# Bone Conduction Lock

**By**

**Alexander Lee**

**Brandon David Powers**

**Ramón Zarate**

Final Report for ECE 445, Senior Design, Spring 2018

TA: Jacob Bryan

May 2nd, 2018

Project No. 3

# Abstract

The Bone Conduction Lock System (BCLS) is a door lock which opens in response to vibrations conducted through the user's finger. A prototype of this system was successfully designed, built, and tested. The user wears a wristband which houses the battery and other circuit components. Out of this wrist-mounted module are wires which connect to a ring worn on the user's finger where a motor is housed. The vibrations are generated from this motor, transmitted through the user's finger, and received by a separate module which controls the lock state of the door. Tests showed human fingers proved a capable channel for conducting a vibration signal, and that the noise introduced into this signal by the user's finger shows enough potential to warrant further investigation as a platform for identifying users based on the anatomy of their fingers.

# Table of Contents

# 1 Introduction

The ability to quickly enter a locked door without the need for a physical key is a convenience the car industry has recognized and worked to implement with keyless entry for vehicle doors. Recently, door locks with keyless entry have been gaining traction with more digital smart locks becoming available on the market. However, the different types of digital smart locks each have their respective vulnerabilities. Keypads are simple to crack with the aid of fingerprinting dust or an infrared camera [1]. Fingerprinting locks can be fooled by pictures of secretly gathered prints [2]. Iris scanners are prohibitively expensive for the average household or office. 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 [3]. Card-swipe or proximity card locks still require users to use a physical key—which can be stolen or lost—to unlock the lock. Smart locks that communicate with the user's phone are only as secure as the communication protocol they use.

The Bone Conduction Lock System (BCLS) provides a new way forward. It is an efficient and secure lock system that is unlocked by vibrations conducted through the user's bones. The BCLS also provides a hardware platform to conduct research on using human bone for biometric authentication. It does this by analyzing channel interference created by the user's finger on the signal's journey from band to lock. Previous research supports the claim that there is enough difference in skeletal structure to potentially warrant unique identification via this interference. Namely a Google Glass based project called Skullconduct, which used vibrations conducted through the skull to correctly identify users with a 97% success rate [4].

To recapitulate, the objectives of the BCLS are to:

- Demonstrate that human bone conduction is a viable communication channel.
- Provide an efficient and secure way to unlock a door using bone conduction.

## 2 Design

Since design review, additional features have been added to the BCLS. Figure 1 shows the system's modulated block diagram. The BCLS consists of two modules: the band (worn on the user's wrist like a watch) and the lock. The modules are powered by different batteries but have identical power subsystems otherwise. The band's motor subsystem is used to generate vibrations, while a servo motor is used in the lock module to act as a physical locking mechanism. Both modules have control subsystems that take in user input, handle data, and provide visual feedback.

To operate the BCLS, the user presses their finger to a designated location on the lock. When the lock detects the user's finger, it wirelessly sends a prompt to the band. The band receives the prompt and generates a sequence of vibrations corresponding to the prompt. The vibrations are conducted through the user's finger to the lock. The lock detects the vibration signal and verifies whether it is correct or not. If the signal is correct, the green LED blinks and the lock unlocks for a predetermined amount of time, then locks itself once more. If the signal is incorrect, the red LED blinks and the lock remains locked. If an incomplete signal is received at the lock, it is treated as an incorrect signal; the red LED blinks and the lock remains locked. The lock activity is stored in a log as a timestamped description of the event. After the lock activity is recorded, both the green and red LEDs blink indicating the lock is ready for the next attempt.

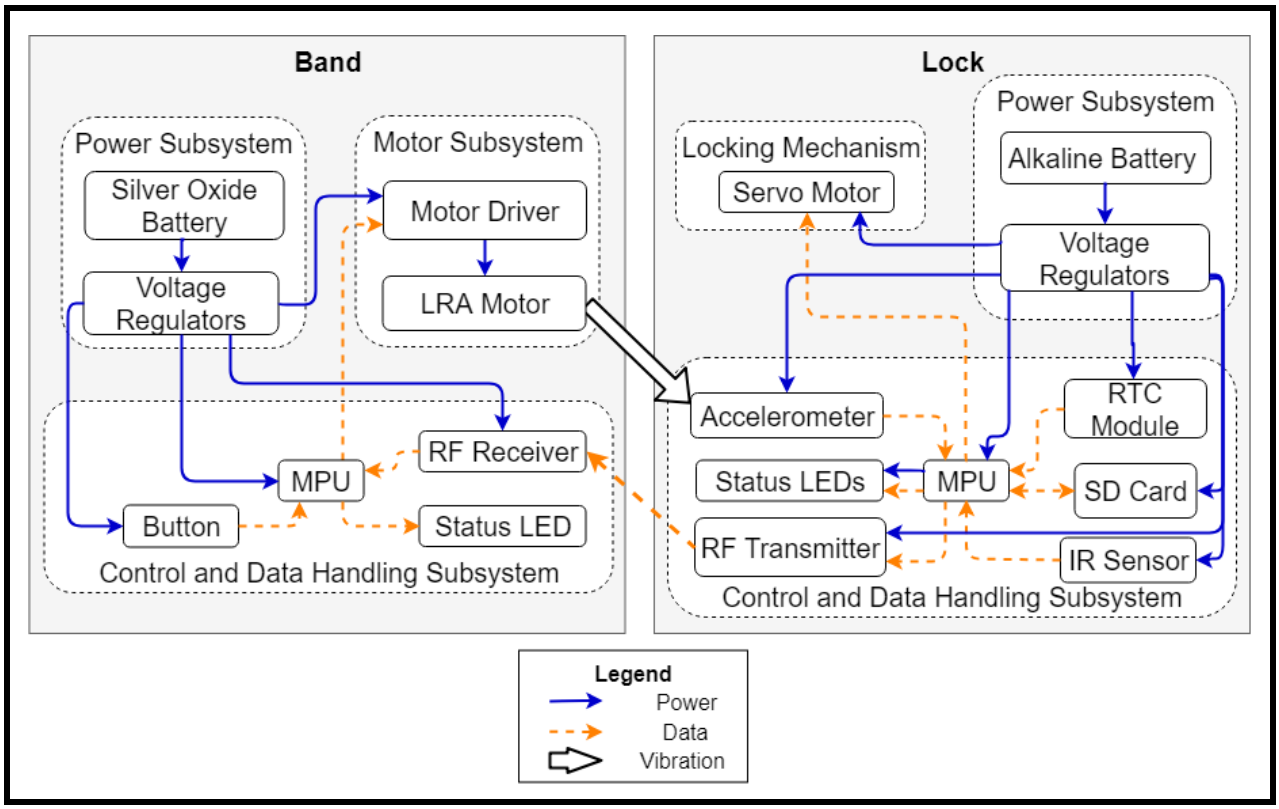


*Figure 1: BCLS block diagram*

## 2.1 Primary Design Considerations

When developing the BCLS, there were three core design considerations: using human bone as the communication channel for the system, the stability of using the system, and the efficiency of the system. The lock module is responsible for detecting the user's finger, sending a prompt to the band, detecting/verifying incoming vibration signals, displaying the state of the lock, recording all lock activity, and determining whether to unlock the lock or not. The band module is responsible for receiving the prompt from the lock and driving a motor to generate a sequence of vibrations corresponding to the prompt. Used together, the lock and band must satisfy these three core design considerations.

### 2.1.1 Human Bone as a Viable Communication Channel

One of the design parameters for the BCLS was that the only communication channel from band to lock must be vibrations conducted through the user's hand. To ensure this design consideration was satisfied, the motor used to generate the vibration signal and the sensor used to receive the vibration signal had to be carefully chosen and integrated.

There are two types of haptic vibration motors: eccentric rotating mass (ERM) and linear resonant actuator (LRA) vibration motors. ERM motors have a small off-centered mass mounted on a DC motor. This design can be seen in Figure 2. When the motor rotates, the motion of the unbalanced weight causes vibrations. An increase in drive power results in an increase in the strength of the vibration. However, the vibration generated by ERM motors is complex due to overlapping resonance harmonics. The complex vibrations cause motion in all directions that is difficult to model and control.

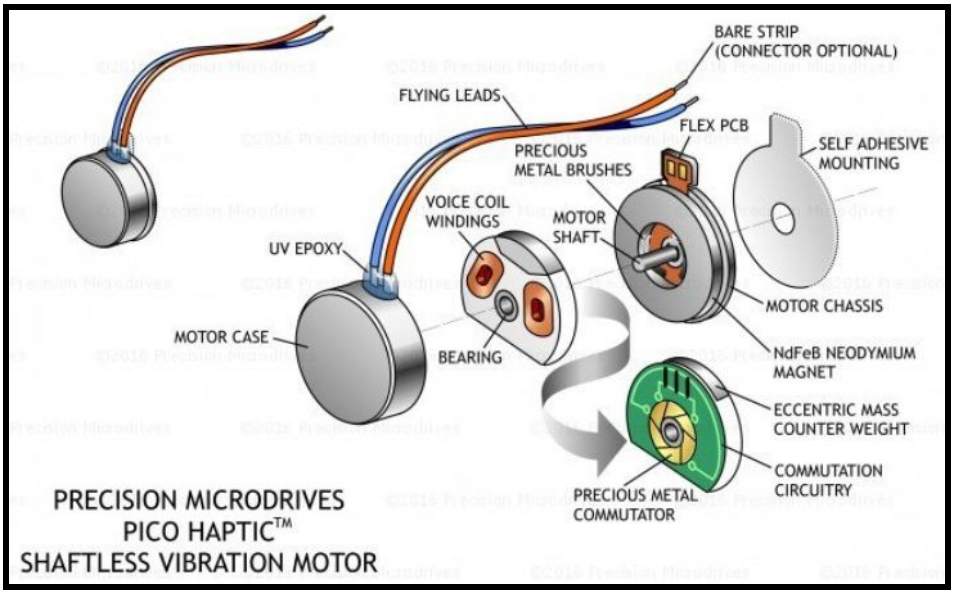


*Figure 2: ERM motor mechanical design*

An LRA motor generates vibrations with a different mechanical mechanism which can be seen in Figure 3. LRA motors are analogous to the classical physical “mass on a spring” model. They contain a small internal mass attached to a coil. When alternating current is applied to the coil, it generates a magnetic field causing the internal mass to oscillate. Since the internal mass is oscillating on the coil, the resulting vibration has linear motion along one axis. LRA motors also allow for more precise control over the frequency the motor is being driven at.

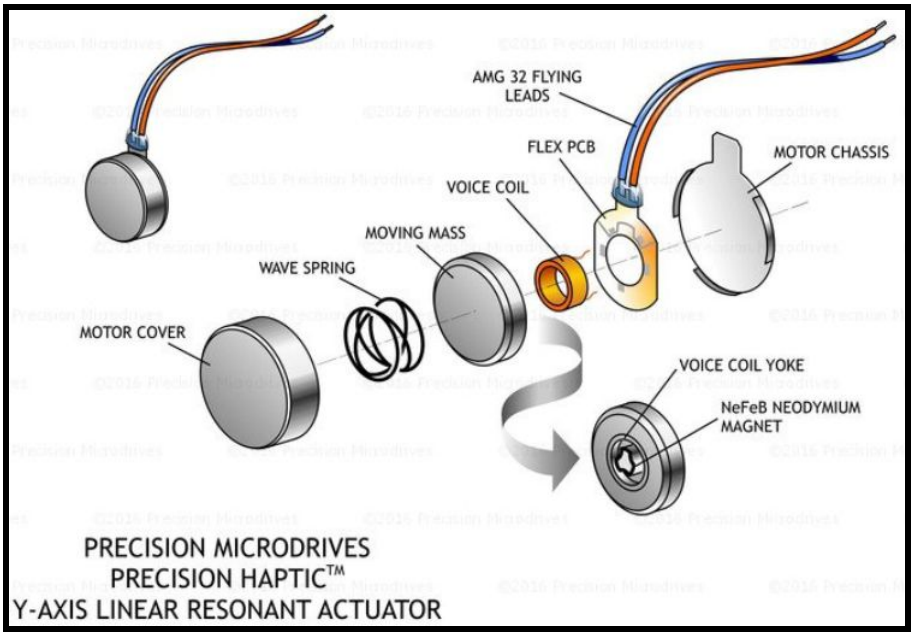


*Figure 3: LRA motor mechanical design*

ERM motors are the haptic motors currently found in smartphones and smartwatches because they are cheap and easily driven with DC power. Unfortunately, the complex vibrational motion is undesirable in the BCLS use case. LRA motors are less common and more expensive. They also need AC power to drive the motor, which requires the use of a motor driver. However, the benefit of precise frequency control and simple single-axis vibrational motion justifies the choice to use the LRA motor. The BCLS uses a DMJBRN0832AF LRA motor to generate the vibration signal. According to the manufacturer datasheet, the resonance frequency of the LRA motor is 198 ± 5 Hz.

To sample the vibration signal generated by the LRA motor without loss, the sensor reading the vibrations must adhere to the Nyquist Sampling Theorem and sample at two times the frequency used to drive the motor. The BCLS uses the MMA8452 3-axis accelerometer to receive the vibration signal generated by the LRA motor. The MMA8452 is a MEMs accelerometer with 12-bit resolution initialized to a sampling rate of 800Hz and a full-scale range of ±2 g. The readings from the accelerometer are outputted as the magnitude of acceleration in units of g-force. The signal is then rectified to see the amplitude of the vibration more clearly. Characterization of the accelerometer gives a noise-floor of 1.02 g and a rectified noise-floor of 1.05 g.

To characterize the motor, the LRA motor was driven with an increasing frequency sweep from 180 Hz to 220 Hz and the output of the accelerometer was read over three trials. A graph of these results is visible in Figure 4. Results of this LRA motor characterization support the 198 ± 5 Hz resonance frequency given in the manufacturer datasheet.

