BeatLock

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***Abstract*—**BeatLock is a dance-based alternative to traditional door-locking mechanisms such as keypads and keys. The Beatlock system comprises a dance pad doormat, a two-factor authentication app, and a wireless door lock with a speaker and backup keypad. The purpose of BeatLock is to create a secure home locking system that provides more security than a traditional door lock and transforms the mundane task of unlocking a door into a fun and engaging experience. Compared to the current market, Beatlock is more secure than a traditional six-digit code, utilizing two-factor authentication and time-dependent dance moves.

***Index Terms*—Design, Bluetooth connectivity, Budget, Door lock, Doormat, Force-sensitive resistors, Functionality testing, PIN pads, Reliability testing, Risk mitigation, Security, Speaker system, Structural design, Two-factor authentication, Usability testing, Weather-resistant materials**

I. Introduction

BeatLock was conceptualized as a fun and lighthearted alternative to a regular key, keypad, or card swipe door access, recognizing the growing concerns around mental health within the younger generations. The users of this product will be young people looking for improved security and a fun experience to add to their home environment. This device would also provide customizable access and improved security compared to the more traditional methods mentioned. The intended use case for the system is in indoor doorways, such as the entry to an apartment or a bedroom in a house, though the design will consider weather-resistant materials to potentially allow for use in outdoor doorways as well.

Traditional door locks pose several problems in terms of security. With a key or keycard system, if the key or keycard is lost, the user loses their only way of entering their home. Additionally, it is possible for locksmiths to create copies of physical keys, and devices that can create copies of keycards are readily available to anyone. On the other hand, with PIN pads, the complexity of codes tend to be limited, and the passcodes can be easily copied by an outside user. Typical PIN pads only require 4 digit passcodes, of which there are only 10,000 unique options. Considering that some passcodes are chosen significantly more often than others (for example, “0000” or “1234”), and that passcodes are often chosen using personal information that may be available to an adversary, these passcodes are not very secure.

The BeatLock doormat mitigates these issues. The system itself employs a two-factor authentication process with the user's smartphone to begin the dance. This system prevents the challenge of maintaining a key or keycard with a backup PIN pad in the off chance that the user has lost their phone. Once the user has been verified and the song selected, a unique dance of ten or more steps is completed on the door mat, creating much more complexity than the traditional PIN pad in addition to adding an active element to the process requiring a further understanding of the system from any perpetrators. Once the dance is completed, the door lock opens, and the entire process takes as little as five seconds.

II. Use-Case Requirements

The following is a list of requirements according to our use case described in the introduction, broken down into three groups: security, hardware and software, and manufacturing.

Security

- The dance routine must create a passcode that is provably more secure than traditional passcodes.
- The backup pin must be a secure alternative in case the user is unable to use the app or dance mat.
- The mat should support multiple songs and dances to provide customization.
- It should be difficult for malicious onlookers to memorize and replicate the dances or discern what the backup keypad code is.

Hardware and Software

- The app, mat, and lock should be connected via Bluetooth to remove the need for Wi-Fi or physical wires.
- The app, mat, and lock Bluetooth connections should happen in a timely manner such that the user is not left waiting for anything to connect.
- The dance pads must have a very low failure rate in regard to step detection so that the user experience is not negatively affected.
- The speaker must play music loud enough to be heard but not loud enough to injure the user’s hearing or to be heard by the neighbors.
- The batteries in the lock and mat must be exchangeable and should last at least one month.

Manufacturing

- Materials and structural design must be able to withstand the weight of most people.
- The dance mat must have some traditional rough doormat material for users to clean their shoe soles with.
- The dance mat must have a bright visual if thicker than a quarter inch so that it is not a tripping hazard.
- The mat materials and design should be able to get wet without breaking, to the extent that it can be used on covered patios or in indoor hallways with potentially wet shoes.

III. Architecture and/or Principle of Operation

The BeatLock system starts with the "BeatLock" mobile application, which can be accessed on their smartphone. On the app, they can scroll through a list of songs and select the song that they plan to use. Using the app automatically activates the mat and verifies that the user is a legitimate user. The result is a secure two-factor system that also enables unique systems for multiple users of the same device. In the case where a phone is not available, a backup PIN keypad is present on the door lock to allow the user to bypass the phone application step. From there, the user can step on the doormat, music is played, and they can perform the required dance.

The uniqueness of the BeatLock system comes from the implementation of a dance pad system in an entryway doormat. The doormat has four foot pads that activate using force-sensitive resistors at each of the foot pads' four corners. When a change in force is detected that indicates a step, the microcontroller can track the timing and order of the step and verify that this was done correctly internally. Once this is done correctly, the door lock will unlock for the user, and it can be promptly locked again by pressing the keypad, similar to other smart lock systems.

The entire system is designed with simplicity from the perspective of the user. This is to maintain a quick and justifiable usage of the doormat. As a result, the three parts of the BeatLock system: the phone application, door lock, and doormat, will all communicate wirelessly with the hardware running off of built-in rechargeable batteries. Additionally, the minimum step count will be ten steps. If the user wants quick entry, this ten-step minimum remains secure yet can be done in around five seconds, assuming they can step at 120 beats per minute. This should result in very short and achievable dance codes that are highly secure.

We used several principles of engineering in the completion of our final product. Firstly, we acknowledged that our entire system comprised three separate modules, connected together via modular integration. Furthermore, each module contained several independent functionalities that could be separated into components implemented separately. So, we broke down one large problem into many smaller problems, which made the development of our project much more manageable. We also recognized the importance of verification and validation of our product, which is an imperative part of the engineering process. Additionally, we used several engineering principles specific to the technologies we used, such as how FSRs work to detect weight, how servers and clients interact, and how audio is transmitted and amplified.

In addition, we used several principles of science in the completion of our final product. Most importantly, we have pursued honesty and openness when it comes to our project. Falsifying data or making false claims about our project has never been considered an option by any team member, because that would take away from the integrity of our team and the accomplishments that we have made during the semester. Furthermore, we have strived to perform verification and validation with quantitative data and empirical observations.

Lastly, we used several principles of mathematics to guide the design of our final product. Security is at its core a mathematical concept, and our numerical calculations of security were used to determine how to structure our dances and keypad combinations. Additionally, our correctness algorithm, which determines whether or not a dance is considered successful, is based on Gaussian distributions, a concept stemming from probability theory. By using probabilistic distributions to determine the correctness of each dance move, we are able to quantify correctness continuously instead of discretely.

