<u>Needs Assessment</u>
Customer Definition

The customer base for this project is people living in residential areas, particularly those living in shared residential areas, some characteristics of the customer base is:

1. The customer base is located in Stratford.[1]
2. The demographics of the customer base is targeted towards old people (65+) as they are more vulnerable to be victims of crimes[2].
3. The socioeconomic position of the targeted customer is lower-class to middle-class as the upper-class are unlikely to live in areas with high amounts of crime.[3]

Customer Challenge

The challenge the customer is facing is the increase in porch pirates (people who steal packages off the porch of customers after the package is delivered to the house) in the country. Those who are old or live in less affluent neighborhoods are more likely to experience this challenge.[2][3] The customer will need a device that can safely store the packages without the risk of another individual gaining access to the contents inside and opening the lid whenever the customer wants to retrieve their package without any issues that may arise in it not unlocking properly. We will design a solution to this challenge by creating a mailbox that uses stepper motors to open/close the hatch as well as an electromagnet that acts as the locking mechanism of the hatch. Regarding the insides of the mailbox, we will need to use ultrasonic sensors to detect the presence of a package as well as the absence of one to automate the opening/closing and locking/unlocking of the hatch using the motors and electromagnet respectively. We will use two STM32F401RE microcontrollers to coordinate between the sensors inside the mailbox as well as send signals from the microcontroller inside the house to instruct the one in the mailbox to unlock/lock the hatch when needed. We have to ensure the device meets safety protocols and will not cause any sort of harm to the customer or any other possible stakeholder.

Competitive Landscape

1. Porch Pirate Bag: This product is a PVC reinforced ballistic nylon bag mounted to a surface with a zipper mechanism with a zipper lock[4]. Whenever the customer is expecting a delivery, they may unlock the bag and leave a note asking the delivery person to leave the package in the bag and use the zipper lock to lock the package in the bag[4]. This reduces the chance of the package being stolen by a criminal. However, this does have its limitations. The nylon bag can still be pierced by a sharp object such as a knife. Furthermore, this product does not notify the customer of the arrival of the package, so it may be left out on the porch for too long which increases the chance of someone eventually trying to steal it.
2. Electronic Signature on Delivery: This system requires the customer to provide their signature on a tablet which the delivery person has on them. Once a signature has been provided, the delivery person may then hand off the package personally to the customer[5]. This ensures that the customer is the one who receives the package and reduces the risk of the package being stolen to

zero. However, this system requires the customer to be present at the time of delivery of the package, and this may not be possible at all times. The customer may be busy with their own personal duties and may not be home, this results in the delivery of the package being delayed until the customer is present at home.

3. Amazon Key: This is a product made by Amazon as an attempt to reduce the porch-pirating problem. Essentially, this requires the customer to change their door's lock to the one Amazon provides. Then, once the delivery person wants to deliver a package, they may request access from the customer through the app provided by Amazon. Once the access has been provided, the delivery driver can open the door and leave the package in the house[6]. This also prevents any chance of theft as the package is already in the house. However, customers may not be comfortable with providing strangers access to their house, even if it is for a temporary amount of time. Furthermore, this service is not suitable for the age of our customer group since it requires a good knowledge of technology and a phone as well to access the app. Older people generally do not have access or have the know-how of using these things, so this product is not very suitable for them.

Requirement Specifications

The design for this project has many important components, each with their own specific requirements.

1. The operating voltage of the microcontrollers must be between 1.7V and 3.6V [7], a voltage above this requirement may cause the microcontroller to fry itself and a voltage under this range will most likely lead to the microcontrollers not working as required.
2. The working voltage of the ultrasonic sensor must be 3V. The ultrasonic ranging module HC - SR04 provides 2cm - 450cm non-contact measurement function [8]. This means the package must be at least 2 cm away from the sensor in order to get an accurate detection.
3. The safety requirements require any design component that connects directly to a building electrical supply outlet (110V AC outlet) must be CSA approved [9].
4. The design must not consume or expend more than 30W of power and it may not store more than 500mJ at any point during its operation. Any power consumption or expenditure or energy storage above this may result in a safety hazard [9].
5. The two communicating STM32F401RE microcontrollers must be at least 1m away from each other at all times during the operation of the device [9].