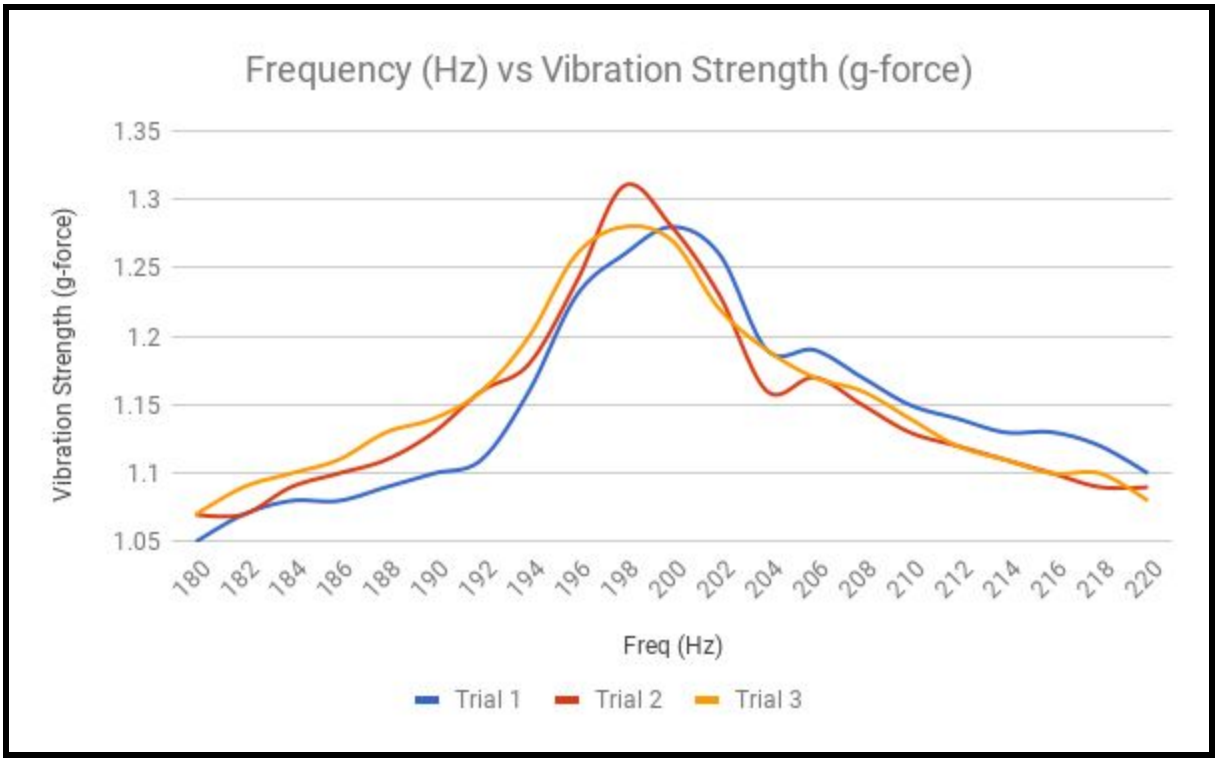


*Figure 4: results of LRA motor characterization*

### 2.1.2 Efficiency of the BCLS

The BLCS must be at least as easy to use as a traditional lock and key. With a traditional lock and key, the user is required to locate the key, insert the key in the lock, turn the key to unlock the lock, place the key somewhere it can be used again later, and lock the lock if desired. To increase the ease of use, the BCLS maximizes the efficiency of the user's movements to unlock the lock. The BCLS emulates the experience of keyless entry systems found in more recent car models. Unlocking the BCLS only requires one movement. The user presses their finger to the designated area on the lock for three seconds. If the vibration signal conducted through the user's finger is verified and determined to be correct, the lock unlocks. The efficiency of the BCLS can be further maximized by decreasing the amount of time the user needs to press their finger to the lock. This is discussed in the following section detailing the stability of the BCLS.

### 2.1.3 Stability of the BCLS

The BCLS must be stable, operating with no more than 5% of correct vibration signals resulting in false negatives. To test the stability of the BCLS, a continuous bit sequence of (10)* was generated by the LRA motor[1]. When the bit is equal to one, the LRA motor vibrates, when the bit is equal to zero, the LRA motor remains idle. The stability of the BCLS is measured by the system's ability to correctly extract the bit sequence from the received vibration signal.

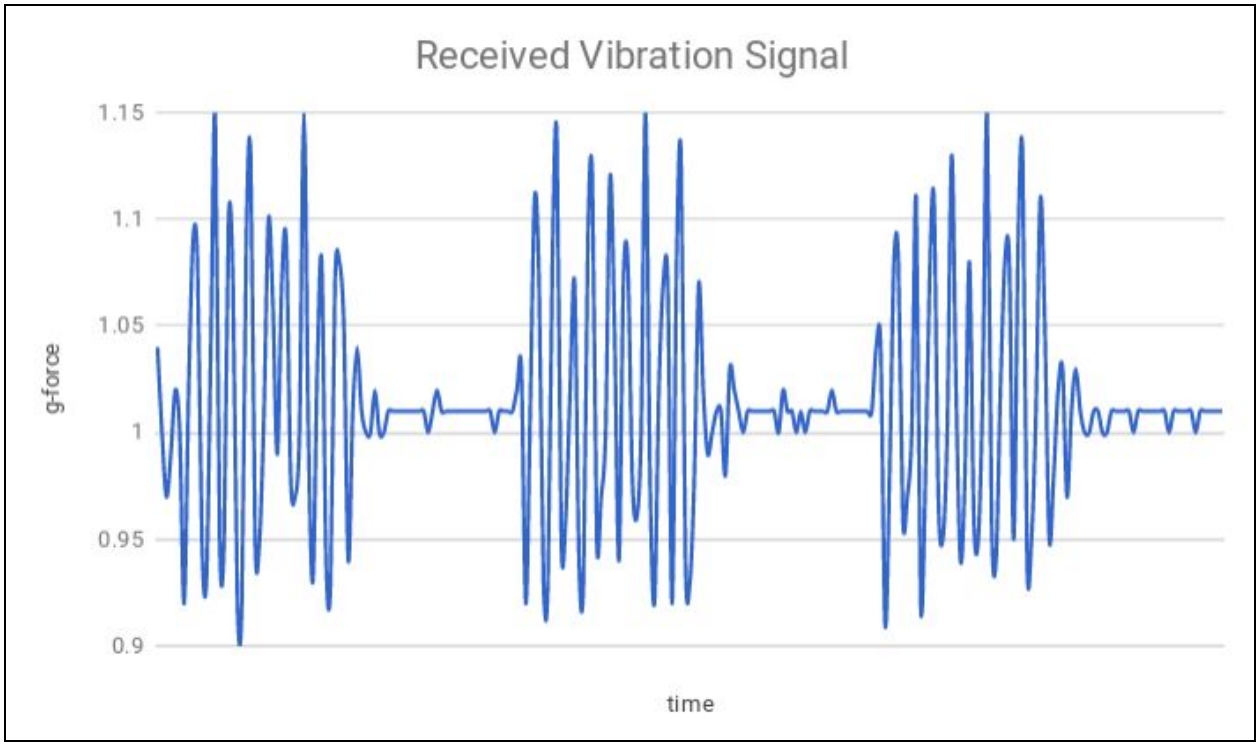


*Figure 5: received vibration signal*

To extract the bit sequence from the received vibration signal—which can be seen in Figure 5—the lock first detects and receives the vibration signal, then uses a bit extraction algorithm to verify the bit sequence. After the vibration signal is received, the start of the first bit in the bit sequence is identified. From the start of the signal corresponding to the beginning of the bit sequence, the algorithm iterates through the signal by the number of samples per bit. For each bit, if the average value is above a predetermined threshold, the bit is classified as an one. If the average value is below the threshold, the bit is classified as a zero.

When extracting the bits from the vibration signal, there are three things to consider: the sampling rate, downsampling, and the ramp up/down of the LRA motor. As mentioned previously, the accelerometer is initialized with a 800 Hz sampling frequency, which is equal to a sample every 1.25 ms. However, the bit extraction algorithm experiences some downsampling due to the time required for code execution and the time required to read/write data on the SD

[1] The notation (10)* is the mathematical notation for a regular expression meaning the sequence "10" repeated an arbitrary number of times.

card. After downsampling, the sampling rate of the bit extraction algorithm is 600 Hz, which is equal to a sample every 1.67 ms. The bit extraction algorithm also considers the ramp up/down of the LRA motor. The motor has two states: vibrating—when the bit is equal to one—and idle—when the bit is equal to zero—. Because the motor is a physical system, it takes some time for the motor to switch between its two states.

To maximize the number of bits the BCLS can transmit in the three second transmission time, the following algorithms were implemented with the *Texas Instruments DRV2605L motor driver*: auto-resonance, overdrive, and assisted braking. With no calibration required, the auto-resonance algorithm ensures the LRA motor is being driven at resonance after half of a cycle. This is accomplished by monitoring the back-EMF of the mass-spring system in the motor. Running the motor at resonance ensures an maximum vibration strength resulting in a larger difference in the average amplitude of the vibration signal when the motor is vibrating versus when the motor is idle. The overdrive algorithm is uses a power greater than the rated power of the motor to decrease the time it takes the motor to go from idle to vibrating. The assisted braking algorithm increases the gain ratio between braking and driving gain to reduce the time it takes for the motor to go from vibrating to idle.

Using the *TI DRV2605L motor driver* with auto-resonance, overdrive, and assisted braking, the fastest vibration pulse achieved was 100 ms. With this vibration's duration, a bit sequence with a length of 30 bits can be transmitted within the three second window. However, the longer the bit sequence, the more likely there is an error in the bit extraction algorithm due to having fewer samples per bit. The requirement for the BCLS to be stable is that it must operate with no more than 5% of correct vibration signals resulting in false negatives. To satisfy this requirement, the BCLS uses a vibration duration of 290 ms. This allows for a bit sequence of 10 bits to be transmitted in the three second window.

## 2.2 Security of the BCLS

Since the BCLS is a lock, security is of the utmost importance. The key to unlocking the BCLS is a vibration sequence corresponds to a 10-bit bit sequence. With 10 bits, there are 1024 possible bit sequences. To increase the security of the lock beyond the 1024 possible keys, the BCLS implements dynamic keys, a secure radio frequency (RF) channel, a time penalty, and an activity log.

The first security feature, dynamic keys, takes advantage of the 1024 possible keys that can be obtained with a 10-bit bit sequence. During the operation of the BCLS, when the lock detects the user's finger, it sends a prompt to the band corresponding to the correct key the lock is expecting. Dynamic keys is a feature implemented to generate the prompt the lock sends to the band. For every attempt to unlock the lock, the key which the lock will be expecting is randomly chosen from the 1024 possible keys. For any given attempt to unlock the lock, the correct key is unknown to the user.

The second security feature is a secure RF communication channel between the lock and the band. After the dynamic keys algorithm determines the correct key for the current attempt, the

corresponding prompt is sent to the band over the 433 MHz RF channel. The 433 MHz RF channel is a public domain. This means anybody with a 433 MHz transmitter can send things over the channel, and anyone with a 433 MHz receiver can listen to the channel. Therefore, certain measures need to be taken in order to prevent people from tampering with the communication between the lock and band. To increase the physical security of the RF channel, the range of RF communication between the lock and band is designed to be limited to a distance of 30 cm. For a device out of the 30 cm range to tamper with the communication between the lock and band, expensive equipment like a signal amplifier is required. Given the situation where someone is able to transmit/listen on the communication channel between the lock and band, further security measures are taken. For every possible key, there is corresponding prompt: a string of characters. The lookup table for the mapping between a bit sequence and its corresponding prompt is stored locally on both the lock and band. Once the dynamic keys algorithm determines the correct key for current attempt, the bit sequence is searched in the lookup table and the corresponding prompt is transmitted from the lock to the band.

Because the 433 MHz channel is public, there may be miscellaneous data packets going back and forth on the channel. All the data packets sent from the lock to the band are appended with a preamble. When the band is listening to the RF channel, it only processes data packets with the expected preamble. Data packets without the correct preamble are simply ignored by the band.

The prompt transmitted from the lock to the band is also encrypted using Advanced Encryption Standard (AES). The prompt corresponding to the correct bit sequence is a plaintext character string. The plaintext is then encrypted with AES, resulting in ciphertext. The ciphertext is then transmitted over the 433 MHz RF channel to the band. When the band receives the data packet from the lock, it decrypts the ciphertext to retrieve the original plaintext prompt. Figure 6 shows the results of implementing 128-bit, 192-bit, and 256-bit encryption. The time of encryption and decryption is displayed in Figure 6 for the example prompt “Team 3: Bone Conduction Lock.” The plaintext prompt, ciphertext, and decrypted ciphertext (this field is labelled “check” in the figure) are displayed to show successful encryption and decryption. The initialization vectors for each encryption/decryption procedure are also displayed to show they are unique.