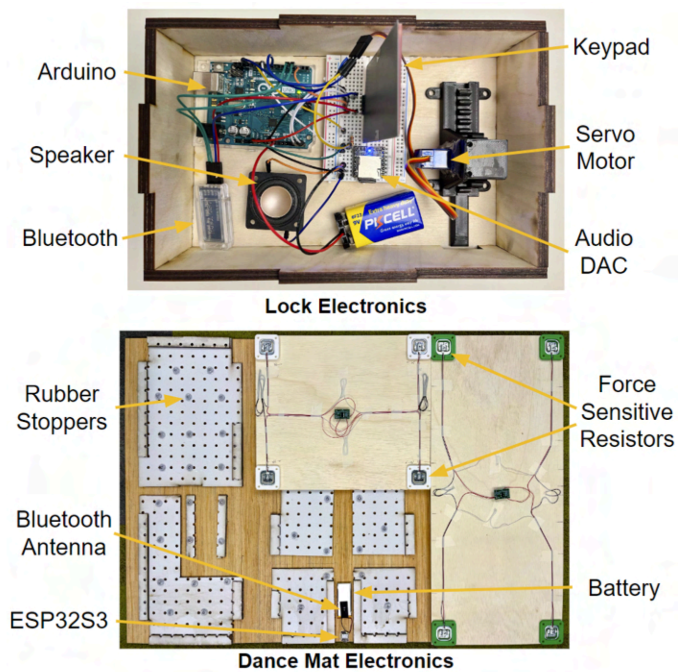

Fig. 1: Lock and Dance Mat Electronics, Labeled

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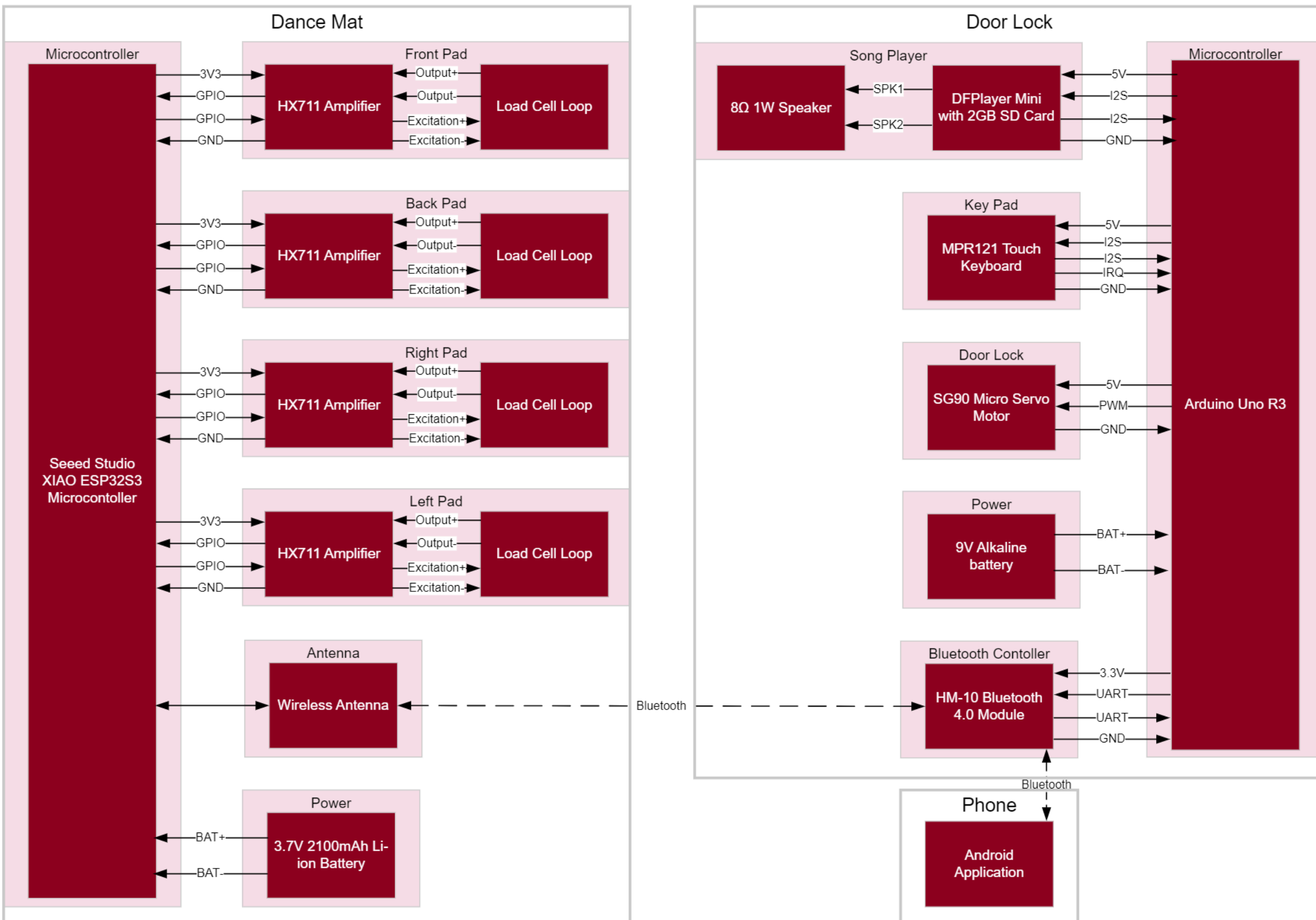

Fig. 1. Full Block Diagram of BeatLock

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IV. Design Requirements

The following is a list of design requirements according to our use-case requirements, broken down into three groups: security, hardware and software, and manufacturing.

Security

- The backup pin must be at least six digits long. The keypad should have twelve possible digits to maximize the number of passcode combinations.
- The mat must work for at least one song for MVP and more than one song post-MVP. So, the mobile app must provide a function to choose between songs. Furthermore, an SD card should be added to take into account the memory requirements of audio recordings.

Hardware and Software

- Bluetooth connectivity must be added to the mobile app, the mat module, and the lock module. This requires an add-on Bluetooth component to be connected to the Arduino UNO R3.
- The weight sensors must detect the existence vs. non-existence of dance steps with 99% accuracy.
- The song playing from the speaker in the door lock must begin within 100 milliseconds in relation to detecting dance routines on the mat.
- The speaker must operate within 100Hz and 15kHz to capture most of every song and must output songs at around 70 dB and no greater than 85 dB for audio safety.
- The batteries in the lock and mat must be exchangeable and should last at least one month. Replacement batteries must be easy to source, or the battery could be rechargeable.

