Fall 2018

Residential Automatic Door Opener

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Executive Summary

The Residential Automatic Door Opener (RADO) aims to provide a cheaper alternative to common yet expensive products on the market for door automation. The intention is to provide such a device for the elderly and disabled for use in homes on exterior doors. What differentiates it is the use of a pulley system in which a steel wire opens the door. A typical motor found in cordless drills provides the torque needed to move the door at an effective cost. It holds a spool in its tip which winds and unwinds the wire. It also comes with a slip clutch for safety; this gear mechanism allows it to spin without moving the wire if a person were to suddenly stop the door. An Arduino UNO contains the code which controls the power, direction, and timing of the motor in opening and closing. To allow use of a weaker and cheaper motor, a lever arm with a pulley wheel is placed next to the motor to provide mechanical advantage. All of these features are housed in a compact box to mounted on the wall parallel to the door. The end of the wire is screwed to the corner of the door and allows the door to be easily used manually in emergencies by not impeding it. The hinges used are torsional spring hinges which closes the door. A wired button under the box initiates the automation. A solenoid, mounted on the edge of the frame, first activates and retracts the bolt holding the door in place. The motor would wind the door open, hold it in place for ten seconds, and then retract slowly as the hinges close the door before being re-locked by the solenoid.

MEMS 411: MECHANICAL ENGINEERING DESIGN PROJECT
FALL 2018

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1 INTRODUCTION

The goal of our senior project is to design an affordable device that is able to open and close residential exterior doors automatically, hereby called a Residential Automatic Door Opener (RADO). Commercially, such devices are commonplace, but for residential use there are few products with less than four digits on the price tag. This sort of price point prevents many elderly and disabled individuals from accessing a device that can greatly improve their lives. Every home of an elderly or disabled person would benefit from such a device, and by developing one that is affordable while still maintaining a respectable quality, more individuals would be able to reap those benefits. The main benefit, of course, is the safety increase of the home by having a hands-free door system. When entering a home carrying groceries or laundry from the laundromat, the RADO reduces the danger of falling while opening the door when one’s hands are full. The main focus is on exterior doors leading in and out of the residence. These doors must be equipped with a locking mechanism and, thus, will be able to engage and disengage a lock using a solenoid. With that in mind, security measures will be in place to prevent intruders from gaining access.

2 PROBLEM UNDERSTANDING

2.1 BACKGROUND INFORMATION STUDY

2.1.1 Existing Designs

2.1.1.1 Power Access Model 2300 Residential Door Opener

Figure 1 Image of the Power Access Model 2300 Residential Door Opener [1]

This automatic door opening device can be installed on most exterior doors and comes in two types: one that is mounted directly onto the door and one that attaches to the frame above the door. The device both opens and closes the door via a double linkage arm driven by a motor. It can be activated via several methods such as a wall button or a wireless trigger that works under the same concept as a wireless garage door opener. This allows for the door to be operable without the use of the device and can be programmed to close automatically whenever the door is left open. It has built in procedures to prevent damage when impediments prevent the door from opening. The motor is also thermally protected to prevent damage from temperature especially in the winter. The product is expensive, costing on average more than $1,000.

2.1.1.2 CONCIERGE® Residential Power Door Opener

Figure 2 Image of the CONCIERGE® Residential Power Door Opener [2]

This automated door opening mechanism can be operated with a wall button, number code on a keypad, or a wireless transmitter. Electricity is supplied through a standard wall outlet. Like the previous product, a motor transmits force via a double linkage arm in order to open the door. It can be installed on either side of most doors, both to the door itself and the frame above it, without the need for alterations to the door or frame and allows for the door to be used manually even in the absence of electricity. It can detect objects impeding the door and will cut power to prevent damage. It can be set to close automatically even if the door was not opened via the device. The product is very expensive, with a listed price of around $1,800.