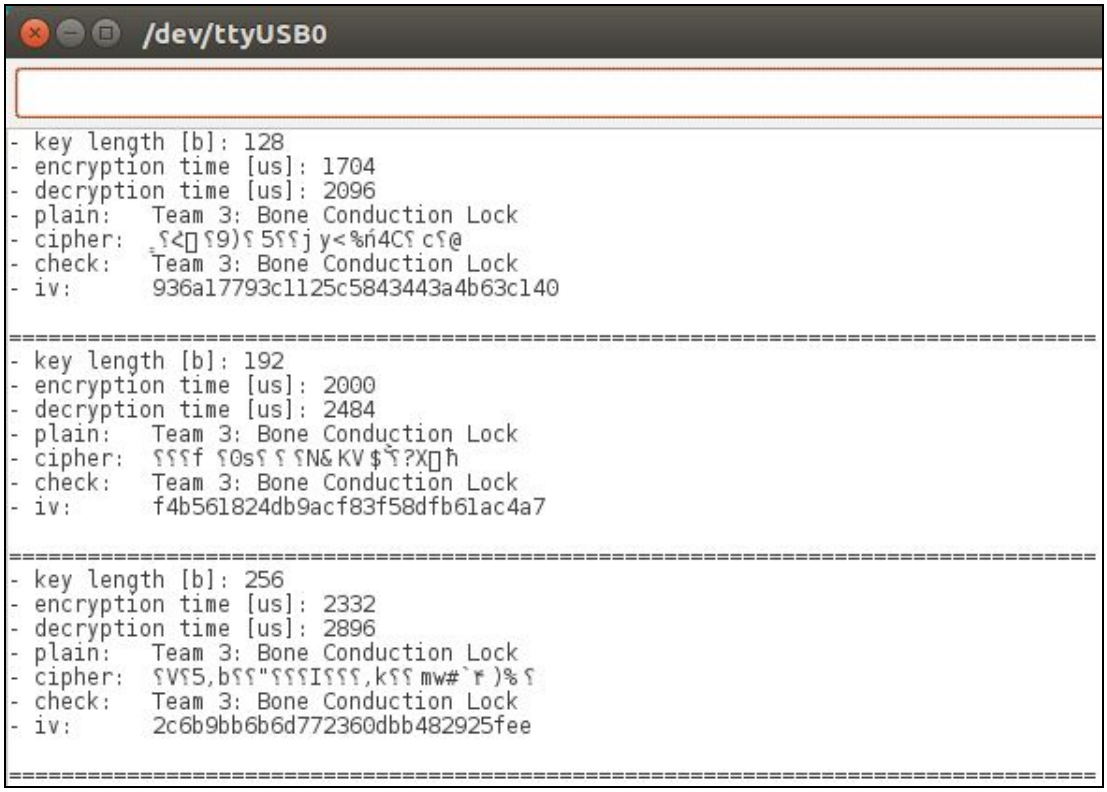


*Figure 6: AES encryption implementation results*

The third security feature is the implementation of a time penalty for consecutive incorrect keys being received at the lock. This feature is similar to being locked out of a smartphone after entering the wrong passcode too many times. The time penalty is reset once the lock has been successfully unlocked. In order to unlock the BCLS, the correct key needs to be transmitted from the band to the lock. Regardless if the key is correct or incorrect, the operation of the BCLS takes around ten seconds. The time penalty model for *n* consecutive incorrect keys is as follows:

n = 2 → wait 10 seconds
n = 5 → wait 30 seconds
n ≥ 10 → wait 60(n-10)+60 seconds

With the time penalty model, the time it takes to open the lock using bruteforce is:

$$\begin{aligned} time_{bruteforce} &= (t_{operation} * num_{possible\ keys}) + p_{n=2} + p_{n=5} + p_{n=10\ to\ n=1024} \\ &= (10 * 2^{10}) + 10 + 30 + \int_{10}^{1024} (60(x-10)+60)\,dx \\ &= 10240 + 10 + 30 + 30906720 \\ &= 30917000\ seconds = 515283\ minutes = 8588\ hours = 357\ days \end{aligned}$$

Where $t_{operation}$ is the time it takes the lock to operate, $num_{possible\ keys}$ is the number of possible keys, $p_{n=2}$ is the time penalty after two consecutive incorrect keys, $p_{n=5}$ is the time

penalty after five consecutive incorrect keys, and $p_{n=10\ to\ n=1024}$ is the sum of the time penalties after 10 consecutive incorrect keys to 1024 consecutive incorrect keys.

357 days is a sufficient amount of time to deter an invader from trying to open the lock using bruteforce, especially since the only communication channel the lock module is receiving data form is physical vibrations measured by the accelerometer. In order to see if a particular key will open the lock, an intruder would need to keep their finger pressed against the lock and wait for the complete transmission a vibration signal to the lock module. In order for an intruder to bypass this process, they would need to perform a man-in-the-middle attack and intercept the communication between the accelerometer and the microprocessor. At that point, it would be more effective for the intruder to break the lock by other means like physically destroying the lock or knocking down the door the lock is installed on. The 357 day calculation also doesn't include the implementation of the dynamic keys feature. The probability that an intruder uses a key that happens to be the correct key is 1 in 1024, which is equivalent to a 0.097% chance.

The final security feature implemented is an activity log that records all the BCLS activity. Lock activity is stored in the log in "*hour:minute:second* | *day_of_week* - *month/day/year* event" format as seen in Figure 7. The activity log can be used to monitor activity, and in the case that the BCLS is compromised, helped reconstruct events that led to the infiltration.

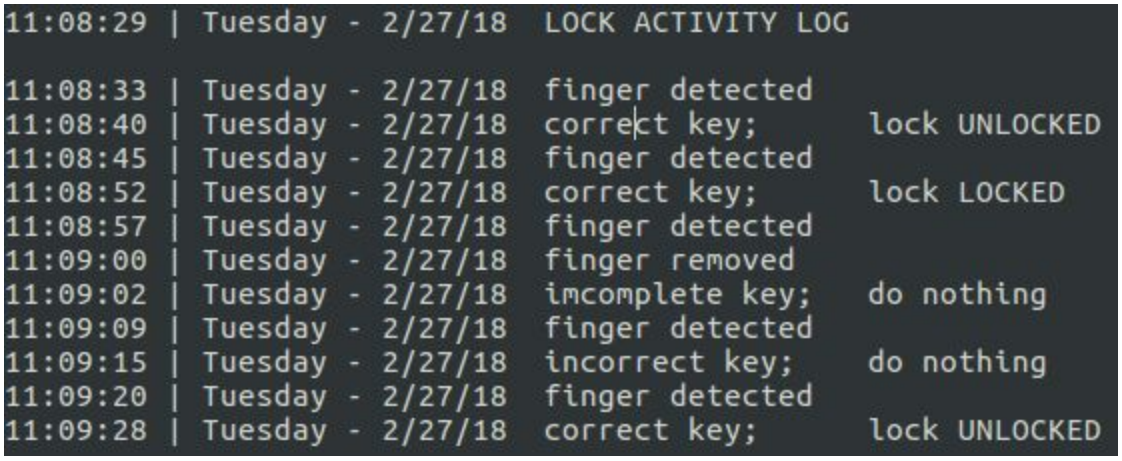


*Figure 7: BCLS activity log*

## 2.3 Physical Design

### 2.3.1 Lock Module

The physical design resembles a wooden lock box. Figure 8 shows the lock PCB (printed circuit board) securely mounted to the top of the box. The side of the box that is covered in black electrical tape is the hinge side of the box. Figure 9 provides a view of the cut out which allows the servo motor to act as a locking mechanism. The servo motor is initialized to be wedged into the box's side cut out. When a user places their finger to the IR sensor the LRA motor on the user's band module will begin sending vibrations that are picked up by the accerolmeter. If the vibrations match the expected key the servo motor moves out from the box's side cut out and the user is able to access the contents of the box. All components not pictured in Figure 8 (SD card, battery, RF transmitter, etc.) are housed inside the box. The final dimensions of the box were 74 mm x 150 mm x 53 mm.

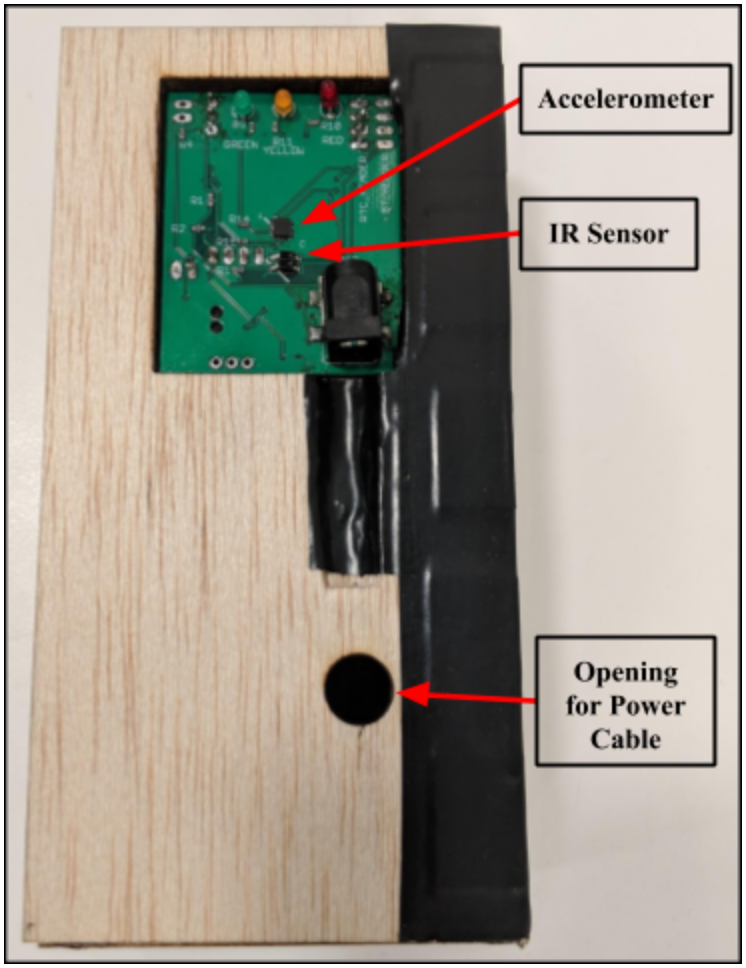


*Figure 8: Physical Design of Lock Module (top view)*

.

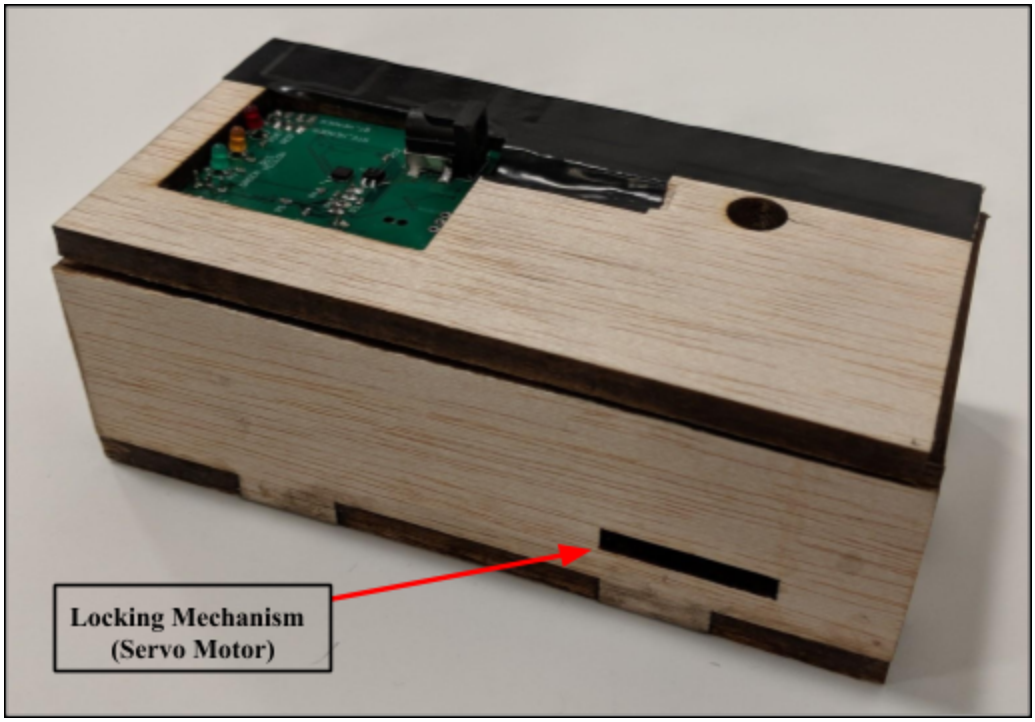


*Figure 9: Physical Design of Lock Module (side view)*

### 2.3.2 Band Module

The band module was designed to have a similar form factor to a smartwatch. The actual band module PCB itself was given dimensions equal to those of an Apple Watch[2] (30 mm x 40 mm). The difference between a typical smartwatch and the band module 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 10. The decision was made to move the LRA motor to a ring because 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.

All components are contained entirely inside the band's housing with the exception of the push button and status LED, which protrude out of the casing when the housing's cover is in place. When designing the physical housing there were two options. Either place the battery under the PCB or to the left side of it. Placing the battery under the PCB would cause the housing to become roughly 10 mm taller. Likewise, placing the battery to the left of the PCB would cause the housing to become roughly 10 mm wider. The decision was made to place the battery to the left of the PCB for two reasons. The first was aesthetic, the second was because placing the battery to the side of the PCB would allow for easier access to the battery than if the battery was underneath. The band module's housing can be seen in Figure 11. Inside the housing there are four small beams that support the PCB. The housing also has a cutout for the LRA motor's pins. The final dimensions for the housing were 42 mm x 52 mm x 26 mm.

[2] The housing of an Apple watch, that is. Breaking one open to measure its PCB dimensions would have been a poor use of resources.