Manufacturing

- Materials and structural design must be able to withstand up to 300 lbs standing force, the 95th percentile of American males.
- Extra space on the mat (at least 36 in^2) will be made of a traditional rough door mat material for users to clean their shoe soles with.
- The dance mat must have a bright visual if thicker than a quarter inch, constituting the minimum height of a tripping hazard. Components like foot pads will be made with 3D printed materials in bright colors like pink and yellow.
- The mat materials and design should reach an IPx3 water resistance rating, described as withstanding spraying water.

V. Design Trade Studies

The following lists design specifications to meet use case requirements and their accompanying discussion of design tradeoffs, as well as additional trade-offs found in the BeatLock system and its subsystems.

A. Design of Foot Pad Placement

A trade-off for the dance mat that impacted our design of the mat layout was the starting foot placement before beginning the dance versus the size of the overall mat. This tradeoff correlates with the requirement of successful step detections, as the user standing before the dance should not be considered a dance step. We opted to have the user stand in the middle of the mat partially on both the front and back arrow foot pads. This placed a greater emphasis on ensuring the timing of the beginning of the dance detection and differentiating between the user standing and dancing. As a tradeoff, the mat will be slimmer than a design with a neutral middle to stand on, keeping within reasonable door mat dimensions. Fig. 1 demonstrates the sizing and foot pad placement tradeoff.

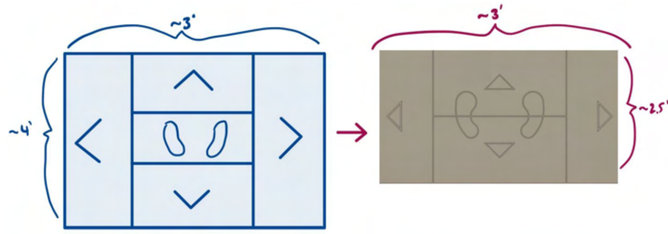


Fig. 1: Foot Pad Placement and Mat Sizing Tradeoff

B. Designing for Slimness and Weight Allowance

Addressing the design requirements of having the dance mat withstand 300 lbs, the weight of the ninety-fifth percentile of weight of American males, and the thickness of the mat not posing as a tripping hazard, as OSHA defines as a quarter of an inch, we observed a trade-off. As the thickness of the mat decreased, it was observed that the weight tolerance of the mat would also decrease, or the material would be too pliable to allow for step detection. Due to budget constraints, stronger and thinner materials, such as true polycarbonate, were not viable options. As such, we had to compromise on the thickness of the mat to ensure that a broader population had the ability to use our product. Our final mat design consists of 6mm plywood foot pads, 5mm pegboard spacers with 6mm rubber stoppers, and a 3mm plywood base. See Table 1 for additional information on the materials that were tested for the foot pads.

Material	Functionality
6 mm plywood	Supports appx. 1800 N, partial flexibility, no waterproofing
Polycarbonate	Supports appx. 1800 N, complete flexibility, complete waterproofing
Steel Supports	Supports appx. 1800 N, complete flexibility, unnecessary bulk

Table 1: Comparison of Foot Pad Materials

C. *Force-Sensitive Resistors*

The tradeoff we found to exist for the force-sensitive resistors used for step detection in the foot pads was assembly time and accuracy. This directly impacts the step detection requirement defined by our use case. More FSRs provide more sensitivity to weight distribution changes but include more wiring and circuitry, whereas fewer FSRs mean a decreased ability to detect weight distribution changes but also a decreased amount of wiring and circuitry. While we decided on kits of four FSRs with a breakout board, another option we considered was using force-sensitive resistive sheets, which would have been much cheaper but also much more difficult to fine-tune.

D. *Placement of Speaker*

Another tradeoff concerning the dance mat is the placement of the speaker. Originally, we were going to place it within the mat; however, this raised two concerns: the increased thickness of the mat, resulting in a greater chance of users tripping, and the vulnerability of the speaker, as it would be subjected to the force of users stomping on it. The tradeoff here was centralized sound from the mat versus speaker integrity. As suggested to us by Professor Gary Fedder, we moved forward with a design where the speaker is located in the door lock housing; this forfeits centralized sound but protects the speaker. As will be discussed in a later trade-off, however, this decision was perhaps not the best given the microcontroller used in the lock.

E. *Audio Clarity and Volume*

The design requirement of speaker outputting at or less than 75 decibels for safe listening introduced another trade-off. Originally, the speaker was directly connected to the Arduino. However, since the 5V digital pins have a current limit of 40mA, by the power equation (1), the 1W speaker we were using was receiving insufficient power to output any substantial audio.

$$V(V) \ * \ I(A) \ = \ P(W) \qquad (1)$$

We then built an amplifier using an LM386 amplifier and various capacitors and resistors, but the audio quality was significantly decreased. To solve this problem, we switched the amplifier circuit for a DAC amplifier module, the DFPlayer Mini, which allowed us to amplify the mp3 files further and consolidate the lock electronics with a built-in microSD card reader. However, as discussed in the next trade-off, the DFPlayer Mini requires I2C communication, posing a significant challenge to the lock design.

F. *Lock Microcontroller*

The lock microcontroller was originally designed to be a Seeed Studio Xiao ESP32S3; however, due to hardware incompatibility with the capacitive touch keypad, the lock microcontroller was switched to an Arduino Uno R3. Two trade-offs emerged because of this. First, the ESP32S3 had built-in Bluetooth capabilities, whereas the Uno R3 did not have Bluetooth and required a separate Bluetooth module. The change thus added complexity and bulk to the lock design but allowed us to move forward with using the capacitive touch keypad, as the Arduino Uno R3 has the necessary AVR hardware. Second, the Arduino Uno R3 can facilitate only one I2C line at one time. This became a detrimental design oversight on our part, as both the Bluetooth and DAC amplifier modules required I2C communication in the lock.

G. *Locking Mechanism*

Another trade-off of the lock was with the power consumption versus the visual aesthetic. The solenoid lock that we originally purchased was visually appealing, as it had an actual metal deadbolt, but it required much more than the 5V that the Arduino supplied it to operate correctly. Because power consumption was the higher priority, we switched to a micro servo motor with a 3D printed linear actuator; this could fully function on the 5V digital pins of the Arduino Uno R3, however, the linear actuator only vaguely resembled a lock deadbolt.

H. *Primary Security*

Our team met with Dr. Lorrie Cranor at the beginning of the semester to discuss security measures and possible holes in our design. From this, we discovered a tradeoff between security and entry time. While the user would like to gain entry to their home within fifteen seconds, the BeatLock system must have secure enough measures and backup measures to attain or better the market standard. Using the Apple iPhone facial recognition as an example, our mat is similar to facial recognition in being the most secure and primary option; just as facial recognition is not always a viable way to unlock the iPhone, there will be times the user cannot use the dance mat due to a dead phone, a dead mat, or even personal injury preventing the ability to dance. Therefore, just as Apple's backup to facial recognition is the four or six-digit pin that most of society deems acceptable security, we have opted for the six-digit keypad as our system's backup, recognizing that the keypad is a less secure but still secure option.