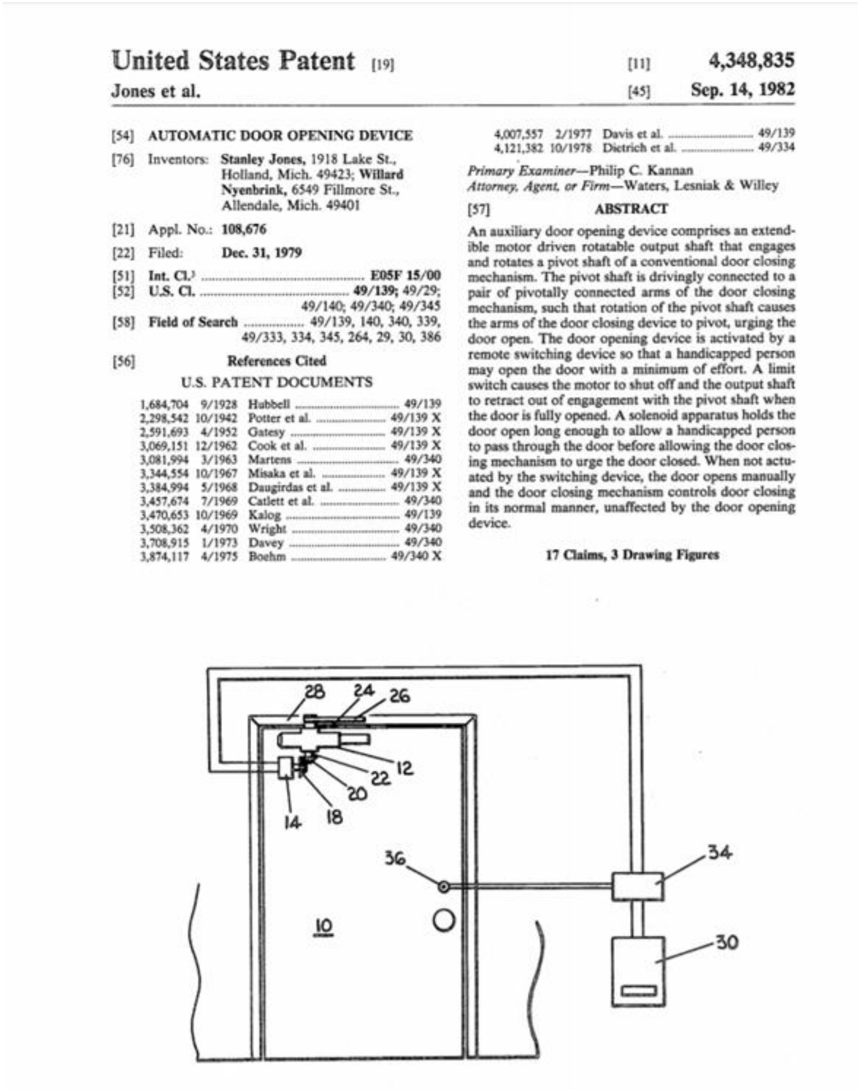
2.1.1.3 Otodor® Model DM-50

Figure 3 Image of the Otodor® Model DM-50 [3]

This automated door opening device is compatible with most doors and is powered by a standard electrical outlet. This differs in that it uses one linkage bar to open the door via a rotary motor, making it slightly more compact. It generates a sound when in operation and has safety features in place to prevent damage when making contact with an obstruction in the path of the door or when the door is pushed open manually. It records the range over which the door can travel to avoid potential damage and can be set to close after a specified time period or to remain open. There are several options by way of activation, including a remote, a motion sensor, and wall button. Available accessories include an electromagnetic lock and an electric strike for security. Product is inexpensive amongst competitors, costing around $200.