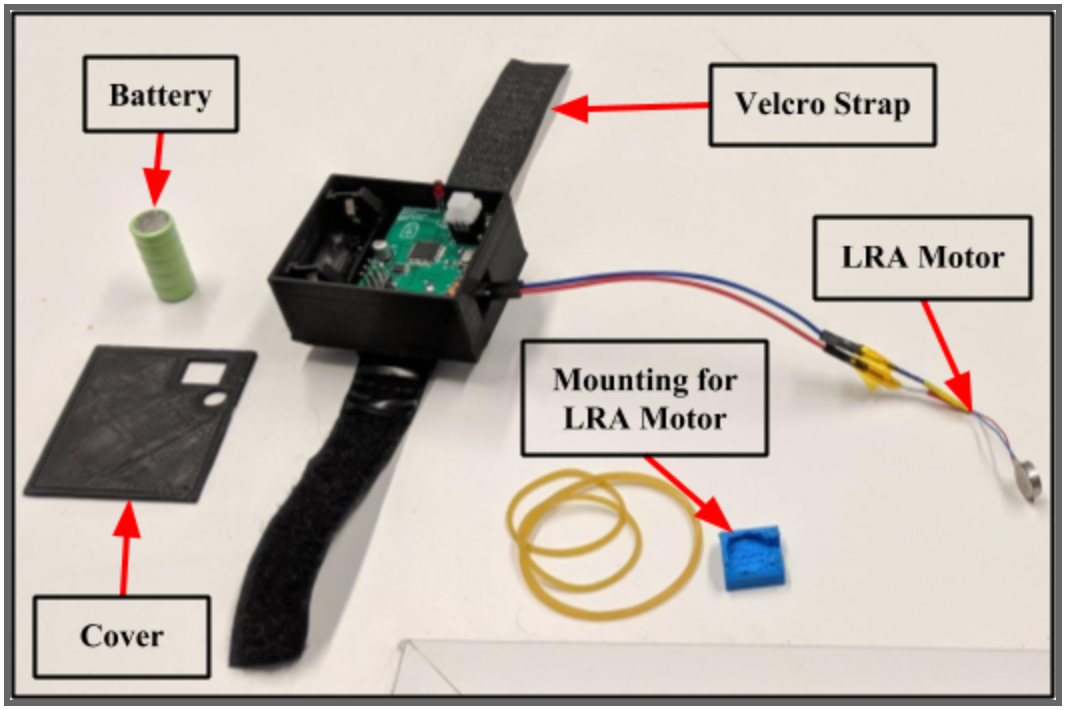


*Figure 10: Physical design of band module*

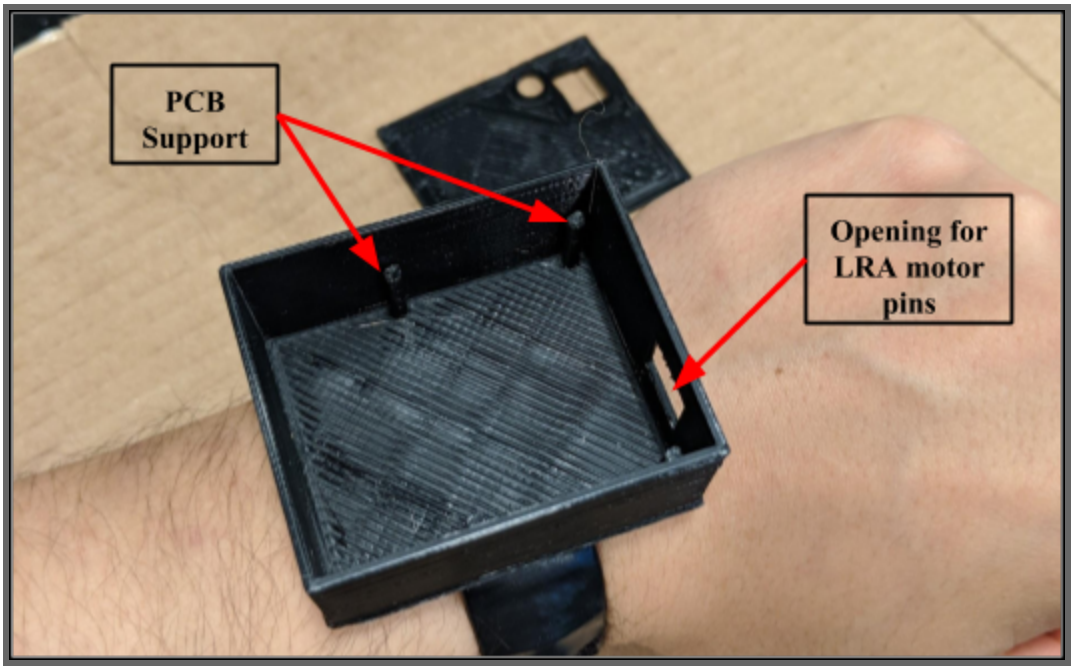


*Figure 11: Housing for band module*

# 3 Cost

## 3.1 Parts

Detailed tables for lock and band parts can be found in appendix D. Table 1 shows a summary of the total cost for all the parts used in one BCLS.

| Description | Cost |
|---|---|
| Lock PCB Parts | $68.45 |
| Band PCB Parts | $50.77 |
| **Total Parts Cost:** | $119.22 |

*Table 1: Parts Cost Summary*

## 3.2 Labor

In 2016 the average UIUC computer engineering graduate made $81,748 a year, and the average electrical engineering graduate made $68,392 [5]. These salaries were weighted proportionally by their representation in the group, making the average yearly salary per group member $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. Assuming a college course warrants two hours of out-of-class studying for every hour of in-class time, and assuming the group spends the extra four hours a week freed up by a lack of lecture on more work for this project, that comes out to 12 hours per person per week on this class. The class is sixteen weeks long. We can use the following formula to estimate labor costs per person:

$$Hourly\ Salary * Total\ Hours * 2.5 \qquad (1)$$

Using this formula each team member's labor comes out to $7,134.72 for the entire semester. This gives us a total labor cost of $21,404.16.

## 3.3 Total

The total cost of the project can be seen in Table 2. Labor clearly comprises the majority of cost, as is to be expected. The cost of physical components was artificially deflated due to the fact the lock's box was made out of surplus wood obtained for free.

| Description | Cost |
|---|---|
| Electronic Parts | $119.22 |
| Physical Components Including PCBs | $34.05 |
| Labor | $21,404.16 |
| **Total Project Cost:** | $21,557.43 |

*Table 2: Total Cost Summary*

# 4 Schedule

Table 3 shows the schedule for each team member through the completion of the BCLS.

| Week | Alex | Brandon | Ramon |
|---|---|---|---|
| 2/12/18 | Breadboard prototype of lock and band modules | Design Doc and RV table | Reviewing reboard eagle files to help pick parts, create parts list |
| 2/19/18 | LRA motor tolerance analysis for design document, proofread design document | MCU Research, condensed findings in spreadsheet | power consumption, power supply design, regulator selection |
| 2/26/18 | Code for band operation (vibration signal generation) | Worked to transition old lock design using ATMEGA328 to ATMEGA2560 | Cost analysis for design document |
| 3/5/18 | Code for band operation (vibration signal generation) | Created new schematics / designs, researched serial code uploading | Band PCB design |
| 3/12/18 | Code for lock operation (key detection/verification) | Lock PCB Design MkI[3] | Band PCB layout |
| 3/19/18 | Spring Break | Spring Break | Spring Break |
| 3/26/18 | RF integration, generation of prompts | Finance tracking, MkII PCB design[4] | Assembled first band PCB, ordered 2nd PCB |
| 4/2/18 | Code for lock operation (security) | MkI Lock PCB assembly MkIII Lock PCB design after discovery of error in previous designs | Order second round of parts, order 3rd version of band PCB after noticing design error |
| 4/9/18 | Make sure code is running properly on prototype (eliminate the possibility of software bugs in PCBs) | MkIII lock PCB assembly / Debugging | 3rd band PCB assembly and debug |

[3] Lock PCB iterations are denoted using the military-esque "Mark" system. Each iteration is denoted by Mk followed by roman numerals indicating the version of the design.

[4] The MkII PCB design was never assembled. The support for additional features conceived of since the MkI (The RF module for example) was included in the MkIII, but the error (discussed in detail in the Uncertainties section) discovered necessitated the MkIII being designed and built

| | | | |
|---|---|---|---|
| 4/16/18 | Integrated lock and band PCB in software | MkIII assembly 2nd attempt[5]. Debugging. | Ensure band module is working, physical design |
| 4/23/18 | Collection of data for investigation into biometric authentication | Serial programming fixed, assorted tests and soldering fixes on Lock and Band | Physical design for band module |
| 4/30/18 | Include all software updates in Final Report since Design Document | Included lock module information in final report, along with writing assorted sections and editing copy | Include band module schematic, PCB layout,etc. In final presentation and report |

*Table 3: Project Schedule*

[5] An error when removing a fried component ripped the pads up on the land for the ATMEGA2560. This, combined with a lack of spare parts necessitated desoldering every component on the first attempt at the MkIII board, and resoldering it onto a new board. That is why such a large amount of time was devoted to MkIII Lock PCB assembly.

# 5 Conclusion

## 5.1 Future Work

In the future the BCLS system could be integrated into existing electronics, namely smartwatches. As previously mentioned, most electronics today use an ERM motor to generate vibrations. Adding support for a system built on the technology in the BCLS would likely necessitate a switch to an LRA motor. In addition to LRA motors being more expensive than ERM motors, the necessary motor driver would take up physical space. Convincing companies that the added features would be worth the cost in both space and money is non-trivial, as are the challenges introduced by moving the motor from the finger to the wrist.

The differentiability of two users' unique channel interference patterns may depend on the key used as well as the users' anatomy. A user's hand may create an especially unique interference pattern when driving at a slightly off-resonance frequency, or when exposed to several consecutive pulses. Seeking out each users' most differentiable key for their hand is a potential avenue to increase the overall differentiability of any given user of the BCLS. If a systematized way to find these most-differentiable keys were developed, there is the potential that the overall success rate of biometric authentication using a BCLS-like system could be increased.

## 5.2 Accomplishments

The project completed all objectives laid out at the outset. The project proved human bone conduction is a viable communication channel with the use of a LRA motor and a MEMS accelerometer. By implementing additional features on top of the lock's core functionality the group was able to increase the system's efficiency, stability, and security. Finally, with a working hardware platform the group was able to begin collecting data from willing participants to investigate the possibility of integrating biomarkers into the algorithm used to verify an unlock attempt.

## 5.3 Uncertainties

While the final product contained no failed deliverables[6], many obstacles along the way were overcome. The most costly in terms of both time and money was an early error in PCB design that stemmed from ignorance of the serial uploading process. The microcontrollers used in the project both had two ways to program them: in-system programming (ISP) and Future Technology Devices International (FTDI) methods. They both used used different pins and had different limitations. Before any code could be uploaded via FTDI, the board required a bootloader to be loaded onto it using ISP. This was not known until after the original PCBs were

[6] While there was one requirement on the RV table which was not fulfilled, redundancies prevented this from affecting any functionality visible to the end user whatsoever. The error was in requirement design, not in project execution.

designed, and the pins necessary for ISP were not exposed[7]. This necessitated two new board designs and a rush-order for two new boards. A new piece of hardware to upload code via USB was also bought.

Another obstacle involved the piece of hardware mentioned above. Unbeknownst to the group, it required a firmware update in order to properly upload code of non-trivial size to the ATMEGA2560, the microprocessor used in the lock module. An attempt to update the firmware ended up breaking the device beyond repair[8]. Eventually, it was discovered that one of the group's dev boards, the Arduino Mega, could act as hardware to upload code to the lock module's microprocessor using a feature known as "Arduino as ISP" . Curiously, this same functionality had been tried using an Arduino Uno[9] and did not work. It is now assumed this was due to the smaller processor on the Uno—the ATMEGA328P—failing to support addresses of the size necessary to address all the memory in the ATMEGA2560. The Arduino Mega—which itself used an ATMEGA2560—on the other hand, would have to support this in order to properly address all of its own internal memory.

## 5.4 Ethical Considerations

Exposure to vibrations is known by the Occupational Hazards and Safety Administration (OSHA) [6] 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 [7]. 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 [8]. 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 $m/s^2$ . Tests of haptic motors used in the BCLS showed a peak strength below that: 13.07 $m/s^2$. Additionally, since the key is transmitted in three seconds, the time of vibration exposure is on the order of seconds, not minutes or hours.

The operating frequency of the motors 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* [9], 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 4. 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".

[7] Technically they were exposed on the lock PCB, but they were exposed to communicate with the SD card reader, and connecting them to the FTDI breakout board would have been a hassle. On the band module, the pins were not exposed at all.
[8] Perhaps not entirely beyond repair, but the group member who paid for the device has elected to violently dismember the device rather than attempt to repair it.
[9] Technically the board was a Sparkfun RedBoard, but these are functionally identical to an Arduino Uno

| 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[10] | 20-30 |
| Eyeballs | 60-90 |
| Lower Jaw-Skull | 100-200 |

*Table 4: Resonant frequencies of various biological structures*

These resonant frequencies are outside the range of ~198 Hz which the BCLS motor operates at. The lower jaw and skull, the biological structure whose resonant frequency is closest to the band motor's operating frequency, is located at great distance from the source of the vibrations, making damage to those body parts an unlikely scenario.

Aside from the user's heath, the major issue which concerns this project is user data safety. If future research shows that a non-trivial amount of information about the bone structure of the user can be reconstructed from vibrations, the vibrations effectively become health information. Legally ethically this warrants additional measures to ensure its security. Additional features such as encrypting the biometric data may be necessary to keep users' information safe from potential thieves. Thieves are not the only danger to user data security however. At the outset of the project, the idea that users' data ought not be sold without their knowledge or permission was thought to go without saying. Incidents in the intervening months have shown that it need be stated explicitly. Any group, individual, or organization wishing to build off this project should keep that ethical obligation in mind. Additionally, projects who wish to build on the BCLS should do so without compromising the low false positive rate (this project's tests yielded no false positives whatsoever). To compromise this would mean compromising the property users wish to protect with the BCLS.

Other ethical issues—namely those listed in the IEEE Code of Ethics[10]—are not made especially relevant by the nature of the work done There are no exceptional safety risks, conflicts of interest, potential for environmental damage, etc. outside of the risks bound to occur on any electrical engineering project.

[10] 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 the band's motor operates well outside this frequency range is clear.

# 6 References


[1] D. Cade, "Here's How iPhone Thermal Cameras Can Be Used to Steal Your Pin Codes", *PetaPixel*, 2014. [Online]. Available: https://petapixel.com/2014/08/29/heres-iphone-thermal-cameras-can-used-steal-pin-cod [es/. [Accessed: 01- Feb- 2018]

[2] Discovery, *Mythbusters: Fingerprints*. 2008 [Online]. Available: https://www.youtube.com/watch?v=MAfAVGES-Yc. [Accessed: 01- Feb- 2018]

[3] A. Alterman, "``A piece of yourself": Ethical issues in biometric identification", *Ethics and Information Technology*, vol. 5, no. 3, pp. 139-150, 2003.

[4] S. Schneegass, Y. Oualil and A. Bulling, "SkullConduct: Biometric User Identification on Eyewear Computers Using Bone Conduction Through the Skull", *CHI '16 Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 1379-1384, 2016.

[5] Engineering.illinois.edu. (2018). *ENGINEERING.ILLINOIS.EDU ENGINEERING AT ILLINOIS SALARY INFORMATION 2015-2016*. [online] Available at: https://engineering.illinois.edu/documents/Salary.Info.Sheet.pdf [Accessed 23 Feb. 2018].