I. *Back-Up Entry Options*

There were four backup entry options that we considered, each with pros and cons. This tradeoff is concerned primarily with the security requirements of our use case. These options and their comparison are as follows.

The first option was to put a backup pin option in the two-factor authentication phone app. The main issue with this solution is that there is a reliance on the phone having a charge; one of the main reasons anticipated for needing a backup entry option is the user's phone having a dead battery and is, therefore, unable to communicate with the dance mat. As such, using the phone as a backup would not be a reliable option.

Similarly, the second option, using the phone's digital wallet, would not be a viable option for the same reason as the app. Although this would be an appealing selling point, having a digital ID loaded into the user's digital wallet still relies on the user's phone being charged at the end of the day.

The third option we considered was having a keypad raised in a corner of the dance mat. Although this moves us away from reliance on the user's phone, it would be in a rather awkward location, requiring the user to crouch down to enter their PIN.

The fourth option we came up with was to include a keypad in the door lock, as in traditional door locks. This makes the most logical sense, though we were concerned about possible security issues, such as an onlooker watching and recording the pin sequence. Because of this concern, we believe that to make this the most viable option, a flat, capacitive touch keypad could be implemented with a piece of opaque acrylic or similar material thinly covering the keypad to conceal the numbers.

J. Wireless Connectivity

The final tradeoff we are concerned with is the method used for wirelessly connecting the phone app, dance mat, and door lock. The two options available are Wi-Fi and Bluetooth. The tradeoff that exists here deals with our team's current knowledge and skills in implementing either of the two options and what the user is likely to prefer. With Wi-Fi, our team has experience implementing this method of connection, however, the user is likely less inclined to want this, as it requires that a stable internet connection be provided, which cannot be the case in a power outage. With Bluetooth, our team has minimal experience implementing this technology and will require more time researching, assembling, and testing the system; however, Bluetooth is a much more reliable option, relying only on user proximity to the mat and lock.

VI. System Implementation

The BeatLock system is broken down into three subsystems: the phone application, the dance mat, and the door lock. These subsystems communicate wirelessly with each other. This section is devoted to going into detail about how each subsystem will be implemented.

A. Two-Factor Authentication App

The two-factor authentication app was developed using React Native and Expo. Since apps created using Expo Go cannot use Bluetooth (react-native-ble-plx package), we pivoted to using Expo EAS Build instead of Expo Go. The app was tested and deployed on an Android Galaxy Note 5, with Android 7.0 as the operating system. BLE permission checks were implemented such that the app could also be run with Android >12.0 and iOS.

The app consists of a splash screen page, a song selection page, and a transmission page. The details of each page are as follows:

- The splash screen page showcases our unique logo in a repeated pattern. While on the page, the app checks for Bluetooth permissions and requests Location access for Bluetooth <12.0. Bluetooth permissions required for Bluetooth <12.0 are BLUETOOTH, BLUETOOTH_ADMIN, and ACCESS_FINE_LOCATION. Those required for Bluetooth >12.0 are BLUETOOTH_CONNECT, BLUETOOTH_SCAN, and BLUETOOTH_ADVERTISE. Once permissions are loaded, users are taken automatically to the song selection page.
- The song selection page contains an image and title for each song. The page is scrollable, so more songs can be added without running out of space. When the user clicks on an image, they are taken to the transmission page.
- The transmission page confirms to the user that their song has been selected and is being sent to the mat. On this page, the app initializes itself as a BLE client and searches for the XIAO ESP3S3 microcontroller in the mat based on its name and Service UUID. Then, it sends the song choice of the user, encoded as an integer.

Focus was placed on creating a sleek and refined user interface as well as an easy and enjoyable user experience. Our logo, colors, and custom font (Timeburner) were used to improve the aesthetics of the user interface, and the layout of the app was chosen to make it straightforward to use, even without any instructions.

B. Dance Mat

The doormat consists of a microcontroller, dance pads, antenna, and power device. The details for each component are as follows:

- The microcontroller chosen was a Seed Studio Xiao ESP32S3. This was chosen for the compact size, low-power settings, and multiple ports for the many connections required.
- The dance pads consist of a loop of four generic load cells with a total weight measurement capability of 200 kilograms for each pad. To digitize and amplify the output of these loops, an HX711 Amplifier is used as this is a popular, affordable option with sufficient frequencies for the application.
- The power system uses a 3.7V lithium-ion polymer battery with the ability to be recharged and a high capacity to last a long time.
- The antenna will be the integrated antenna extension that comes available with the Xiao ESP32S3.

The mat will use rubber stoppers, 3D-printed plastic FSR holders, plywood, pegboard, and adhesive grip tape for the construction. This will keep the durability of the device at a maximum with metal supports and make sure it is immune to environmental factors if the rubber encloses the entire system.

C. Door Lock

The door lock comprises a capacitive touch keypad, an Arduino Uno R3 microcontroller, a micro servo motor and a 3D-printed linear actuator door lock, an external Bluetooth module, a battery, a speaker, and a plywood exterior to house the electrical parts. The block diagram for the connection of these components is found in Fig. 2. Specifically, the parts that our team has decided to move forward with are as follows:

- The capacitive touch keypad chosen is an MPR121 Proximity Capacitive Touch Sensor Controller. For general functionality, the example code[10] was utilized and modified for our specific implementation.
- The microcontroller currently decided on is the Arduino Uno R3 due to its compatibility with the

capacitive touch keypad and the Arduino's ease of use and expansive documentation.

- The door lock mechanism we have chosen is an SG90 micro servo motor. This servo motor was fixed to a 3D-printed linear actuator, found on Thingiverse[9].
- The Bluetooth module chosen is an HM-10 Bluetooth 4.0 module.
- The battery chosen is a 9V alkaline battery. The Arduino Uno R3 requires 7-12V, attached to the VIN and GND pins. During testing and for the final demo, we found issues with the voltage stability and connection. With more time, we would have ordered and tested other battery options that may have been more stable. In its current state, the lock requires power from its USB connection.
- The speaker we have chosen is an 8-ohm, 1W speaker used in 18-100, the introductory electrical and computer engineering course at CMU. We ordered more robust speakers to implement in the lock; however, these speakers required more power than the current speaker, which would have increased audio clarity issues. We found that as the volume was increased through the DFPlayer Mini and when the Arduino was powered via USB, there was less "crackling" in the background of the speaker output. Because of these observations, we could safely assume that the nicer speakers, operating at 3W, would have worse audio quality on this specific system.
- The laser-cut housing was modeled in Fusion360 and converted to cuttable files on Adobe Illustrator, as shown in Fig. 1. The housing is made out of 6mm plywood found in the scrap material in Ideate. If given more time, the housing would be better made with a thin, 3-D printed shell, allowing for a more compact design and better speaker quality, as the 6mm plywood muffled the speaker pretty substantially. The Fusion360 model and Illustrator file can be seen below.