2.1.2 Patents

2.1.2.1 Patent US4348835A



United States Patent [19] [11] **4,348,835**

Jones et al. [45] **Sep. 14, 1982**

[54] **AUTOMATIC DOOR OPENING DEVICE**

[76] Inventors: **Stanley Jones,** 1918 Lake St., Holland, Mich. 49423; **Willard Nyenbrink,** 6549 Fillmore St., Allendale, Mich. 49401

[21] Appl. No.: **108,676**

[22] Filed: **Dec. 31, 1979**

[51] **Int. Cl.**[3] **E05F 15/00**

[52] **U.S. Cl.** **49/139;** 49/29; 49/140; 49/340; 49/345

[58] **Field of Search** 49/139, 140, 340, 339, 49/333, 334, 345, 264, 29, 30, 386

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Primary Examiner—Philip C. Kannan
Attorney, Agent, or Firm—Waters, Lesniak & Willey

[57] **ABSTRACT**

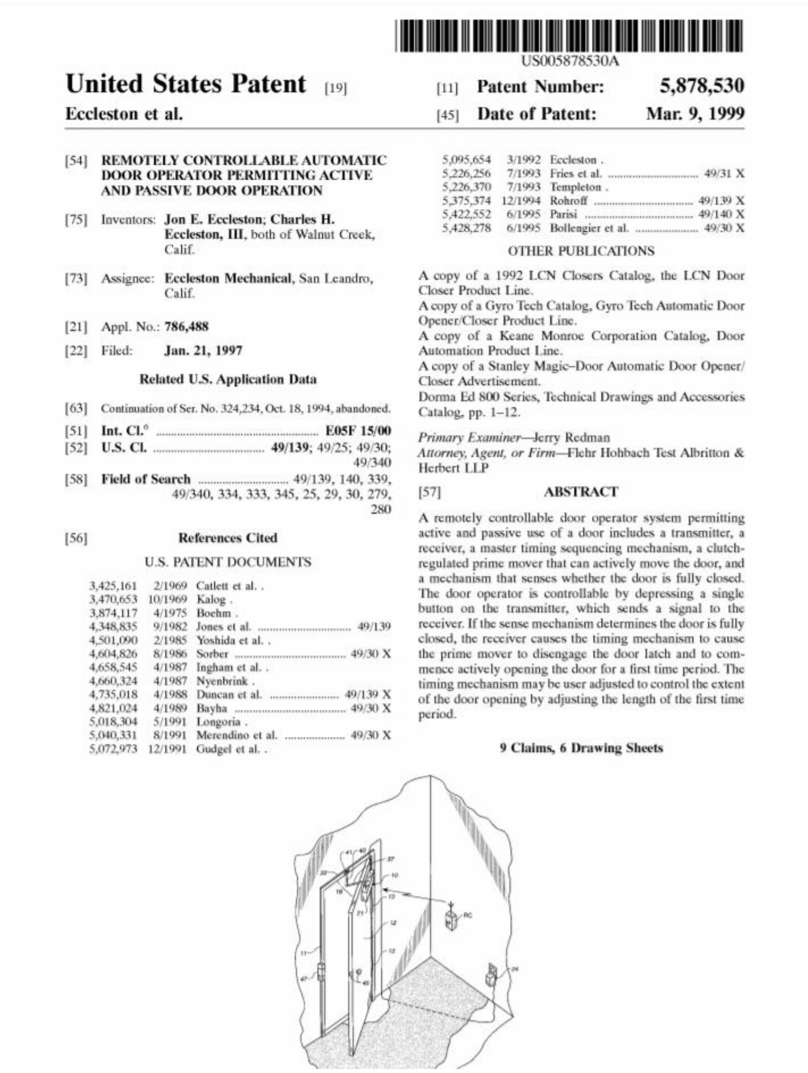
An auxiliary door opening device comprises an extendible motor driven rotatable output shaft that engages and rotates a pivot shaft of a conventional door closing mechanism. The pivot shaft is drivingly connected to a pair of pivotally connected arms of the door closing mechanism, such that rotation of the pivot shaft causes the arms of the door closing device to pivot, urging the door open. The door opening device is activated by a remote switching device so that a handicapped person may open the door with a minimum of effort. A limit switch causes the motor to shut off and the output shaft to retract out of engagement with the pivot shaft when the door is fully opened. A solenoid apparatus holds the door open long enough to allow a handicapped person to pass through the door before allowing the door closing mechanism to urge the door closed. When not actuated by the switching device, the door opens manually and the door closing mechanism controls door closing in its normal manner, unaffected by the door opening device.