[6] OSHA, "OSHA Technical Manual (OTM) | Section II: Chapter 3 - Technical Equipment: On-site Measurements | Occupational Safety and Health Administration", *Osha.gov*, 2014. [Online]. Available: https://www.osha.gov/dts/osta/otm/otm_ii/otm_ii_3.html. [Accessed: 01- Feb- 2018]

[7] "Vibration - Health Effects", *Canadian Centre for Occupational Health and Safety*, 2017. [Online]. Available: https://www.ccohs.ca/oshanswers/phys_agents/vibration/vibration_effects.html#shr-pg-pnl1. [Accessed: 01- Feb- 2018]

[8] P. Pelmear and D. Leong, "EU Directive on Physical Agents — Vibration", *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 21, no. 3, pp. 131-139, 2002.

[9] S. Kumar, *Biomechanics in ergonomics*, 2nd ed. Boca Raton: CRC Press, 2008.

[10] "IEEE IEEE Code of Ethics", *Ieee.org*, 2018. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 01- Feb- 2018]

# Appendix A: Requirement and Verification Tables

| Requirements | Verification | Points | Verification Status |
|---|---|---|---|
| 1. Must output 3.3 V ± 5% with a current load of up to 800 mA | a. Measure the output voltage using a multimeter.<br>b. Vary the load current by changing load resistance.<br>c. Show on multimeter that voltage stays in its tolerance range as current is varied up to 800 mA. | 2 | Yes |
| 2. Must output 5 V ± 5% with a current load of up to 800 mA | a. Measure the output voltage using a multimeter.<br>b. Vary the load current by changing load resistance.<br>c. Show on multimeter that voltage stays in its tolerance range as current is varied up to 800 mA. | 2 | Yes |
| 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. | 1 | Yes |

Table 5: RV Table for the Lock Module's Power Subsystem

| Requirements | Verification | Points | Verification Status |
|---|---|---|---|
| 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.<br>b. Show that frequency response does not get clipped at 2 g on the serial monitor. | 5 | Yes |
| 2. Accelerometer output has 0.01 g precision and maximum noise floor of 1.02 g | a. Show the output has 0.01 g precision on serial monitor.<br>b. Show accelerometer has maximum noise floor of 1.02 g on the serial monitor. | 5 | Yes |
| 3. IR sensor detects finger when in contact with the lock module target area | a. Send IR sensor output to microcontroller.<br>b. Display sensor output on the serial monitor.<br>c. Show change in IR sensor output is a function of proximity of finger when within one inch of the lock module target area. | 2 | Yes |
| 4. Status LEDs show state of the lock | a. When lock is in locked state (0°), the red LED is on.<br>b. When lock is in unlocked state (90°), the green LED is on. | 2 | Yes |
| 5. Status LEDs give visual feedback on attempts to lock/unlock the lock | a. When correct “key” is received at the lock, green LED blinks.<br>b. When incorrect “key” is received at the lock, red LED blinks. | 2 | Yes |

Table 6: RV Table for the Lock Module’s Control Subsystem

| Requirements | Verification | Points | Verification Status |
|---|---|---|---|
| 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.<br>- locked state (position of 0°).<br>- unlocked state (position of 90°). | 2 | Yes |
| 2. Status LEDs correctly correspond to the state of the lock | a. When lock is in locked state (0°), red LED is on.<br><br>b. When lock is in unlocked state (90°), green LED is on. | 2 | Yes |

Table 7: RV Table for the Lock Module's Lock Mechanism

| Requirements | Verification | Points | Verification Status |
|---|---|---|---|
| 3. Must output 3.3 V ± 5% with a current load of up to 800 mA | d. Measure the output voltage using a multimeter.<br>e. Vary the load current by changing load resistance.<br>f. Show on multimeter that voltage stays in its tolerance range as current is varied up to 800 mA. | 2 | No[11] |
| 4. Must output 5 V ± 5% with a current load of up to 800 mA | d. Measure the output voltage using a multimeter.<br>e. Vary the load current by changing load resistance.<br>f. Show on multimeter that voltage stays in its tolerance range as current is varied up to 800 mA. | 2 | Yes |
| 3. Maintain a temperature below 120°C | b. Use an IR thermometer or IR camera when the IC is in operation to show that the temperature stays below 120°C. | 1 | Yes |

Table 8: RV Table for the Band Module's Power Subsystem

[11] Despite this, the only component (motor driver) on the band that used the 3.3 V power ended up working just fine due to that component's own supply correction feature picking up the slack. We believe the 3.3 V regulator failed due to a error in designing the band PCB ($V_{IN}$ and 3.3 V traces too close together)

| Requirements | Verification | Points | Verification Status |
|---|---|---|---|
| 1. Signal from push button is momentary | a. Display output from push button on serial monitor<br><br>b. Show the microcontroller only receives signal when button is pushed. | 2 | Yes |
| 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.<br><br>b. Push the button and observe the motor generate a complete signal on the serial monitor.<br><br>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. | 2 | Yes |
| 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.<br><br>b. Show two complete signals were transmitted on serial monitor. | 6 | Yes |

Table 9: RV Table for the Band Module's Control Subsystem

| Requirements | Verification | Points | Verification Status |
|---|---|---|---|
| 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.<br><br>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. | 5 | Yes |
| 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.<br><br>b. Conduct the signal through the hand to the fingertip, show the received signal on the serial monitor.<br><br>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. | 5 | Yes |