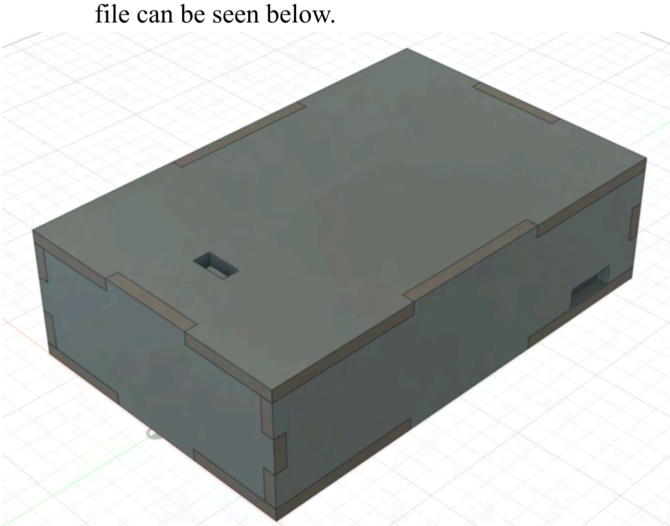


Fig. 1: Fusion360 Model of Lock Housing

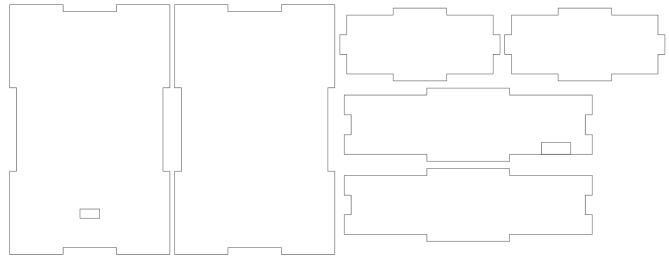


Fig. 2: Adobe Illustrator File for Laser Cutting Lock Housing

During the final integration of the three subsystems, it was found that the Arduino in the lock could not adequately handle the Bluetooth module, the DFPlayer Mini, and the capacitive touch keypad simultaneously due to having only one I2C line available. We attempted to implement a pseudo-concurrency for the three devices, however, this was in the last days of the semester. Given more time, we would likely swap the Arduino Uno R3 for another Arduino, such as the Arduino Mega, or another microcontroller that has both the necessary AVR architecture for the keypad and the two I2C lines for the Bluetooth and amplifier modules.

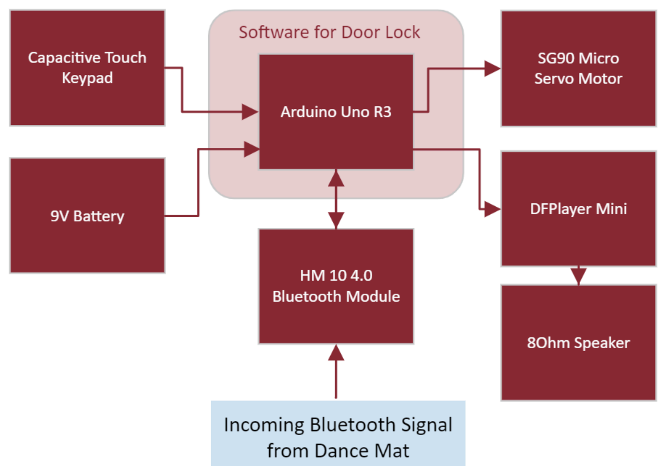


Fig. 3: Updated Lock Block Diagram

VII. Test, Verification and Validation

We tested our product in three major areas: functionality, usability, and reliability. Functionality testing ensures that the user of the product experiences the correct functionality from the product. Usability testing evaluates the usability and user experience of the product. Reliability testing ensures that the product remains functional after consistent use. In the following section, testing and verification plans and results for major use-case and design specifications will be discussed.

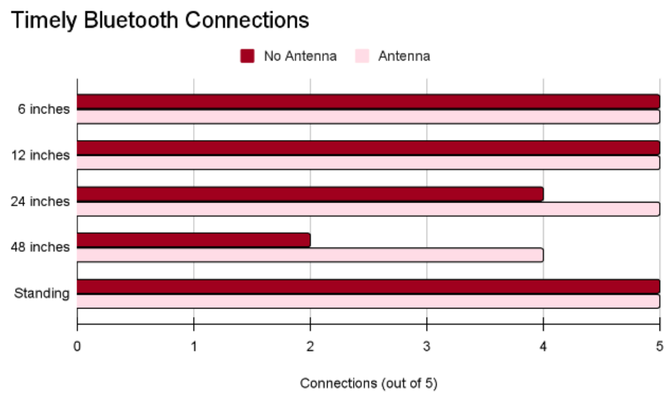
A. *Results for Backup PIN Design*

The backup pin must be at least six digits long to match the security of existing door lock keypad options. In testing, the door lock should open upon providing the correct six-digit pin 100% of the time. Reliability testing will be performed to ensure that using the backup pin always opens the door and never causes any errors. The keypad will be used to open the door 100 times, and the test will be considered a success if the door opens 100 times without any errors.

After testing the backup keypad, it was found to perform exactly as expected. The system worked extremely well with every tap being detected without error. The system was found to perform quickly and easily providing the additional function of locking the door when the user needs to lock it from the outside.

B. Results for Dance and Bluetooth Timing

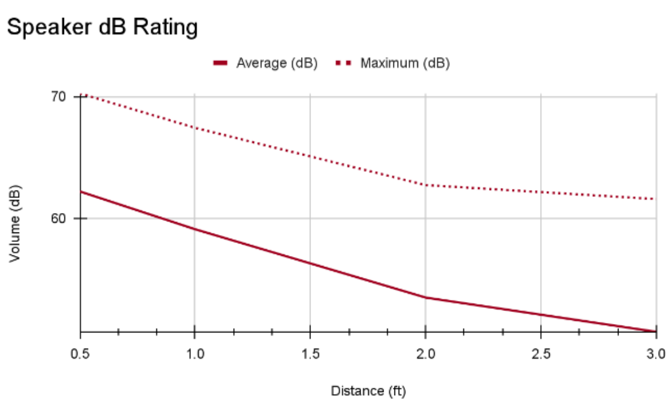
The song audio must begin at the same time relative to the dance step detection on the mat. Functional testing will involve starting the system multiple times using the same song and dance routine combination and measuring the timing via software. If the timing is off by more than 100 milliseconds, the difference may be noticeable to the user, so changes must be made to decrease the timing difference. The system must also connect within short time frames or else it fails as a sufficient alternative to current door lock systems.