17 Claims, 3 Drawing Figures

Figure 4 Patent of an automatic door opening device

This patent details an automatic door opening device that is mounted to the top of a door and is activated by use of a nearby triggering device. Once triggered, the door shall open and remain so for a programmed amount of time before closing automatically. The design allows for the door to be used manually, and a sensor on the lock will stop the device from activating when the lock is engaged.

2.1.2.2 Patent US5878530A



US005878530A

United States Patent [19]

Eccleston et al.

[11] **Patent Number: 5,878,530**

[45] **Date of Patent: Mar. 9, 1999**

[54] **REMOTELY CONTROLLABLE AUTOMATIC DOOR OPERATOR PERMITTING ACTIVE AND PASSIVE DOOR OPERATION**

[75] Inventors: **Jon E. Eccleston; Charles H. Eccleston, III**, both of Walnut Creek, Calif.

[73] Assignee: **Eccleston Mechanical**, San Leandro, Calif.

[21] Appl. No.: **786,488**

[22] Filed: **Jan. 21, 1997**

Related U.S. Application Data

[63] Continuation of Ser. No. 324,234, Oct. 18, 1994, abandoned.

[51] **Int. Cl.**[6] **E05F 15/00**

[52] **U.S. Cl.** **49/139**; 49/25; 49/30; 49/340

[58] **Field of Search** 49/139, 140, 339, 49/340, 334, 333, 345, 25, 29, 30, 279, 280

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Primary Examiner—Jerry Redman
Attorney, Agent, or Firm—Flehr Hohbach Test Albritton & Herbert LLP

[57] **ABSTRACT**

A remotely controllable door operator system permitting active and passive use of a door includes a transmitter, a receiver, a master timing sequencing mechanism, a clutch-regulated prime mover that can actively move the door, and a mechanism that senses whether the door is fully closed. The door operator is controllable by depressing a single button on the transmitter, which sends a signal to the receiver. If the sense mechanism determines the door is fully closed, the receiver causes the timing mechanism to cause the prime mover to disengage the door latch and to commence actively opening the door for a first time period. The timing mechanism may be user adjusted to control the extent of the door opening by adjusting the length of the first time period.

9 Claims, 6 Drawing Sheets

Figure 5 Patent of a remotely controllable automatic door operator permitting active and passive door operation

Details an automated door opening mechanism which can be activated via a wireless transmitter. A sensor is used to detect whether or not the door is fully closed and can detect if any obstructions are in the path of the door, in the event of which the power supply shall be cut off. In addition, the length of time for which the door remains open can be altered to one’s needs.

2.1.3 Standards

2.1.3.1 BRE GG48

This standard (BRE GG48) by Building Research Establishment Limited details how automatic door controls can assist people who are disabled or elderly or both. The main focus is the control interface and the installation of the various components of such system. The former can provide insight for a user interface that is accessible for those with certain impairments. The latter will help provide the ideal setup in relation to the door and the frame. An improper placement could be both an impediment and a danger.

2.1.3.2 ANSI/BHMA A156.19-2013

This ANSI/BHMA A156.19-2013 standard specifies what evaluations are used to certify power operated doors. Among those are durability, safety, appearance, building codes, accessibility, and sustainability. What stands out as a potential influence is the relation of the standard to the American Disability Act (ADA) and A117.1 requirements for accessibility. Understanding how ADA reflect user needs will make the product more popular. Safety and partly durability will require a careful look into the functionality of the door opener in a zero-power state. The product must be designed to allow the door to move when it is not active.

2.2 USER NEEDS

A customer interview was conducted, from which the following was collected.

Table 1 Customer Needs Interview

Question	Customer Statement	Interpreted Need	Imp.
Is it important for the motor to be silent?	A little noise is fine but not too much.	RADO is reasonably quiet.	2
Would you prefer the device mounted onto the door or the frame?	Whichever is the least obtrusive.	RADO is not so large or heavy.	2
Do you have any concerns about the device?	I wouldn't want a stranger to be able to use to get in.	RADO does not weaken security.	5
When would it be the most helpful?	When carrying things, such as groceries.	RADO can be activated without using hands.	3
How might it be inconvenient?	If there was a power outage and the door wouldn't open.	Door can be used manually.	5

Table 2 Interpreted Customer Needs

Need no.	Need	Importance
1	RADO is reasonably quiet	2
2	RADO is not large or heavy	2
3	RADO does not weaken security	5
4	RADO can be activated without using hands	3
5	Door can be used manually	5

2.3 DESIGN METRICS

Keeping the results of the interview in mind, the following specifications were decided on.