Table 10: RV Table for the Band Module's Motor Subsystem

# Appendix B: Circuit Schematics

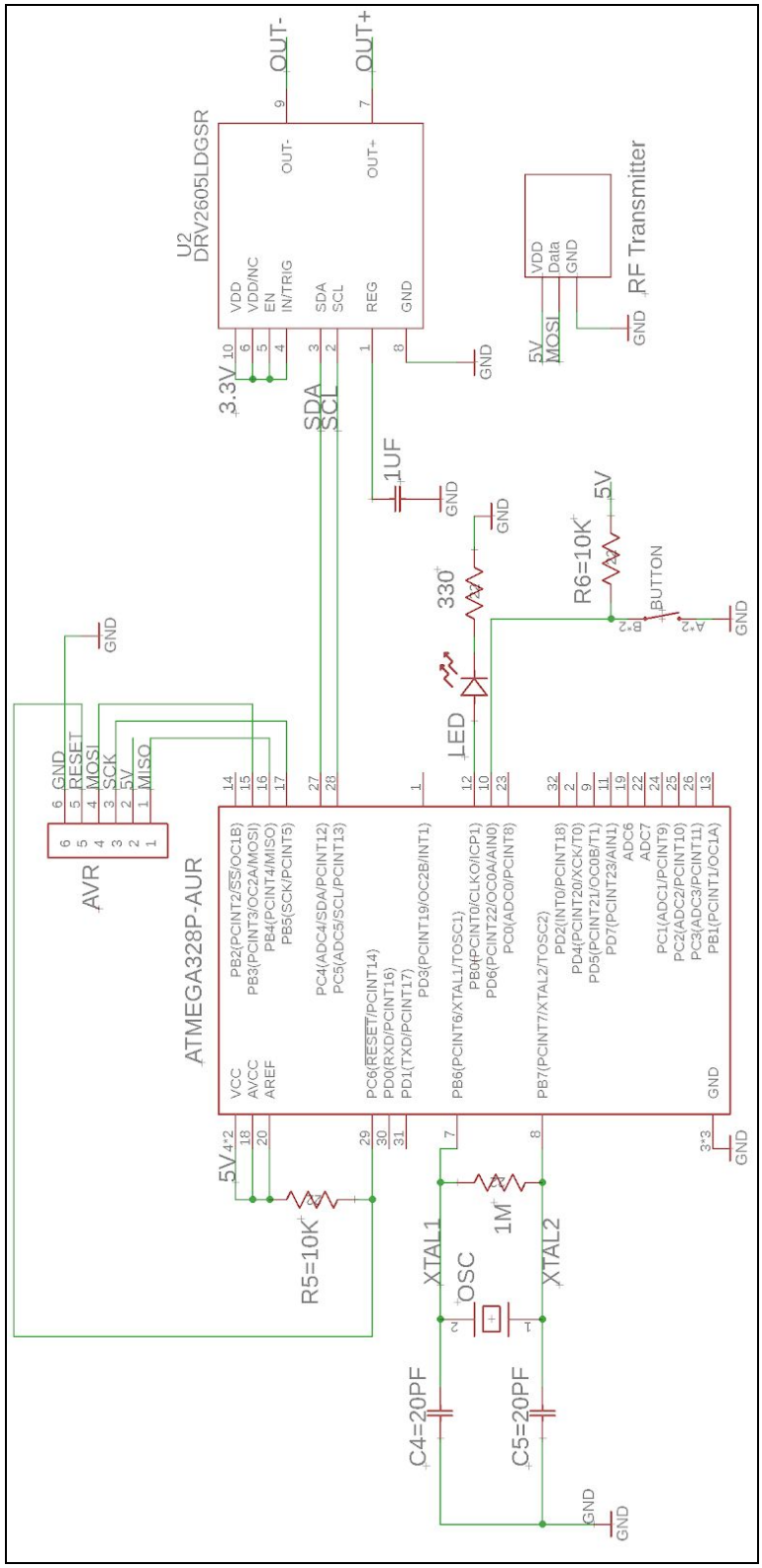


*Figure 12: Band module schematic*

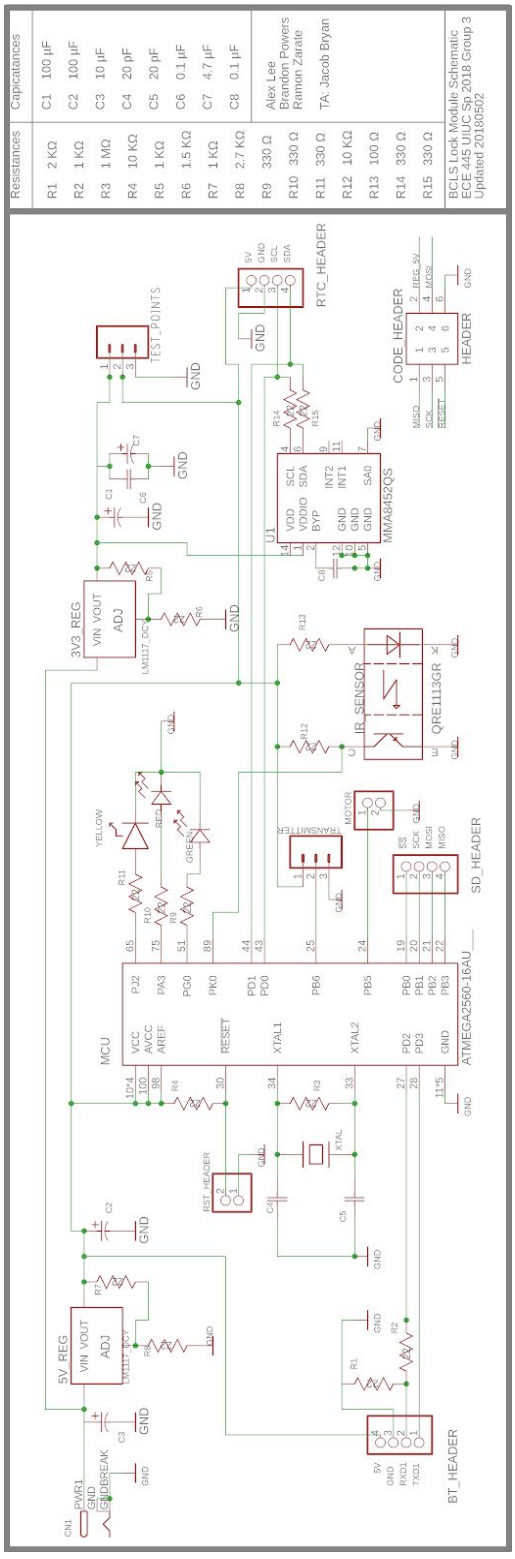


*Figure 13: Lock module schematic, Full*

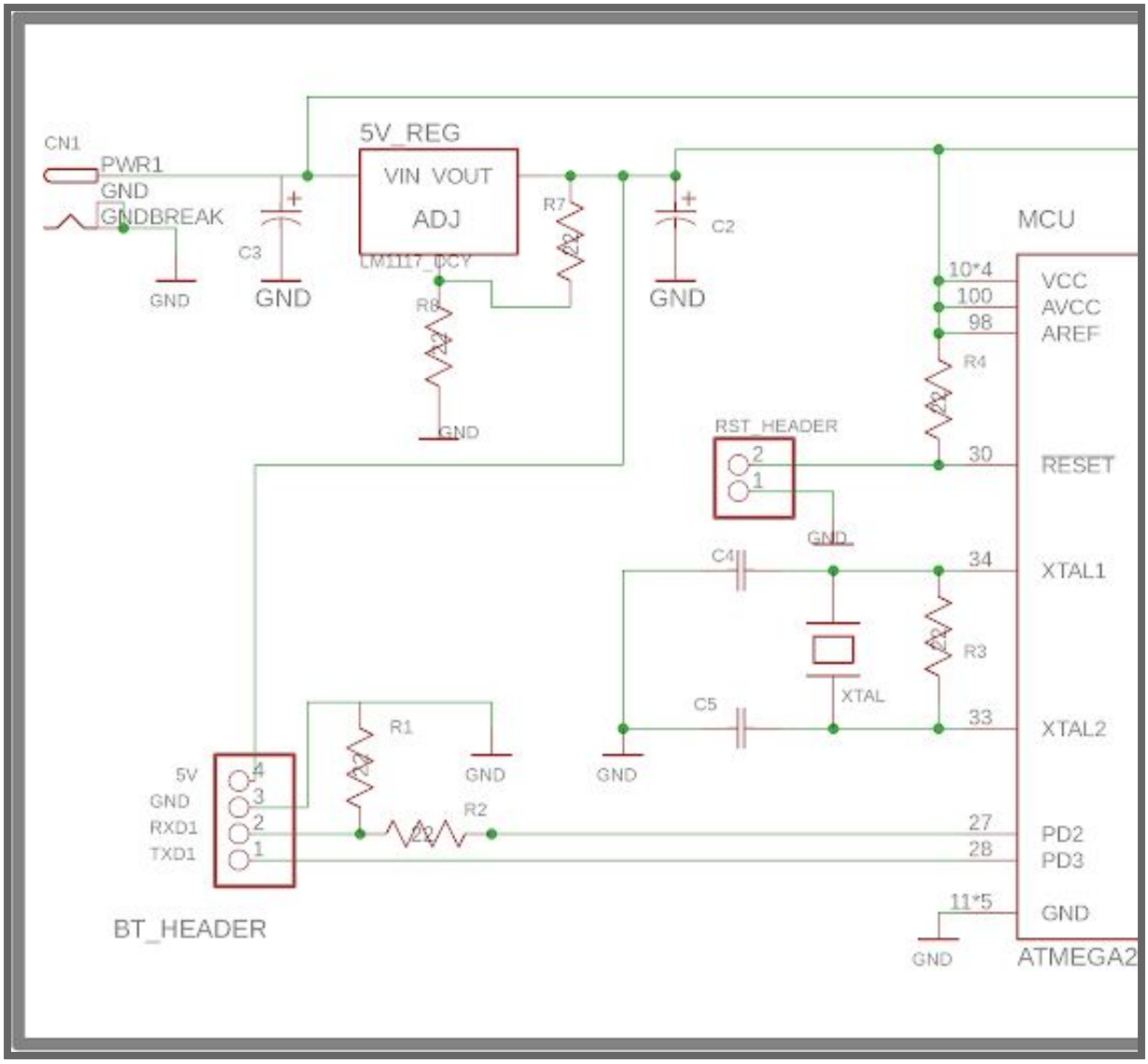


*Figure 14: Lock module schematic, left section, zoomed in.*

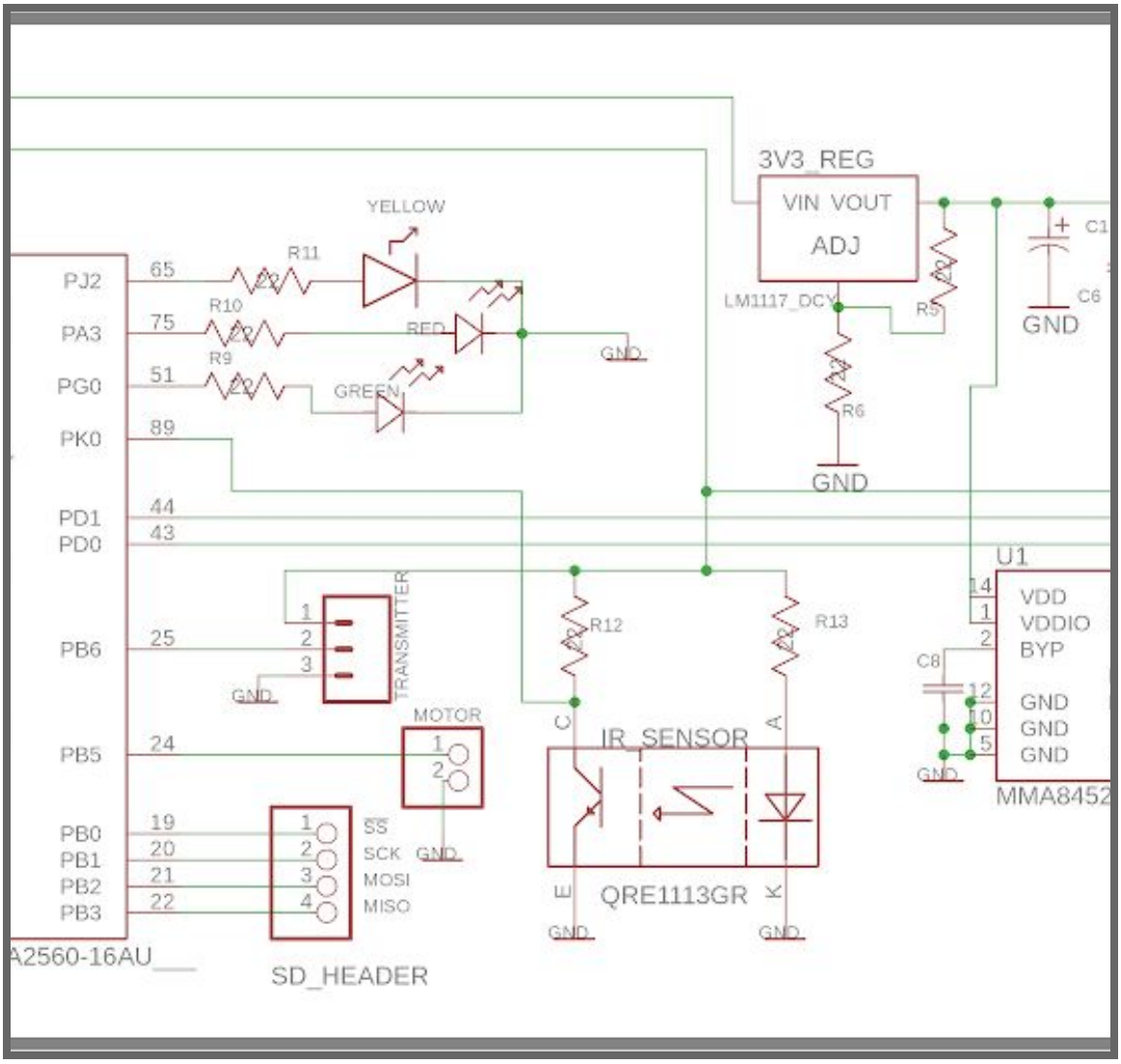


*Figure 15: Lock module schematic, center section, zoomed in.*

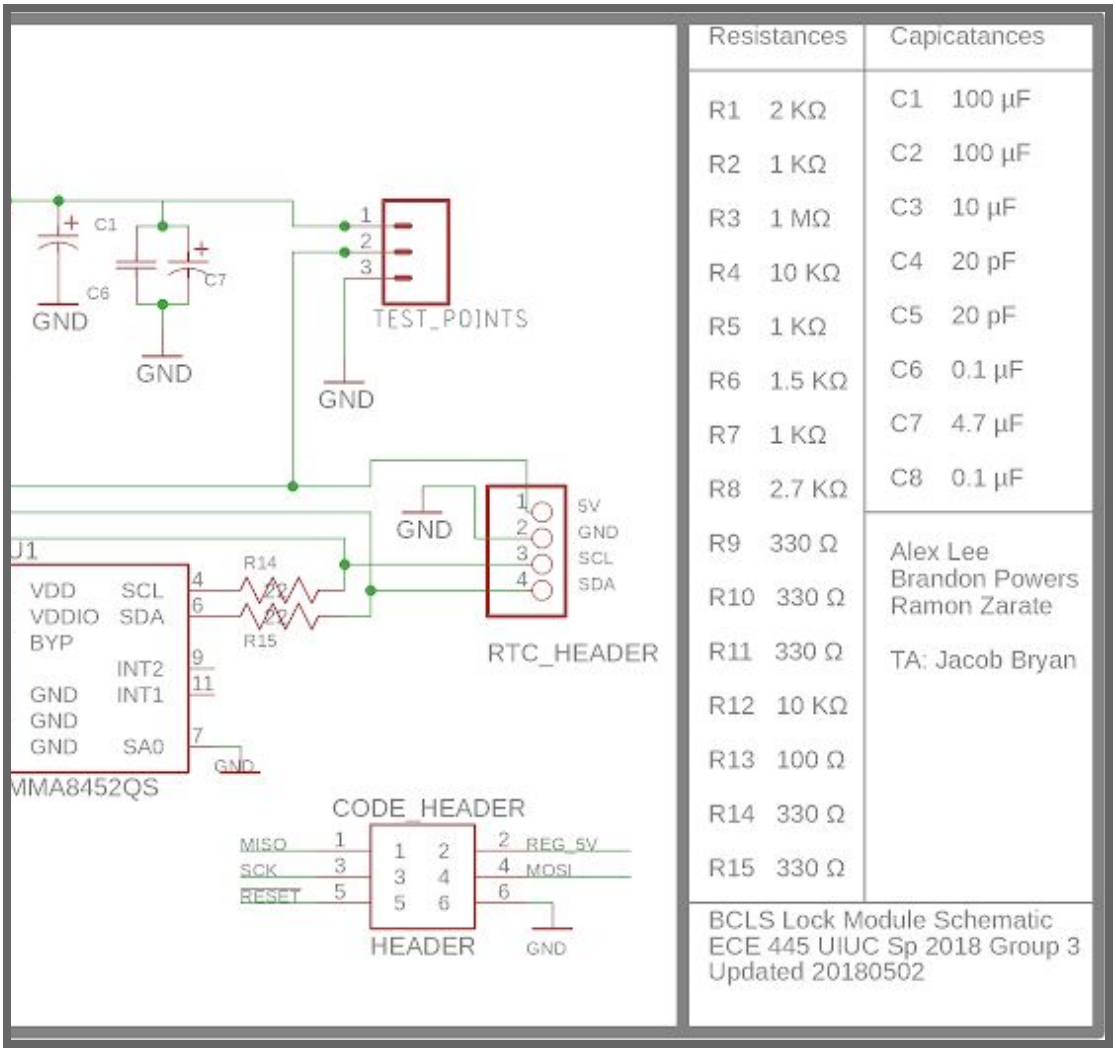


*Figure 16: Lock module schematic, right section, zoomed in.*

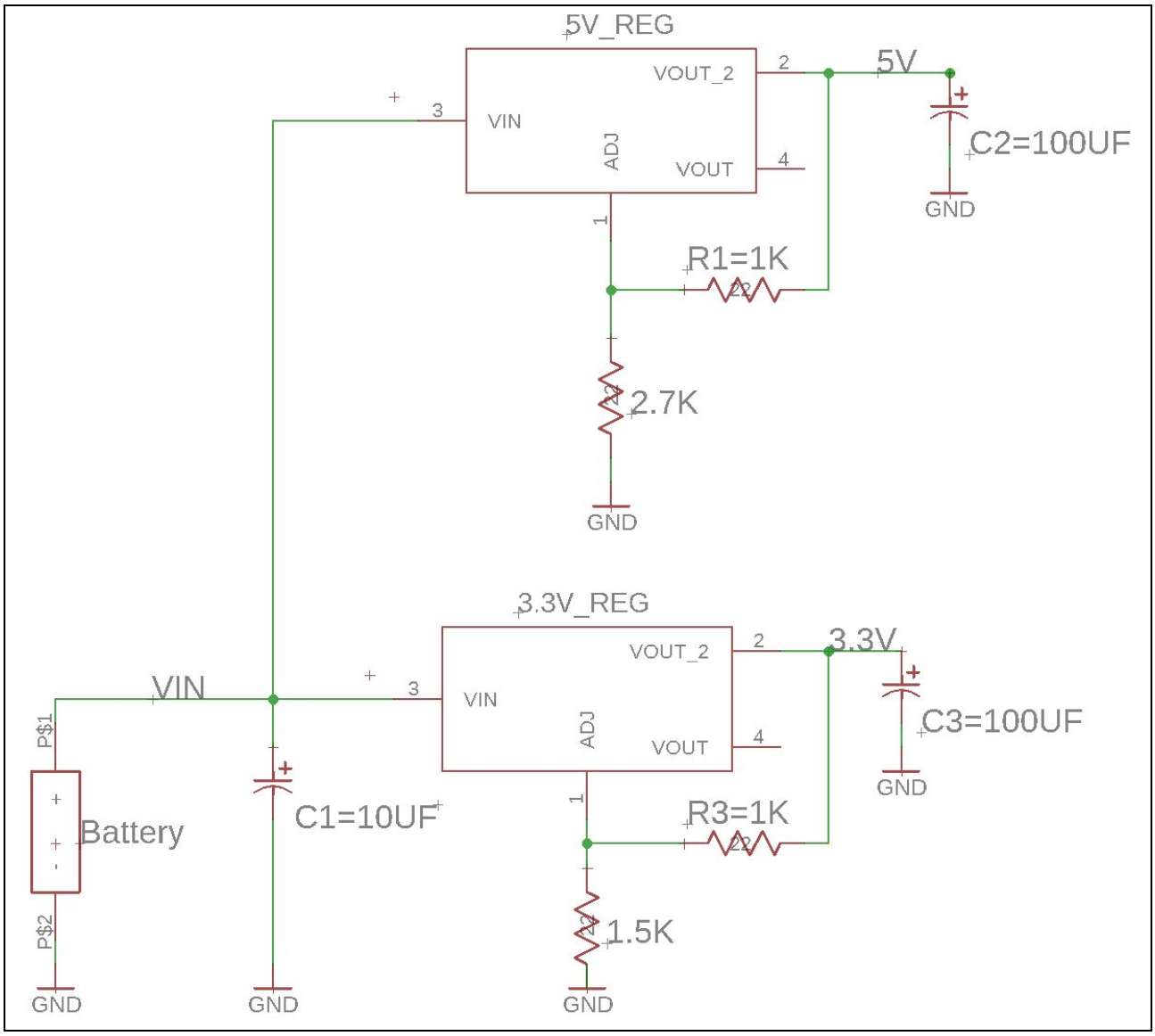


*Figure 17: Power supply schematic*

# Appendix C: PCB Layouts

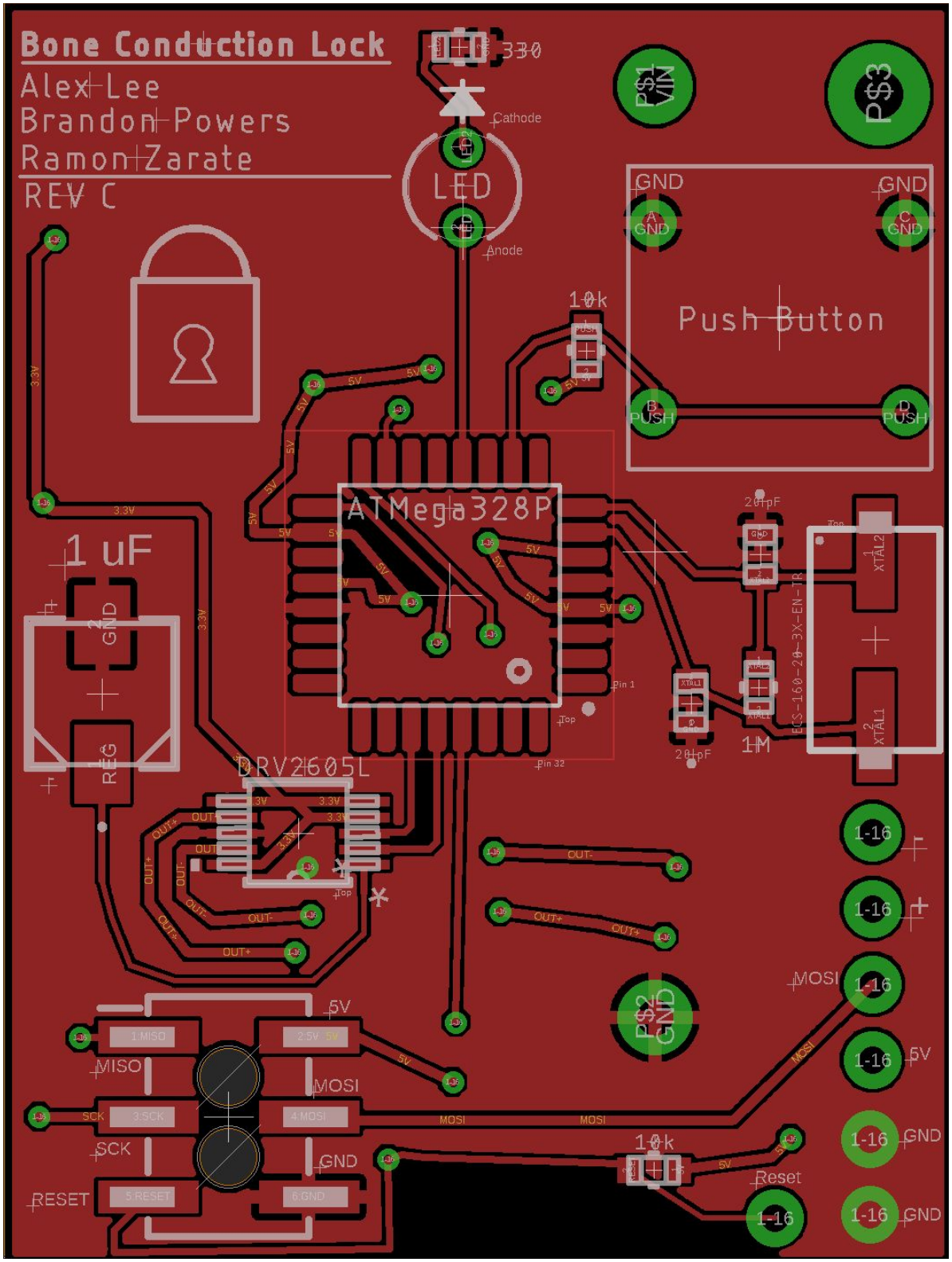


*Figure 18: Band module PCB (top side only)*

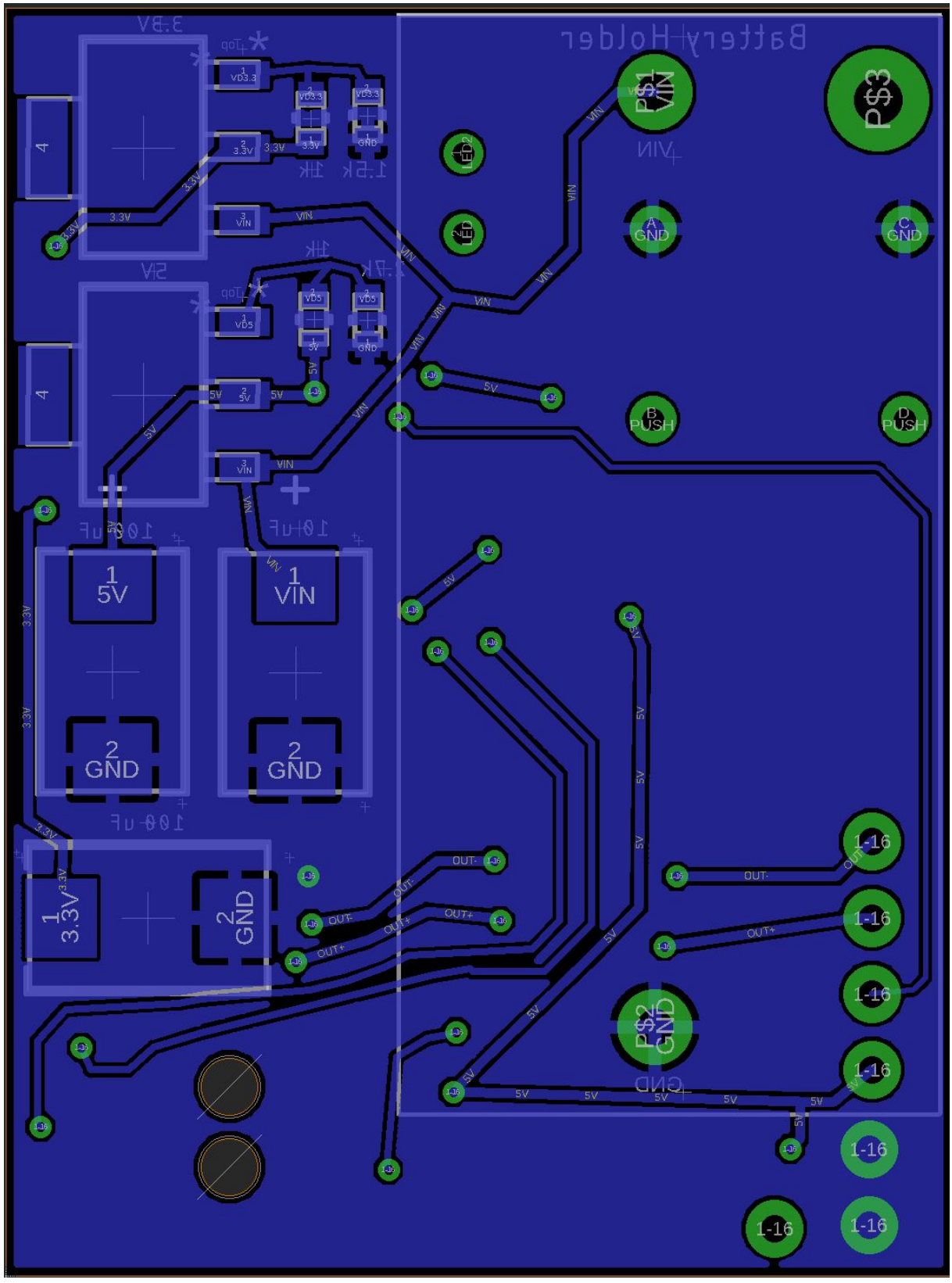


*Figure 19: Band module PCB (bottom side only)*

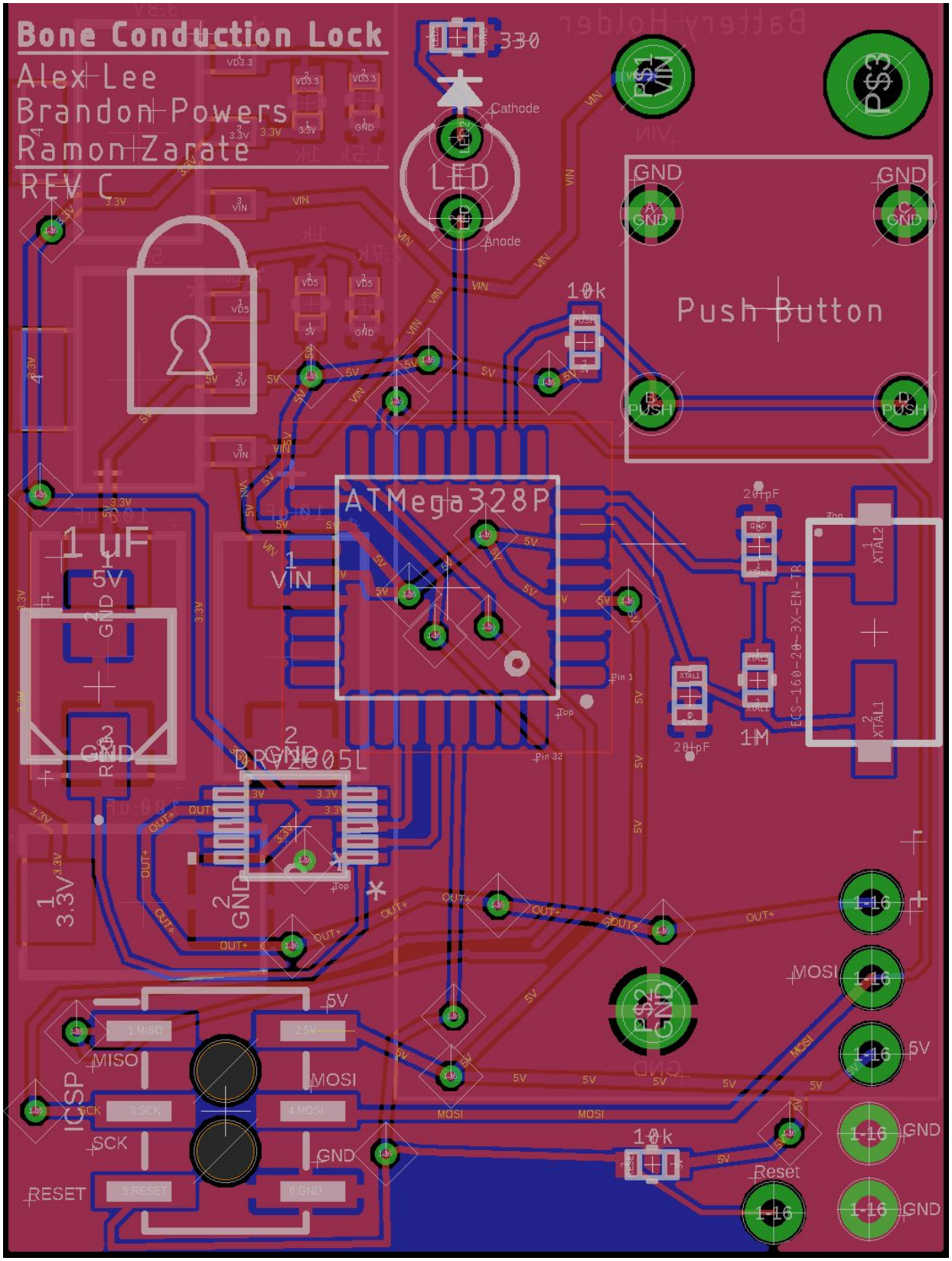


*Figure 20: Band module PCB (complete layout)*