Analysis

Design

1. Required Components:

Ribbon cables	An electromagnet	Push Buttons
Jumper wires	An ultrasonic sensor	Bread boards

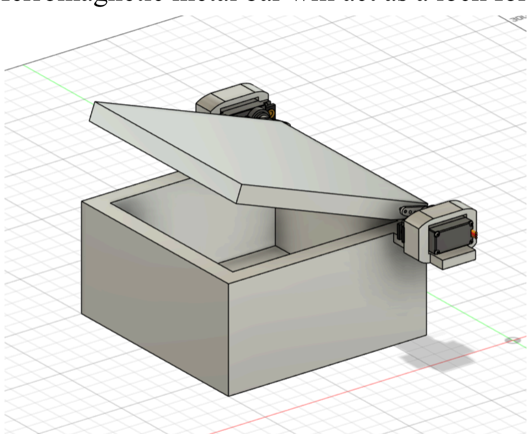
Resistors: 1Ω to 5kΩ	Two STM 32 microcontrollers	A ferromagnetic metal bar
Two servo motors	Green LEDs	A one meter wire

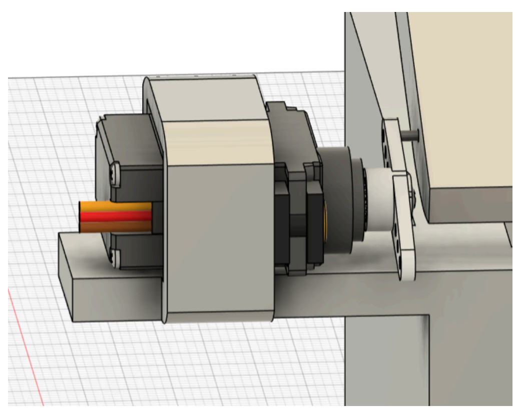
A 3D printer is also required to print the main body of the project. It is recommended to keep spare parts in case of any unforeseen circumstances while building the project.

2. Design Shape and Function:

The physical shape of the project will be in the form of a 30cm x 30cm x 15cm 3D printed box. This box will hold the package for the customer and it will contain one of the STM 32 microcontrollers, the two servo motors, the ultrasonic sensor with an operating voltage of 3V, and a breadboard with wires to connect them altogether.

The box will have a lid that opens and closes. This will be done through the use of the servos. The servos will be connected to both sides of the lid and they will be connected to the box as well through the use of small, 3D printed axles with diameters of 0.25cm passing through small holes on the sides of the box. The lid will have a circular edge to allow ease of rotation of the motor blades and it will have dimensions of 30cm x 30cm x 0.25cm. There is a 3D model of the lid and the box provided at the bottom of this section. The lid will need to have a mechanism to lock itself to prevent anyone but the customer from accessing it. To do this, an electromagnet will be attached to the bottom of the lid and a ferromagnetic metal bar will be attached to the side of the box from which it will open from. The attraction force between the electromagnet and the ferromagnetic metal bar will act as a lock for the entire device.