In testing it was found that adding an antenna to the door mat's electronics allowed for the system to perform as intended. Once it was attached, all systems were able to quickly connect to each other without any lag between systems that would be noticeable or any lengthy wait times.

C. Results for Speaker Decibel Levels

The speaker must operate within 100Hz and 15kHz and must output songs around 70 dB (no greater than 85 dB) for audio safety. Functional testing will involve, for all current songs, using a sensor to detect the dB levels. If the dB levels are too high for any songs, the volume will be turned down in the software.



After testing, we found that the speakers functioned as intended, functioning in the 60-70 dB range for all reasonable distances and remaining sufficiently audible without exceeding safe hearing levels of at or below 75dB[1]. This volume level also works well in an environment such as an apartment building, proving adequate for the target audience of the device.

D. Results for Dance Mat Weight Tolerance

Materials and structural design must be able to withstand up to 300 lbs standing force, the 95th percentile of American males[2]. Testing will involve stress testing the FSRs and mat construction. 300 lbs standing force will be applied to the mat components for 200 trials, with 15 dance moves per trial. Assuming the average person unlocks their door twice a day, this amounts to 100 days of usage. The sensitivity of the weight sensors will be measured before and after this test in software to see whether the test affects the quality of the sensors. In addition, the product will be examined for any external damage.

The testing found that many upgrades needed to be made throughout the design process. The final design was tested successfully with the usage of 6mm plywood pads, rubber stoppers distributed approximately 50mm apart, and wooden supports in areas with sensitive electronics. Additional tuning was necessary in the final iteration of the dance mat, as the sensors were initially too sensitive for heavier weights.

E. Results for Dance Mat Sizing

The dance mat must have at least 36 in^2 of a traditional rough door mat material for users to clean their shoe soles with. Usability testing will involve having multiple users try to clean their shoes using our mat and asking about their experience with our mat, compared to their past experiences with other doormats. The goal of our product is to provide an equivalent experience to other doormats.

With the addition of multiple layers of textured rubber covering the entirety of the mat, both of these requirements were found to be accomplished. Users noted how the device looked and functioned like any other doormat they had seen and was functional and aesthetically pleasing.

F. Results for Dance Mat Waterproofing

The mat materials and design should reach an IPx3 water resistance rating, described as withstanding spraying water. Reliability testing will be conducted on the mat after manufacturing. 30 trials will be conducted, each trial involving getting the mat wet with water from a spray bottle and drying the mat with paper towels and an electric hair dryer. After the trials, we will check the integrity of the housed electronics using visual inspection and continuity testing. If there is any water visible in the electronics, or there are closed circuits between parts that should not be connected, the test will fail.

Testing this had found that the device exceeded these standards. The rubber coverings allowed for water to be sprayed as well as spills on the mat. Even with significant spills of water, the mat retained the integrity of its electronics and its functionality as a doormat, with its grip still remaining.

VIII. Project Management

A. Schedule

See Gantt Chart in Figure 2. The schedule changed from our design document in several ways in order to accommodate for the outside responsibilities of team members and to work around unforeseen problems that made tasks harder than anticipated. Due to our busy schedules outside of the class, some tasks were unfortunately pushed back for several weeks, which led to less time for integration and testing. In addition, some problems arose, which caused some deadlines to be pushed back. For example, it was determined that the DFRobot Bluetooth module was not a good fit for our project, and we ordered an HM-10 Bluetooth module to replace it. It took three days for the new part to ship, which blocked us from finishing the lock module's Bluetooth connectivity for three extra days.

B. Team Member Responsibilities

Each member of the team had distinct responsibilities that took advantage of their strengths and backgrounds. Zoe developed the software for the mat and the mobile application because she has a background in software development and embedded systems. Brooke and Jada have similar backgrounds in circuits and hardware development, so they split work in these areas by the module. Brooke worked on the circuitry and hardware in the mat, and Jada worked on the circuitry and hardware in the lock as well as the software for all lock modules aside from the Bluetooth module. All members of the team worked together to integrate the systems. Zoe ensured that the Bluetooth connection between the app, mat, and lock worked. Then, Jada and Brooke integrated their parts with the existing software. In terms of testing, in addition to testing for the functionality of their individual systems, Jada focused on functional testing primarily on the lock electronics, Zoe focused on usability testing primarily on the mobile app, and Brooke focused on reliability testing primarily on the dance pad sensors.

Fig. 2. Gantt chart

C. Bill of Materials and Budget

The Bill of Materials for our project is located in Table II on page 12. Items that we decided not to buy are marked by strikethrough. We did not have a problem staying within our maximum budget of $600.

D. Risk Management

Throughout the semester, we handled multiple project risks from the standpoints of design, schedule, and resources and used fallback designs and risk reduction measures to mitigate risk.

One risk that we attempted to mitigate was that different software and hardware components would not be able to effectively and consistently communicate. We have three different modules that must wirelessly communicate with each other: the app, the mat, and the lock. Furthermore, the mat and lock modules consist of several components that must work together to perform their tasks. Without good communication, the product will not work as intended. To mitigate this risk, we conducted thorough testing of our Bluetooth communication protocols as early as possible in our assembly process so that we could identify problems early enough that we had enough time to debug. Something we did not prepare for was that the simplicity of the microcontrollers could disallow our communication protocol from working concurrently with our other components on a given microcontroller. We ran into this problem when trying to use the HM-10 Bluetooth module at the same time as the DAC amplifier because both required I2C, and the Arduino Uno R3 board only has one I2C line.

Another potential risk was in the design and method of manufacturing of the dance mat itself. The mat had to be thin but also strong, and it had to fit the required electronics. If the design or manufacturing process was done poorly, or the incorrect parts were ordered, these requirements would not be met. Although the CAD model was sufficient to meet our requirements, translating this model to be a real product posed some challenges.

Additionally, there was a risk associated with ordering and testing components. If there were shipping delays after we ordered parts, it would set us back in terms of testing components and manufacturing. This risk was mitigated by ordering components early and by splitting up work so that there was always work to be done that was not dependent on incoming components. In addition, we considered that testing components might take up a lot of time if the code or method to use the components is difficult to understand or if none of us have used a similar component in the past. To mitigate this issue, we bought highly rated parts when possible because these are often simpler and are likely to work as intended. We also gave ourselves a lot of time to do component testing because it often took a while to figure out how to get a component to work.