Table 3 Target Specifications

Metric No.	Associated Needs	Metric	Units	Acceptable	Ideal
1	2	Weight of mounting piece	lb	<15	<10
2	2	Volume of mounting piece	in^3	<108	<96
3	2	Time to open	s	<8	<5
4		ANSI/BHMA A156.19-2013 Durability Requirement*	cycles	$3*10^5$ (Minimum)	10^6
5	1	Operating noise	db	<40	<30
6		ANSI/BHMA A156.19-2013 Motor Force**	lbf	15	5

*Door opener must be able to operate for a minimum of 300,000 cycles its life.
**Device cannot exert more than 15 lbf, measured 1 inch from latch edge at any point in operation, when closing or opening door.

2.4 PROJECT MANAGEMENT

A Gantt chart was used for project management and is shown in fig. 6.

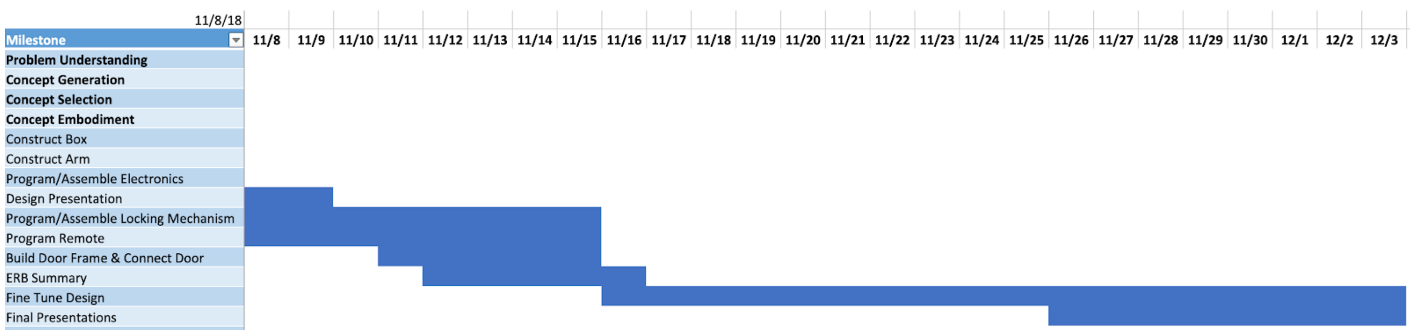


Figure 6 Gantt Chart

3 CONCEPT GENERATION

3.1 MOCKUP PROTOTYPE

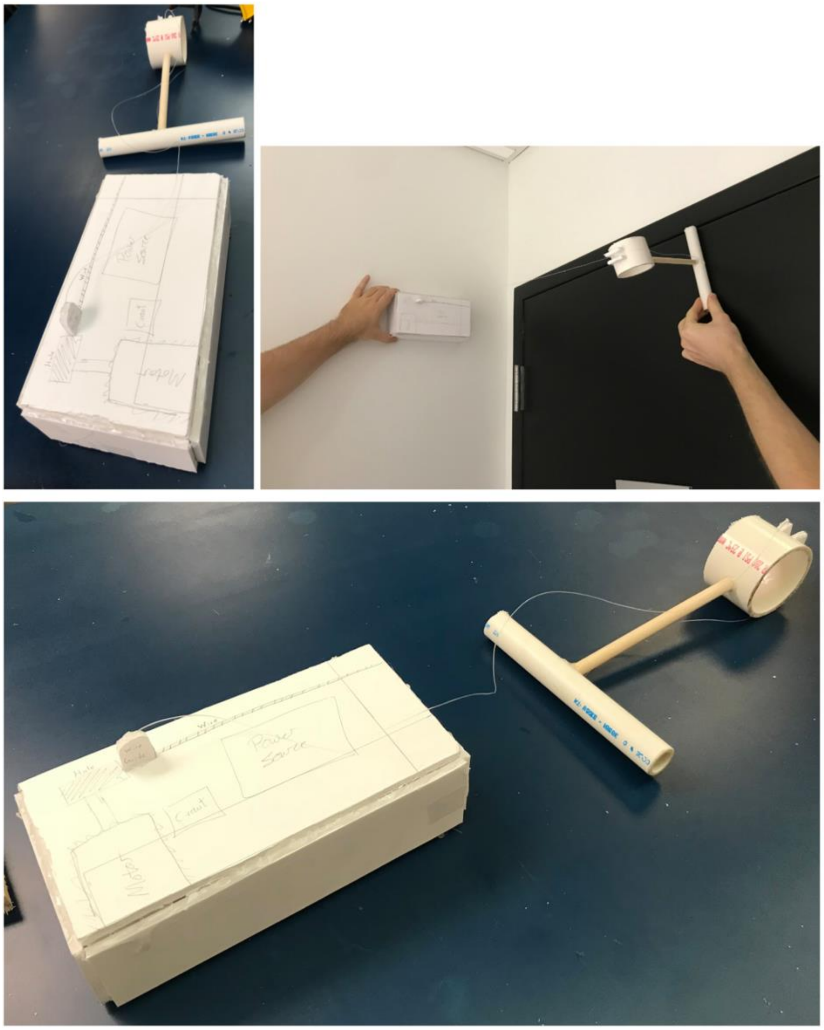


Figure 7 Photos of mockup

Creating the mockup gave our team more insight into the limitations of our device, especially features that would prove to not be as feasible. Initially, for example, the aim was to mimic products that used an arm mechanism. The most common option involved a motor rotating a linked pair of metal arms which would push the door open and close it by pulling. A problem with this design is that it requires a stronger and thus more expensive motor to open the door since the arm is connected to the center of the frame. The limiting