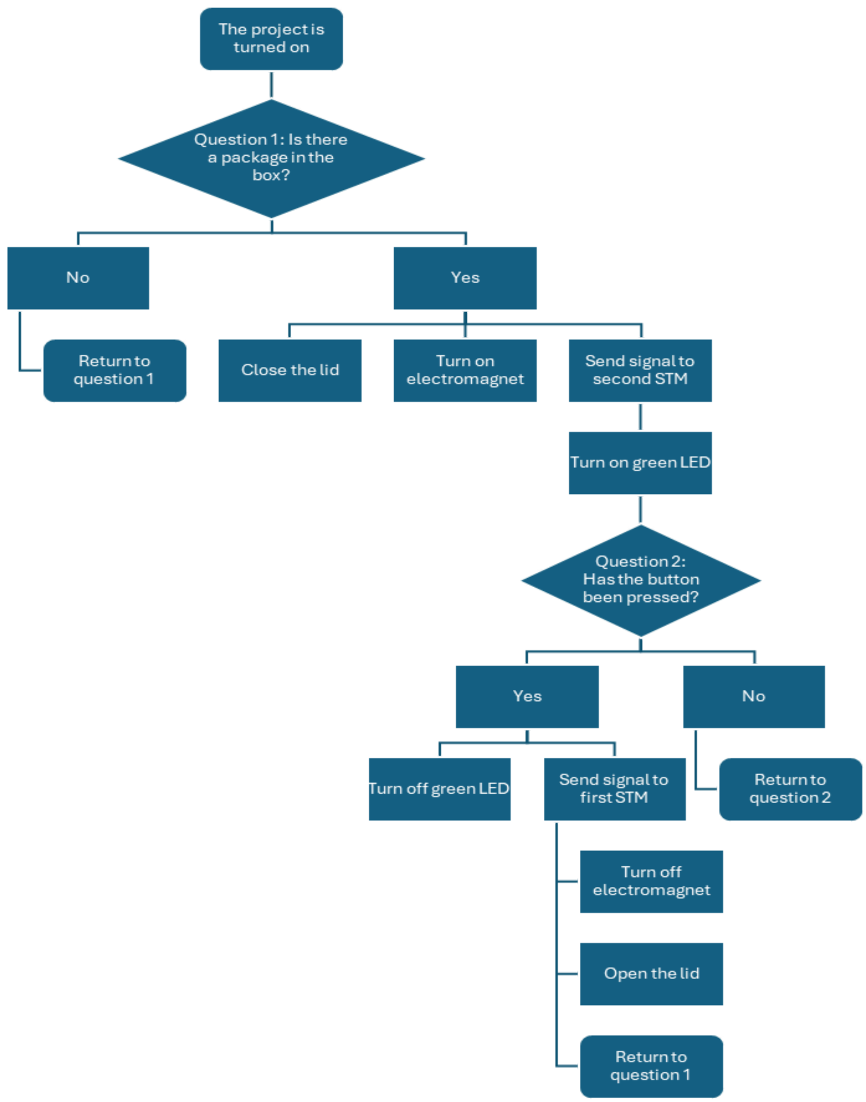




The box is then connected via a wire to the other STM 32 microcontroller which is placed 1 meter away. This microcontroller is responsible for notifying the customer of the arrival of the package via a green LED that lights up once the package has arrived and it will be connected to a push-button which will be used to unlock the box. Both STM 32 microcontrollers must be running on an input voltage between 1.7V and 3.6V. Furthermore, the STM 32 microcontrollers may have to be directly plugged into a building electrical supply outlet (110V AC outlet) using a USB wall wart. If that is the case, it must be CSA approved and it must not exceed the maximum power usage of 30W. Finally, the design will not store energy of any kind, so the safety requirements on the limit of the amount of energy stored will be satisfied.

3. Design Behavior:

The ultrasonic sensor inside the box is responsible for the detection of a package. When a package is inserted into the box, it sends a signal to the STM in the box. The STM then sends signals to both servo motors to close the lid and it turns on the electromagnet to keep it locked. It then sends a signal to the STM outside of the box, informing it of the delivery of the package. The second STM then turns on the green LED and waits for the customer to push the button. Once the button is pressed, the green LED and the electromagnet are both turned off, and the servo motors will rotate 90 degrees to open the lid. The same process will keep on repeating as shown by the flowchart below.



