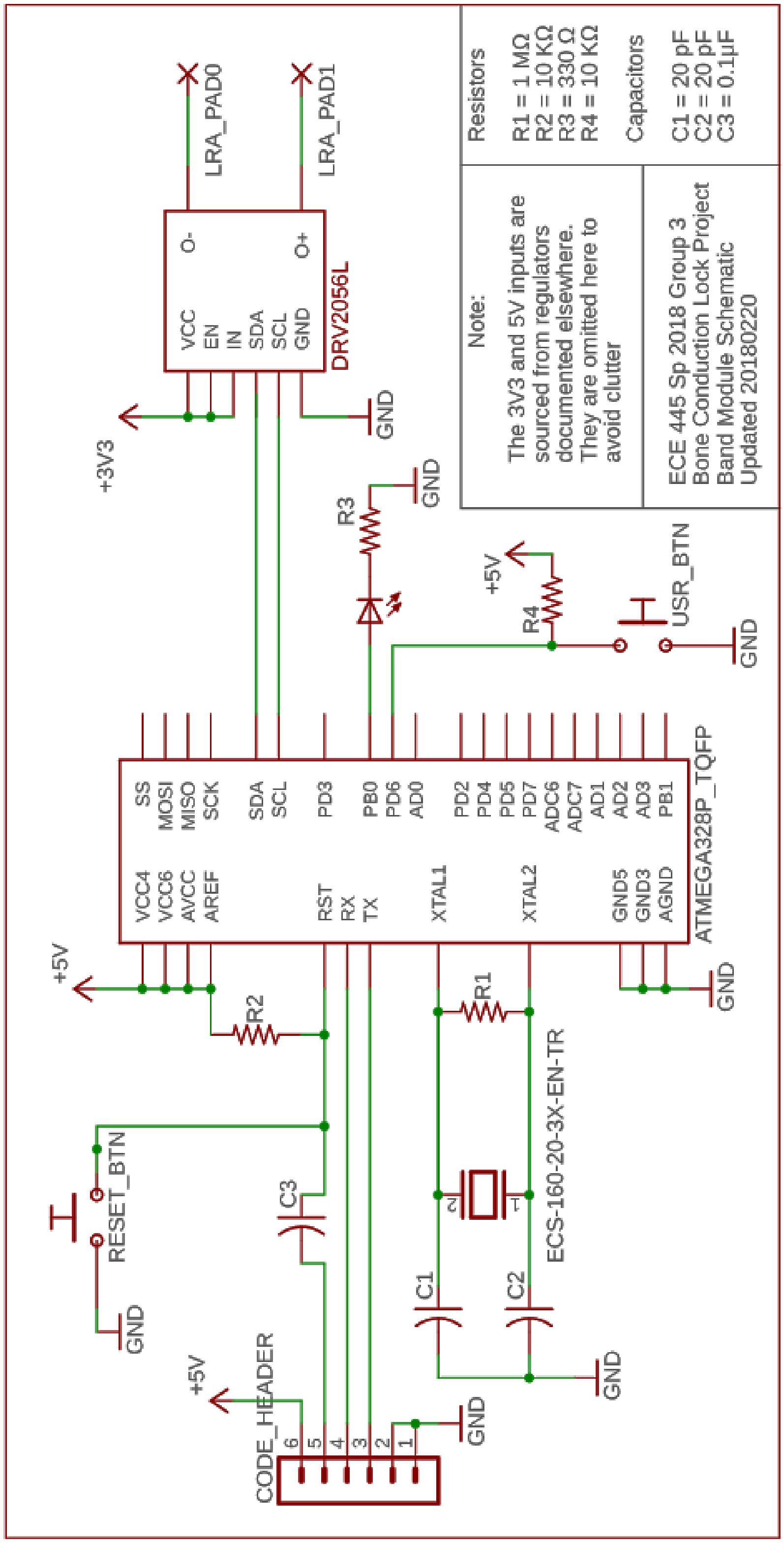

Figure 27: Band module schematic, large

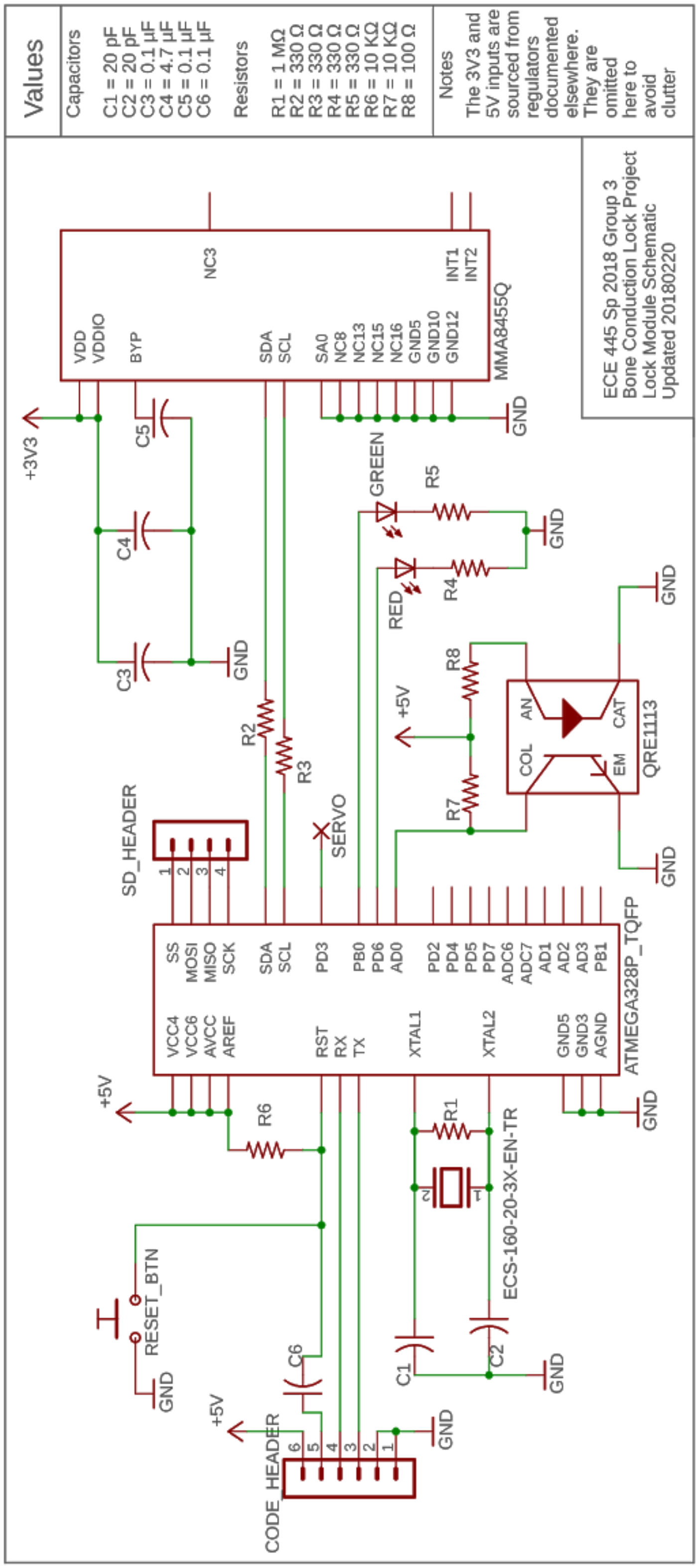

Figure 28: Lock module schematic, large