IX. Ethical Issues

There are several ethical issues related to our product that have been considered throughout our design and manufacturing. These issues can be divided into three categories: safety and public health, social awareness, and economics.

First, several considerations were made regarding the safety of the product for users. As a door lock system, this product stands as a front-line defense against dangerous crime, so the security of the product must be ensured. The product must be at least as secure as the forms of home security with which it has been compared. In addition, public health was a motivator for the design of the product. One benefit of using a dance pad as a keypad is that dancing provides physical and emotional benefits. As such, it was imperative that our design maximizes these benefits while minimizing the effects of the product that might negate these benefits. For example, if the product is frustrating to use, this would overshadow the fun of dancing.

Next, social issues were also considered while designing this product. We wanted to make the product usable for as many people as possible. To do this, we designed our product to withstand force from the weight of the majority of people. We decided to have an upper limit of 300 lbs, which is the 95th percentile weight of the American male. We also consulted people of different heights when deciding how large to make the mat and where to place the foot pads so that the dance experience would be comfortable for all users. Unfortunately, due to the diversity of the human population, there will be edge cases who cannot use our product. These would include people above 300 lbs, non-able-bodied people who cannot dance, and people with a body type that would not allow them to dance comfortably on the mat. To mitigate adverse impacts, the best option would be to provide several products that cater to different individuals. For example, non-able-bodied users would prefer a tablet-sized dance pad where they could perform the dance with their fingers, and there could be different-sized dance pads to cater to people with different body types. On the other hand, while we aimed to create a product that was inclusive towards most people, we recognized that there was a small target audience for this product, and with this in mind, we chose to design the product to appeal to this specific audience. Our target market was active young adults who lived in dorms or apartment complexes.

Lastly, economic issues were taken into consideration when deciding the design of this product. Based on our target audience, we knew that the product should be as affordable as possible. So, we made efforts to use affordable materials and to limit the electronic components used in our product.

X. Related Work

There are several related products that inspired the creation of BeatLock. In short, our product is a fusion of a dance mat designed for arcade games and a security system based on biometric passcodes.

The inspiration for our doormat was the Dance Dance Revolution dance mat. The most well-known arcade dance mat is a type of hard mat, which is usually made of metal due to its strength and durability [5].

In 2008, Google introduced Android lock patterns – a password system in which 9 nodes are presented to the user in a 3 x 3 grid, and the password is a continuous pathway between the nodes. It has been in use for 15 years by millions of people worldwide. There are 140,704 combinations of patterns to be used as passwords. However, according to Marte Løge of the Norwegian University of Science and Technology, this system of pattern-based passwords is not very secure. 44% of passwords start in the top-left corner, and 77% start in one of four corners. A significant number of patterns used only connected 4 nodes, which reduced the number of potential combinations to 1,624 [6]. While Android lock patterns might be secure if used as intended, the human tendency to choose the same patterns and limit the length of the patterns reduces the security of the system.

Gait-based biometric systems for user identification and security have been proposed for various applications. These involve analyzing a user's unique foot shape and kinesiological movements to identify the user, similar to fingerprint and facial recognition. Given the variability and uniqueness of individual behavior and movement patterns, these gait-based biometric systems propose a promising alternative to current security measures [7].

While there are many related products, no other security system has used a dance mat doormat and lock interface as used in our product.

XI. Summary

Our system was able to meet most of the design specifications. Limits on our system's performance include the Arduino system and the wooden materials. To improve the system performance, we would improve the materials used and cut down on the bulk of electronics. The materials were sufficient in creating a functional device but things could always be improved. The Wheatstone bridge could potentially be replaced with a force-sensitive material cutting down on thickness and weight with sufficient tuning and the wood could be replaced with polymers with further development. The lock may also have the ability to be more aesthetically pleasing with a smaller design with the electronics being smaller than the final design and the power consumption problems sorted out with the solenoid lock.

There are several lessons we have learned throughout the completion of this project that would be beneficial for other student groups in future semesters to be aware of. First, it is more complicated than it seems to choose microcontroller architecture and components that work with each other and do not cause issues during integration. Second, we did not allow for enough time to integrate our system fully, and this led to issues with the compatibility of our different parts and the reliability of our system in general.

Glossary of Acronyms

PIN– Personal Identification Number
FSR– Force-Sensitive Resistor
BLE– Bluetooth Low Energy
DAC– Digital to Analog Converter
I2C– Inter-Integrated Circuit
CAD– Computer Aided Design

References

[1] American Speech-Language-Hearing Association, *Loud Noise Dangers*, Accessed on Mar 1, 2024, [Online]. Available: https://www.asha.org/public/hearing/loud-noise-dangers/#:~:text=You%20can%20listen%20to%20sounds,noise%20levels%20over%2085%20dBA.

[2] Fryar CD, Carroll MD, Gu Q, Afful J, Ogden CL. *Anthropometric reference data for children and adults: United States, 2015–2018*. National Center for Health Statistics. Vital Health Stat 3(46). 2021. Tables 4 and 6. Accessed on Mar 1, 2024. [Online]. Available: https://www.cdc.gov/nchs/data/series/sr_03/sr03-046-508.pdf

[3] OSHA, Slips, Trips, and Falls: Preventing Workplace Trip Hazards. Accessed on Mar 1, 2024. [Online]. Available: https://www.osha.com/blog/slips-trips-falls-prevention#:~:text=Officially%2C%20OSHA's%20trip%20hazard%20height,or%20cords%20across%20walking%20surfaces

[4] Polycase, *Ultimate Guide to IP Water Resistance Ratings*, Accessed on Mar 1, 2024. [Online]. Available: https://www.polycase.com/techtalk/ip-rated-enclosures/ultimate-guide-to-ip-water-resistance-ratings.html

[5] "Dance Pad." *Wikipedia*, Wikimedia Foundation, 10 Jan. 2024, en.wikipedia.org/wiki/Dance_pad. Accessed 01 Mar. 2024.

[6] Goodin, Dan. "New Data Uncovers the Surprising Predictability of Android Lock Patterns." *Ars Technica*, Conde Nast, 20 Aug. 2015, arstechnica.com/information-technology/2015/08/new-data-uncovers-the-surprising-predictability-of-android-lock-patterns/. Accessed 01 Mar. 2024.

[7] Olade I, Fleming C, Liang HN. BioMove: Biometric User Identification from Human Kinesiological Movements for Virtual Reality Systems. Sensors (Basel). 2020 May 22;20(10):2944. doi: 10.3390/s20102944. PMID: 32456023; PMCID: PMC7288269.