Alternatives
Before the current design of the closing mechanism of the box, many other forms were considered. The first idea was a traditional lock, however it did not include any scientific principles or any complexity. Also, the lock system included disadvantages such as the requirement of a physical key and risk of key loss. Another idea the group explored were door locks. This system was disregarded since door locks are generally bulkier and are designed for larger structures. Also, there are some complexities such as the need for drilling for installment and the unnatural turning motion of a door being less convenient than than a simple magnetic lock, which can engage or disengage smoothly with minimal physical interaction. The final and chosen design was the magnetic lock. The main reasoning behind this decision was the convenience of having a controllable electronic engagement as the lock mechanism. This facilitates automation of closing and opening the gate with a simple switch. Also, a magnetic lock is typically small and lightweight, fitting into the compact design of the box. This makes it an ideal choice for the compact design, where other locking mechanisms might take up too much space or add unwanted bulk.

Technical Analysis

<u>Torque</u>

1. Torque is defined as the measurement of how well a force can rotate an object[10] and it has the formula:

$$\vec{\Gamma} = \vec{r} \times \vec{F} = (|r||F|sin\theta) \text{ [10]}$$

   In the equation, $\vec{r}$ is the vector from the pivot point to the point of the applied force, $\vec{F}$ is the vector of applied force, θ is the angle between $\vec{r}$ and $\vec{F}$, and $\vec{\Gamma}$ is the torque.

   The use of torque will be an integral part of the project's locking mechanism, being used to operate when to open and close the hatch when necessary. The design will feature two servo motors that move the lid back and forth as packages enter and leave the mailbox, however, in order for that to occur the motors have to overcome the torque of the force of friction and gravity acting on the lid. To do this, the motors need to output a rotational torque greater than that of the combination of both of those torques, ie:

$$\Gamma_R > \Gamma_g + \Gamma_k$$

   Where Γ_R is the rotational torque, Γ_g is the torque of gravity, and Γ_k is the torque of kinetic friction.
   The rotational torque is equivalent to the torque in the motors, so in order for the motor locking mechanism to work, the motors must be geared to output a greater torque than the combination of gravity and kinetic friction.

   - The hatch is 30 x 30 x 0.25cm which means it has a volume V = 30*30*0.25 cm^3 = 225 cm^3

- We will be using PLA filament for our 3D printer, this has a density of 1.24 g/cm^3[11]. Using the formula Density = (mass/volume) [12], the mass of the lid can be calculated as mass = 1.24 * 225 = 279 grams or 0.279 kgs
- We can then calculate $\Gamma_g = |r||F|sin\theta$. Since the lid is uniform, it is a fair assumption to put the center of gravity of it right at the center of the lid. The hinge is located on the edge of the box, therefore r would be half of the length of the lid, so r = 15 cm. F is simply the force of gravity on the lid. F = mg[13] = 0.279 * 9.81 = 2.74N. Finally, $sin\theta$ = 1 since $\theta = 90°$ as the force of gravity is vertically downwards and thus perpendicular to the $\vec{r}$ vector. Thus Γ_g = 2.74 * 15 = 41.1 N•cm = 0.411 N•m
- The friction will be acting on the hinge, therefore we can say that r is very small, so $\Gamma_k \approx 0$
- In the end, we get $\Gamma_R > \Gamma_g \Rightarrow \Gamma_R >$ 0.411 N•m. Therefore the minimum amount of torque that both motors can exert at the same time has to be greater than 0.411 N•m.

<u>Ampère-Maxwell Law</u>

1. The Ampère-Maxwell Law will be used to understand how an electromagnet works. It states that a current-carrying coil can induce a magnetic field through the center of that coil. This means that if we run a current through the coil while it has a metal bar inserted in the middle of it, it will induce a magnetic field through that metal bar as well. This creates a magnetic dipole on the metal bar, essentially turning it into a magnet [14]. We will use the idea of creating an electromagnet to create the locking mechanism for our device. When the locking mechanism needs to be turned on, we will run a current through the coil which turns on the electromagnet that attracts a ferromagnetic material inside the locking mechanism. When we want the lid to open, we simply turn off the current in the coil, and the magnet quickly loses its magnetic properties, allowing the lid to be opened without any problems.