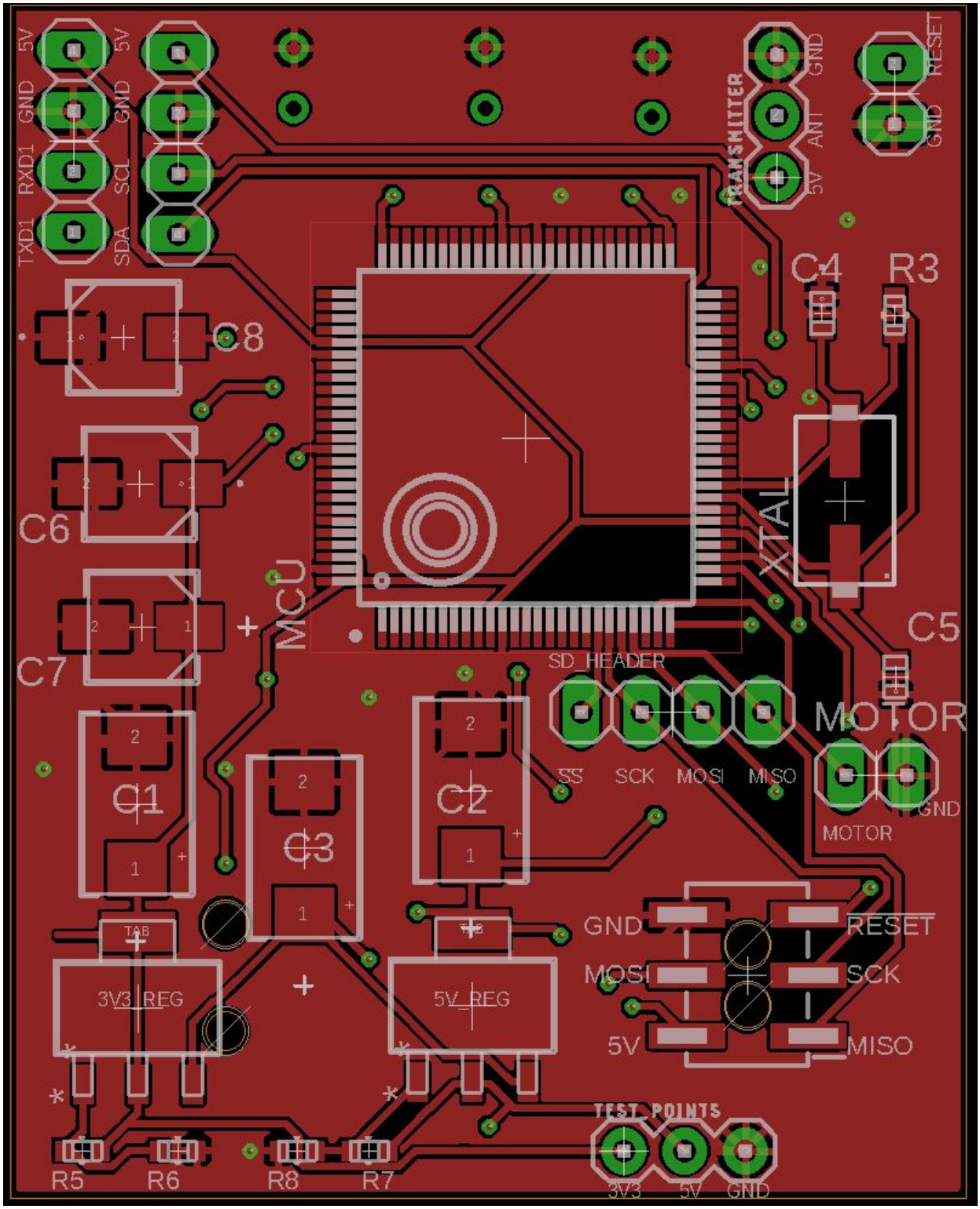


*Figure 21: Lock module PCB (top side only)*

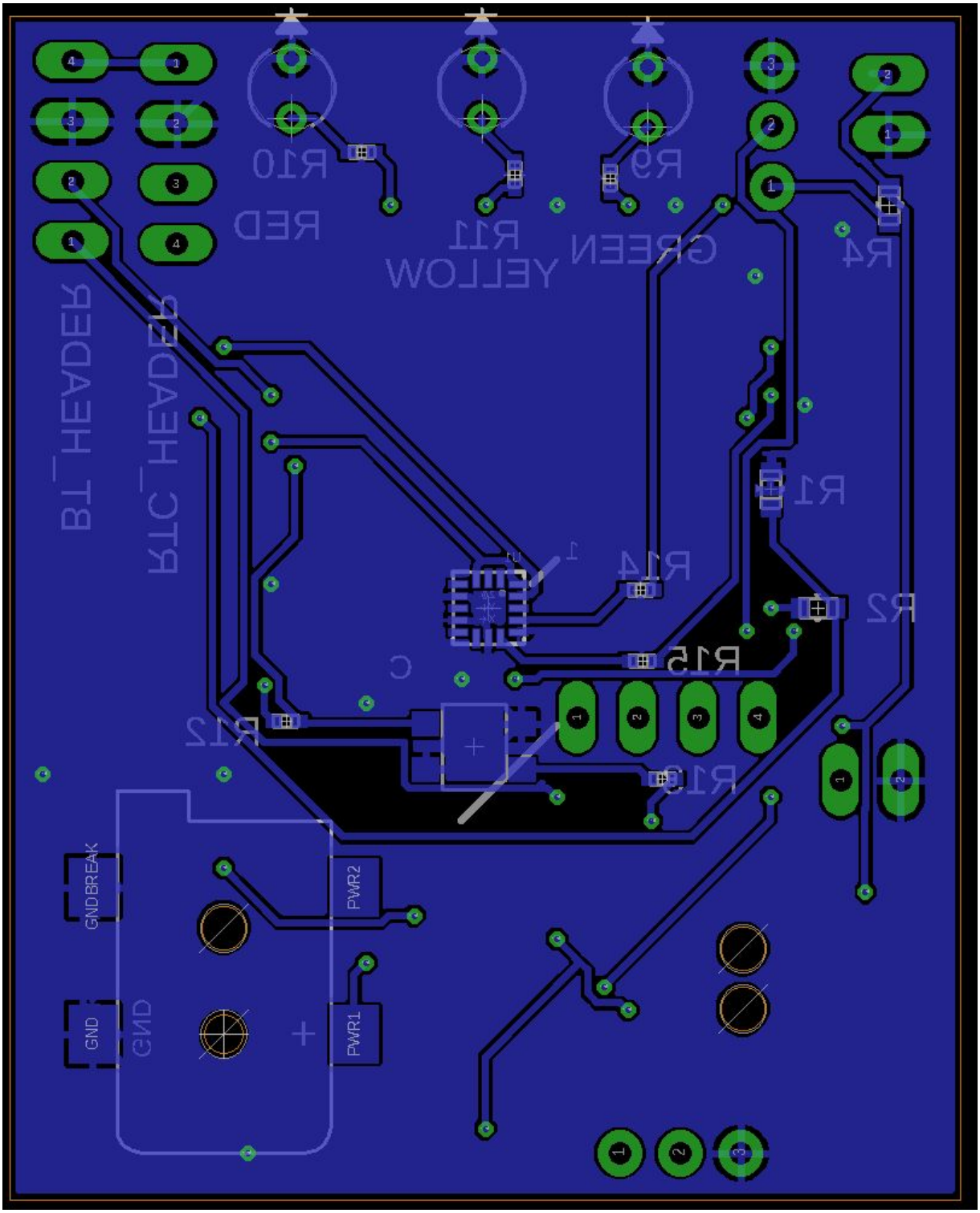


*Figure 22: Lock module PCB (bottom side only)*

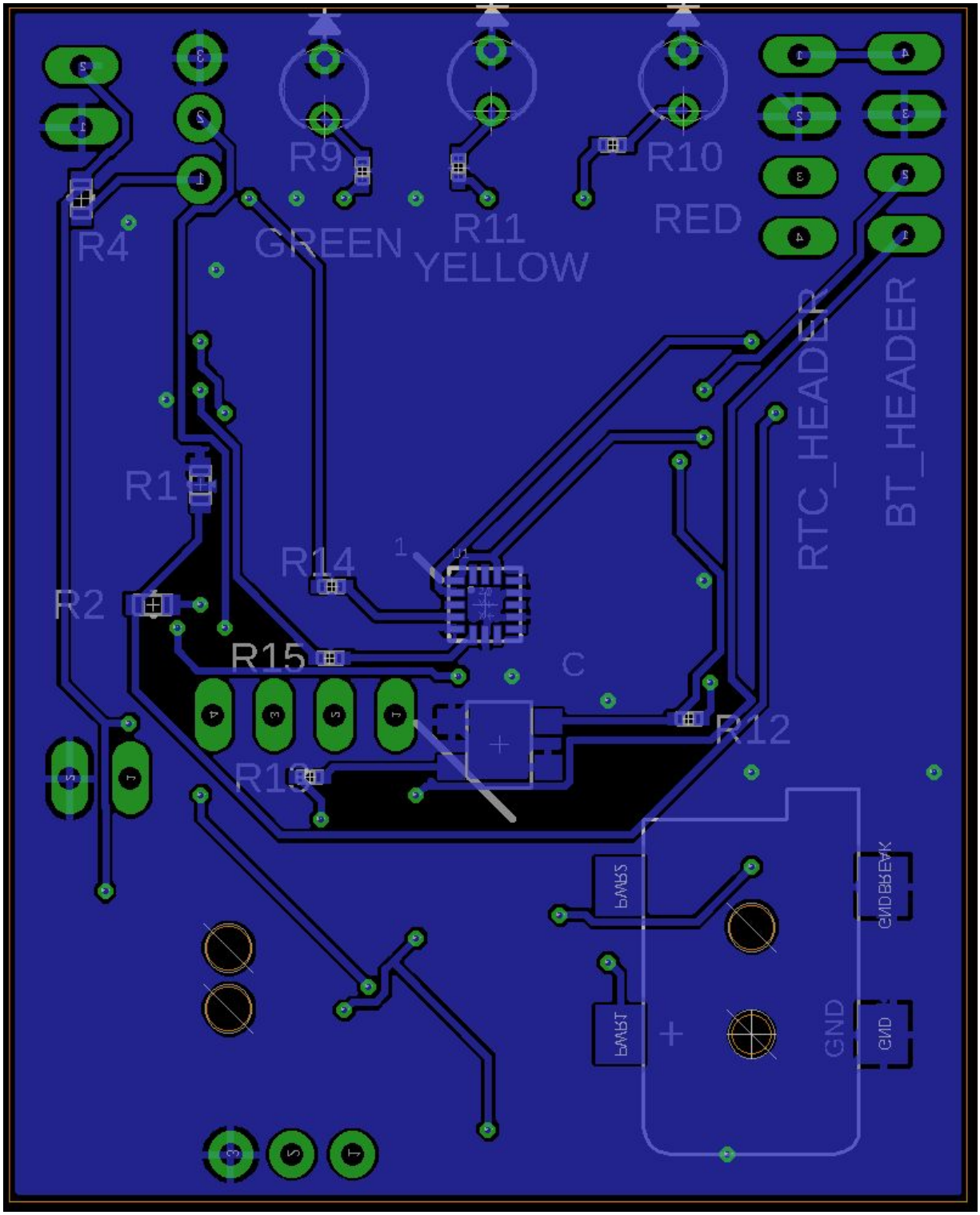


*Figure 23: Lock module PCB (bottom side only), mirrored so certain labels are more easily read*

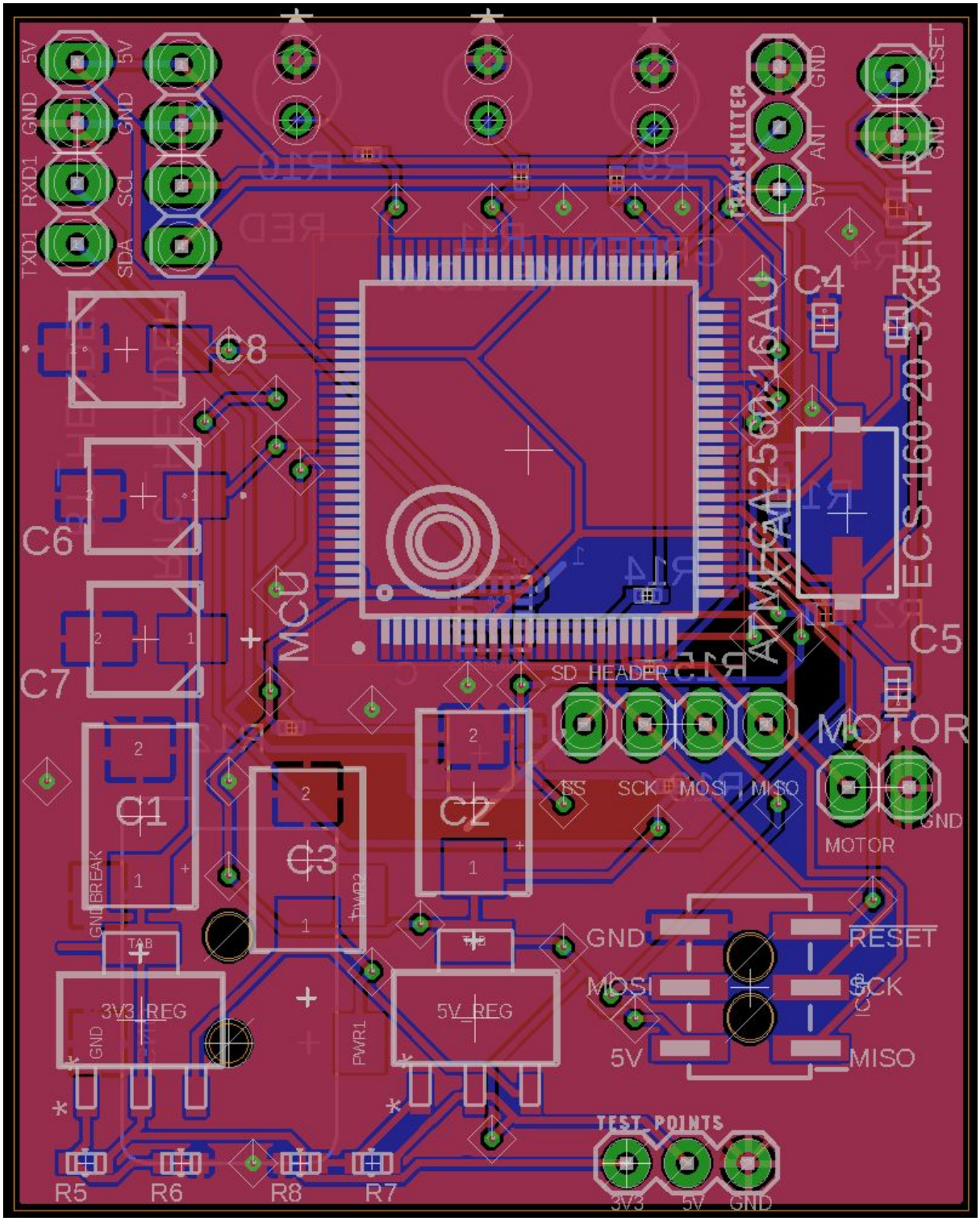


*Figure 24: Lock module PCB (complete layout)*

## Appendix D: Part Cost Tables

| 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 | S-17590 | Duracell | 1 | $15 |
| 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 |
| RF Transmitter | XD-FST | Arduino | 1 | $3.85 |
| Status LEDs | HLMP-1301 | Broadcom Limited | 3 | $1.23 |
| 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 | ERJ-3GEYJ105V | Panasonic | 1 | $0.10 |
| 10 kΩ Resistor | ERA-3AEB103V | Panasonic | 2 | $0.70 |
| 2.7 kΩ Resistor | ERA-3AEB272V | Panasonic | 1 | $0.35 |