[8] "Bluetooth for Both Versions: Seeed Studio Wiki." *Seeed Studio Wiki RSS*, wiki.seeedstudio.com/xiao_esp32s3_bluetooth/. Accessed 4 May 2024.

[9] Saimun1, Servo Linear Actuator. https://www.thingiverse.com/thing:4623180/comments.

[10] Bboyho. Github. MPR121_Capacitive_Touch_Keypad. https://github.com/sparkfun/MPR121_Capacitive_Touch_Keypad.

Part	Used?	Amount	Cost	After Tax	Manufacturer	Model	Name	Description	Link
~~Lock Solenoid~~		~~1~~	~~$10.00~~	~~$10.60~~	~~YXQ~~	CYJ0905A7			~~https://www.amazon.com/YXQ-1-3Amp-Solenoid-Electric-Ca~~
Lock Solenoid	No	1	$10.00	$10.60	YXQ	CYJ0905		Lock/unlock door	https://www.amazon.com/dp/B075D8XLNF/ref=sspa_dk_det
Touch Pad for Lock	Yes	2	$18.00	$19.08	Hyuduo	MPR121	Capacitive 12 digit Touch Pad		https://www.amazon.com/MPR121-Capacitive-Keyboard-Butt
~~Force Sensors and Amplifier~~		~~4~~	~~$35.96~~	~~$38.12~~	~~HEXTRON~~		~~4pcs 50kg Load Cell Half Bridge Strain Gauge Human Body Scale Weight Sensor + 1pcs HX711 Amplifier AD Module for Arduino~~	~~Each pad will use four load cells with an amplifier that converts to digital signals to measure the weight applied to each dance pad and send to the controller.~~	~~4pcs 50kg Load Cell Half Bridge Strain Gauge Human Body~~
Force Sensors and Amplifier Two Pack	Yes	3	$32.94	$34.92	DIYmalls	HX711	DIYmalls 8pcs Load Cell 50kg Weight Sensor Half Bridge Strain Gauge Human Body Digital Scale + 2pcs HX711 Amplifier AD Module for Arduino	Each pad will use four load cells with an amplifier that converts to digital signals to measure the weight applied to each dance pad and send to the controller.	DIYmalls 8pcs Load Cell 50kg Weight Sensor Half Bridge Str
Microcontroller for Mat	Yes	1	$16.99	$18.01	Seeed Studio	ESP32S3	Seeed Studio XIAO ESP32S3-2.4GHz Wi-Fi, BLE 5.0, Dual-core, Battery Charge Supported, Power Efficiency and Rich Interface, Ideal for Smart Homes, IoT, Wearable Devices, Robotics	BLE 5.0 + WiFi compatible microcontroller on ESP32 chip. Very small	Amazon.com: Seeed Studio XIAO ESP32S3-2.4GHz Wi-Fi, E
Speaker		1	$25.00	$26.50	sparkfun	COM-10102	Surface Transducer		https://www.sparkfun.com/products/10102
		1	$7.00	$7.44	sparkfun	COM-18379	Cheap speaker		https://www.sparkfun.com/products/18379
		1	$9.99	$10.59	Gikfun	EK1725	Gikfun 2" 4Ohm 3W Full Range Audio Speaker Stereo Woofer Loudspeaker for Arduino (Pack of 2pcs) EK1725	lock speaker	https://www.amazon.com/Gikfun-Speaker-Stereo-Loudspeak
SD Card Adapter	Yes	1	$4.99	$5.29	Warsurs		USB3.0 Micro SD Card Reader, 5Gbps 2-in-1 SD Card Reader to USB Adapter, Warsurs Memory Card Reader for SDXC, SDHC, MMC, RS-MMC, Micro SDXC, Micro SD, Micro SDHC and UHS-I Cards (1Pack Black)	Micro SD to USB adapter	https://www.amazon.com/Reader-Adapter-Camera-Memory-|
SD Card Holder	Yes	1	**$5.99**	$6.35	Stemedu		2PCS Micro SD Card Module TF Card Memory Storage Adapter Reader Board SPI Interface with Integrated Circuit Breakout for Arduino for Raspberry Pi	Micro SD Card holder for door lock arduino, holds up to 2GB	https://www.amazon.com/Integrated-Circuit-Interface-Raspbe
micro SD Card	Yes	1	**$10.46**	$11.09	Cloudisk		2Pack Micro SD Card 2GB MicroSD Memory	2 GB micro SD cards	https://www.amazon.com/Cloudisk-2Pack-Micro-MicroSD-Me
Bluetooth Module	No	2	$7.00	$15.58	DFRobot	DFR0781	RF TXRX MODULE BT PCB TRACE SMD	Bluetooth module to connect door lock to phone and mat, hinging on the Seeed microcontroller working.	https://www.digikey.com/en/products/detail/dfrobot/DFR0781/
Bluetooth Module	Yes	1	$10.99	$11.65	DSD Tech	HM-10	DSD TECH HM-10 Bluetooth 4.0 BLE iBeac	Bluetooth module for lock Arduino	https://www.amazon.com/dp/B06WGZB2N4?psc=1&ref=ppx
Lock Battery	Yes	1	$7.97	$8.45	PKCell		PKCELL 9V Battery Carbon Zinc for Smoke Detectors 6F22 Battery,Ultra Long-Lasting	9V Batteries (10 pack)	https://www.amazon.com/PKCELL-Maximum-Long-Lasting-L
Lock Battery Connectors	Yes	1	$4.99	$5.29	VVIEICYY		9V Battery Connector, 10 PCS T-Type 9 Volt I	9V Battery Connector	https://www.amazon.com/Battery-Connector-Plastic-Experim
Lock Stepper Motor	Yes	1	**$6.99**	$7.41	WWZMDiB		SG90 Micro Servo Motor for Arduino Raspbe	3 pack mini servo motors	https://www.amazon.com/WWZMDiB-SG90-Control-Servos-/
Acrylic (NOT)			**$36.89**	$39.10			2 pack 2x3' "Acrylic"		https://www.amazon.com/Art3d-Pack-Thick-Plexiglass-Sheet
Pad Battery	Yes								
Audio amplifier	Yes	1	$11.50	$12.19	TI	LM386N-1	National Semiconductor LM386N-1 Semiconductor, Low Voltage, Audio Power Amplifier, Dip-8, 3.3 mm H x 6.35 mm W x 9.27 mm L (Pack of 10)	10 pack of lm386 amplifiers	https://www.amazon.com/gp/product/B00CN8487S/ref=ox_li

TABLE II. BILL OF MATERIALS