2. The formula for the Ampère-Maxwell Law is:

$$\oint \vec{B} \cdot \vec{dl} = \mu_0(I_c + I_d) \text{ [15]}$$

Where $\vec{B}$ is the magnetic field, $\vec{dl}$ is an infinitesimally small segment of the coil, μ_0 is the magnetic constant ($4\pi \times 10^{-7}$ H/m) where H is Henries and m is meters [16], I_c is the conduction current, and I_d is the displacement current.

This equation explains the electromagnetic behavior that was stated in part 1 in a mathematical way.

<u>Biot-Savart Law</u>

1. The Biot-Savart Law will be used to adjust the parameters of the electromagnet. Depending on the material we will use for the device and the type of metal bars we will use in the locking mechanism, the force required to keep the lid closed in a secure fashion without the risk of

someone easily breaking it open will vary. Thus, we need to calculate the proper amount of attraction force between the electromagnet and the ferromagnetic material. The Biot-Savart Law allows us to calculate the total magnetic field through the electromagnet by using the formula:

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{Id\vec{l} \times \hat{r}}{r^2} \text{ [17]}$$

Where $d\vec{B}$ is the infinitesimally small magnetic field produced by the infinitesimally small segment of wire $d\vec{l}$, I is the current through the wire, r is the distance from the infinitesimally small wire to the location where we are measuring $d\vec{B}$, μ_0 is the magnetic constant ($4\pi \times 10^{-7}$ H/m) where H is Henries and m is meters [16], and $\hat{r}$ is the unit vector acting in the direction of $\vec{r}$ The above formula can then be integrated to get:

$$\vec{B} = (\frac{\mu_0}{2})(\frac{Ni}{r}) \text{ [17]}$$

Where N, i, r, $\vec{B}$, and μ_0 are the number of turns in the coil, current through the coil, radius of the coil, magnetic field through the coil, and the magnetic constant ($4\pi \times 10^{-7}$ H/m) where H is Henries and m is meters [16] respectively.

2. We can then use this in the formula:

$$F = \frac{B^2 A}{2\mu_0} \text{ [18]}$$

Where F is the mutual force between the ferromagnetic metal and the electromagnet, B is the magnetic flux density through the metal, A is the cross sectional area of the metal, and μ_0 is the magnetic constant ($4\pi \times 10^{-7}$ H/m) where H is Henries and m is meters [16].

We will use this formula to figure out the amount of force our electromagnet will impart onto the ferromagnetic material. We can then adjust the current running through the coil to match the desired magnitude of force that we need to keep the lid secured.

- The electromagnet we are using will have a wire length of 24 cm with a thread diameter of 4mm [19]. So the number of loops of the coil will be N = length of wire/circumference of thread = (24)/(0.4*π) ≈ 19 loops.
- Our chosen ferromagnetic bar has a diameter of 1 inch = 2.54 cm[20]. Thus the cross sectional area is simply $A = \pi(r^2)$ [21] $= \pi(2.54/2)^2 = 5.07\ cm^2 = 5.07 \times 10^{-4}\ m^2$.
- The magnetic flux density $B = \vec{B} \bullet \vec{A} = BA\cos\theta$ [22]. Where $\vec{B}$ is the magnetic field and $\vec{A}$ is the vector perpendicular to the surface with magnitude equal to the cross sectional area of the surface. Thus we can combine the second equation with the magnetic flux density $\Rightarrow B = (\frac{\mu_0}{2})(\frac{Ni}{r})A\cos\theta$, since our surfaces are going to be parallel, θ is 0° so $\cos\theta = 1$ so $B = (\frac{\mu_0}{2})(\frac{Ni}{r})A$

- Replacing this in the third equation above: F = $((\frac{\mu_0}{2})(\frac{Ni}{r})A)^2A) / (2\mu_0) = (\mu_0 N^2 i^2 A^3) / (8r^2)$. We can then plug in all these known values and replace a desirable force (F) for the locking mechanism and simply find the current (i) needed to pass through the electromagnet. The desirable force will be determined through physical testing.