| 2 kΩ Resistor | ERA-3AEB202V | Panasonic | 1 | $0.35 |
| 1.5 kΩ Resistor | ERA-3AEB152V | Panasonic | 1 | $0.35 |
| 1 kΩ Resistor | ERA-3AEB102V | Panasonic | 3 | $1.05 |

| | | | | |
|---|---|---|---|---|
| 330 Ω Resistor | ERA-3AEB331V | Panasonic | 4 | $1.40 |
| 100 Ω Resistor | ERA-3AEB101V | Panasonic | 1 | $0.35 |

*Table 11: 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 | SDDC-S1114 | Synergy Digital | 1 | $9.16 |
| 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 |
| RF Receiver | XD-RF-5V | Arduino | 1 | $3.85 |
| 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 | ERJ-3GEYJ105V | Panasonic | 1 | $0.10 |
| 10 kΩ Resistor | ERA-3AEB103V | Panasonic | 2 | $0.70 |
| 2.7 kΩ Resistor | ERA-3AEB272V | Panasonic | 1 | $0.35 |
| 1.5 kΩ Resistor | ERA-3AEB152V | Panasonic | 1 | $0.35 |
| 1 kΩ Resistor | ERA-3AEB102V | Panasonic | 2 | $0.70 |
| 330 Ω Resistor | ERA-3AEB331V | Panasonic | 4 | $1.40 |

*Table 12: Band PCB Parts Cost*