Cost

Manufacturing and Implementation Cost

Bill of Materials (BOM):

Component	Quantity	Price Per 1 Quantity	Total Cost
Servo motor	2	$11.74	$23.48
Electromagnet	1	$7.86	$7.86
Ultrasonic sensor	1	$6.18	$6.18
3D printing	≈ 729g	$0.06/g	$43.74
Pack of resistors of variable resistance	1	$10	$10
Pack of jumper wire	1	$2.86	$8.58
Ferromagnetic bar	1	$5.23	$5.23
Bread boards	2	$4.23	$8.46
Green LED	1	$0.16	$0.16
Push Button	1	$1.96	$1.96
Total Cost			$115.65

Deeper Costs:

1. The STM Microcontrollers: These are printed circuit boards (PCB) which are made out of FR-4(fiberglass-reinforced epoxy resin) and Polyimide most commonly [23]. These both offer good electrical conductivity and high heat resistance, making them ideal for a PCB. The boards are made by STMicroelectronics which are located in Switzerland. The FR-4 is made by Massive PCB Technologies Co. which is located in China, Guangdong [24]. The Polyimide is manufactured by Sheldahl Flexible Technologies which is located in Northfield [25].

2. The servo motors: The motors are made by Adafruit Industries LLC which are located in New York [26]. The motors are mainly made out of plastic polymers which are mostly manufactured in China [27].
3. Jumper wires: The wires are produced by Adafruit Industries LLC which are located in New York [26]. The insides of the wires are made out of copper which are mostly mined from the copper mines in Chile [28].
4. Electromagnet: The electromagnet is simply a copper wire wrapped around a metal core. The producer of the electromagnet is Uxcell which is located in Hong Kong, China [29]. As previously mentioned, the copper wire is from the mines in Chile. The metal core is made by Glencore which is a natural resources company which specializes in mining iron ore and operates in Australia, Colombia, and South Africa [30].
5. Ultrasonic sensor: The ultrasonic sensor we will use is manufactured by Adafruit Industries LLC which operates in New York[26]. The ultrasonic sensor consists of an aluminum cylinder placed on top of a PCB. The insides of the cylinders are simply many electronic components that are also made of a combination of aluminum and other miscellaneous metals. The aluminum is mostly sourced from mines in China [32].
6. Casing: The box and the lid will be 3D printed using a filament called PLA (Polylactic acid plastic) which is made from renewable sources and is biodegradable [31]. We will be using this filament with the 3D printers available on the University of Waterloo campus to make the casing of the project.

Installation Manual:

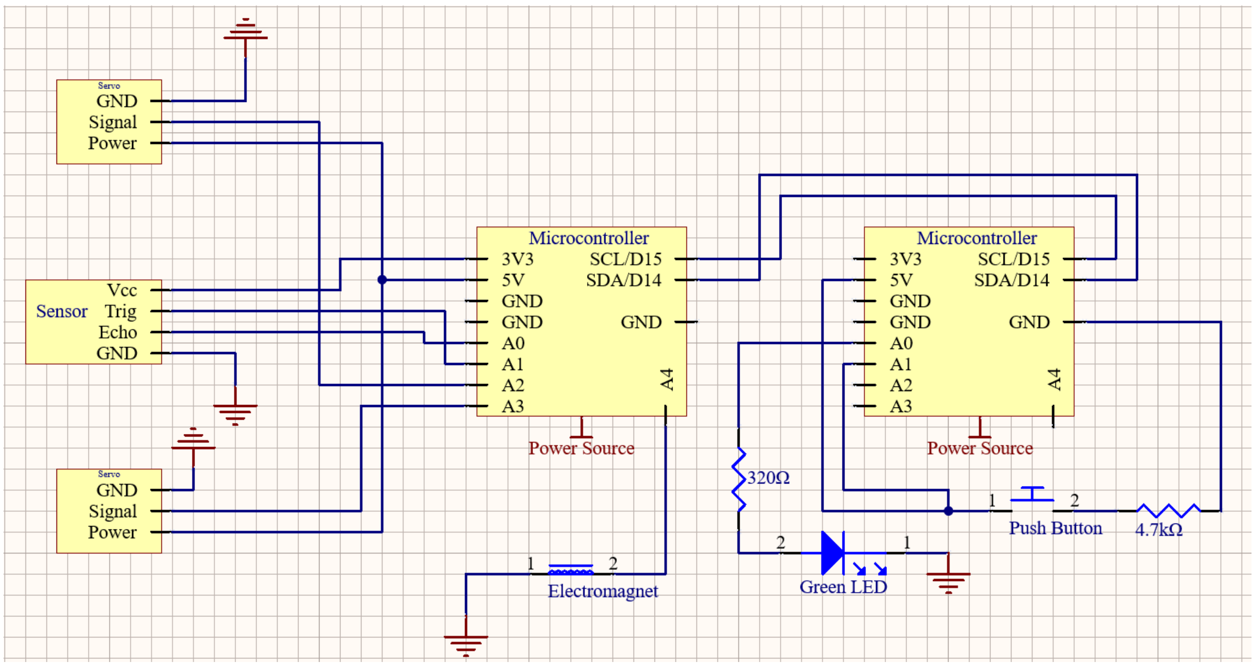
1. Unbox the product from the packaging and make sure the contents are as follows:
    - The main box with the lid properly attached.
    - Two servo motors attached to the sides of the box
    - The inside of the box contains an ultrasonic sensor and one of the STM microcontrollers.
    - Make sure the wirings are not damaged or disconnected in any way.
    - The STM microcontroller outside the box is properly wired to the one in the box and it is also wired properly to the push-button and green LED.
2. Make sure the motors on the side of the box are properly attached and are not loose.
3. Plug in both STM microcontrollers to a power source. It is recommended to connect your computer via a USB 2.0 cable - A to mini B (which is provided) to the microcontrollers. This will provide the power that the product needs. The power can also be provided through a wall outlet, but it is recommended to use a wall wart that does not exceed the power limit of 30 W and has been CSA approved.
4. Then place the box outside of the house and leave the second STM microcontroller inside the house.
5. The product is now ready to be used.

User Manual:

1. Product Features and Functionalities: The main purpose of the product is to prevent porch pirates from stealing the customer's belongings. This will be done through the use of the revolving lid on the box. Once a package has been delivered, the box will close itself and lock.
2. Operating the product: Once the package has been delivered, the green LED inside the house will light up. This means that the package has arrived and has been successfully secured in the

box. To retrieve the package, simply press the push-down button, the green LED will then turn off and the box will be unlocked. The motors will then rotate and open the lid of the box. The package can then be retrieved.

3. Troubleshooting: In the event where the product does not work as intended, please refer to one of the following:
    - Try to disconnect and reconnect both STM microcontrollers from the power to hard restart the system.
    - Press and hold the black reset button on both STM microcontrollers to soft reset the system.
    - If none of the above work, make sure that there are no loose or broken wirings according to the diagram below:



Risks

Energy Analysis

All components within the design operate at 5V or less, with the primary power source being a USB connection from an external source such as a personal laptop. This 5V limit serves as the reference standard for the design, ensuring that no component requires more than this voltage.

The servo motors operate at 5V, the sensors also operate at 5V, and the STM functions within a range of 3.3-5V. Therefore, it is appropriate to set the reference standard at 5V.

A typical 5V battery can store around 1.8 Wh (watt-hours) of energy. Since 1 Wh corresponds to 3600 Joules, this 5V battery would contain approximately 6,480 J of energy. This significantly exceeds the power storage limit set at 500 mJ. Since external sources such as a personal laptop will replace a battery for this design, there won't be significant energy storage.

The maximum current of used out of components used is 100mA at 5V, resulting in a total discharge rate of:

$$Power = Voltage \times Current = 5V \times 0.1A = 0.5\,Watts$$

This discharge rate is well below the project limit of 30 Watts, ensuring safety within operational limits. There are no additional forms of stored energy, as the design does not include mechanical, chemical, or significant thermal energy sources.

Risk Analysis

Some possible negative consequences of using the design as intended might be from accidentally pinching or injuring fingers when closing the box, as the magnets engage quickly upon close. Applying excessive force to the magnetic lock could damage the components within the box, which can cause broken pieces and or sharp edges, leading to potential injuries. A possible negative consequence on safety from misusing the design is that a child or pet could accidentally become locked inside the box, posing risks of suffocation or panic. Some possible ways the design could malfunction would be due to bad weather, such as rain damaging the electronics, or excess moisture interfering with the electrical components. Another point of malfunction could be that the sensor does not detect the presence of a package. Both of these malfunctions could have some consequences on safety. Rain could lead to electric shock as water conducts electricity, and if the sensor fails to detect a package, it could be stolen, compromising the safety of private information.

Testing & Validation

Test #1

Description

The first test will be to insert a package into the box and detect that the package is there. To detect this, the box will have a built-in ultrasonic sensor that detects when a package is less than 25 cm from it. This detection system is vital to the design of the box as without it, the box could never lock and would be useless.

Environmental Parameters

Ensure the humidity and temperature are at standard levels.

Test Inputs

The test input would be a small package that fits within the dimensions of the box.

Quantifiable Measurement Standard

The sensor should send a signal to the LED within 1 second of the package being placed inside the box, and the ultrasonic should not start the locking mechanism unless it detects a package closer than 25 cm.

Pass/Fail Criteria

If the ultrasonic sensor detects a package once it has been added through the signal to the LED, then the test is a pass. If the ultrasonic fails to recognize that a package is in the box, the box won't lock, and the test has failed.

Test #2

Description

The second test will ensure the motors rotate in sync. This occurs when the lid of the box is opening or closing, however, for this test, the closing mechanism will be tested. Ensuring that the motors are in sync is important because if not, the motors may oppose each other and possibly fry themselves or bend the axle.

Environmental Parameters

Ensure the humidity and temperature are at standard levels.

Test Inputs

Click the button that opens the box, causing both motors to spin.

Quantifiable Measurement Standard

The motors should both rotate at a speed of 40 RPM with the axle.

Pass/Fail Criteria

This test will be passed if the motors spin in sync and the lid turns. If the motors don't rotate in sync, then the test has failed, possibly resulting in frying the motors as they oppose each other.

Test #3

Description

The third test will be testing to make sure that the box will stay locked once a package is inside of it. This test involves applying a force against the lit to try and open it once it is closed, recreating what an attempt at stealing a contained package might look like.

Environmental Parameters

Ensure the humidity and temperature are at standard levels.

Test Inputs

Once a package has been placed inside the box, the lid will close and will allow us to test the magnet

Quantifiable Measurement Standard

The magnet should lock within 1 second on the box being closed.

Pass/Fail Criteria

To pass this test, the box should not be able to be opened once the box is locked. If it can still be opened after being locked, then the test has failed.

Test #4

Description

The fourth test will be testing whether the box automatically closes after a package has been delivered. This should occur roughly 10 seconds after a package has been detected, giving ample time for the delivery person to remove their hands and position the package properly in the box.

Environmental Parameters

Ensure the humidity and temperature are at standard levels.

Test Inputs

Once a package has been placed inside the box, the lid will automatically close
Quantifiable Measurement Standard
The box should close within 10 seconds of the package being placed inside the box.
Pass/Fail Criteria
This test will be passed if the box automatically closes into its locked position 10 seconds after a package has been inserted. If the box doesn't close or fails to close properly, then the test has failed.

Test #5

Description
The fifth test will check if the box will open after the button is clicked. This involves pressing the button while the package is in a locked state, and having the box stay open so that the recipient can successfully retrieve their package.
Environmental Parameters
Ensure the humidity and temperature are at standard levels.
Test Inputs
Click the button that opens the box.
Quantifiable Measurement Standard
The program should monitor inputs from the button, changing a boolean to true upon being pressed.
Pass/Fail Criteria
To pass this test, the box must open if it is in a locked position and the button is pressed. If the box doesn't open when the button is pressed, then the test has failed and the package will be trapped in the box.

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