length of the arms could not allow it to be placed at the end of the door, which would have required less force and allowed a cheaper motor. Due to these disadvantages, it was decided that a wire method would be more suitable for our goal of reducing costs as it would provide cheaper and simpler mechanical advantage. A mockup using this allowed the team to visualize issues with the angle of the resultant force on the door. The wire was initially anchored too close to the door, so the solution was to design a pulley system to shift the location upon which the force acts to make better use of it. This is notably seen by the use of a mechanical arm to provide distance for a more effective torque. The mockup also helped reveal unintuitive flaws that could not be clearly spotted in sketches, leading to further discussion on possible alternatives which highlighted new parts that had to be considered. One such example was to incorporate springs, whether to help close or open the door, as a key feature in the design.

3.2 FUNCTIONAL DECOMPOSITION

To help with making a design, a function tree was made to highlight the features needed in the design and is shown below in fig. 8.

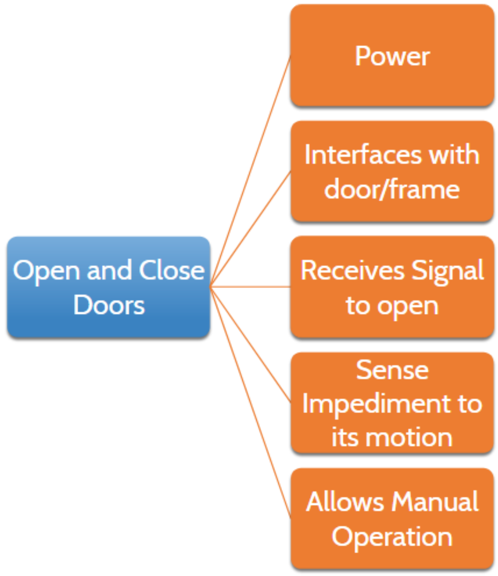


Figure 8 A function tree for the Design

Using this as a reference, a morphological chart was made to determine some design options.

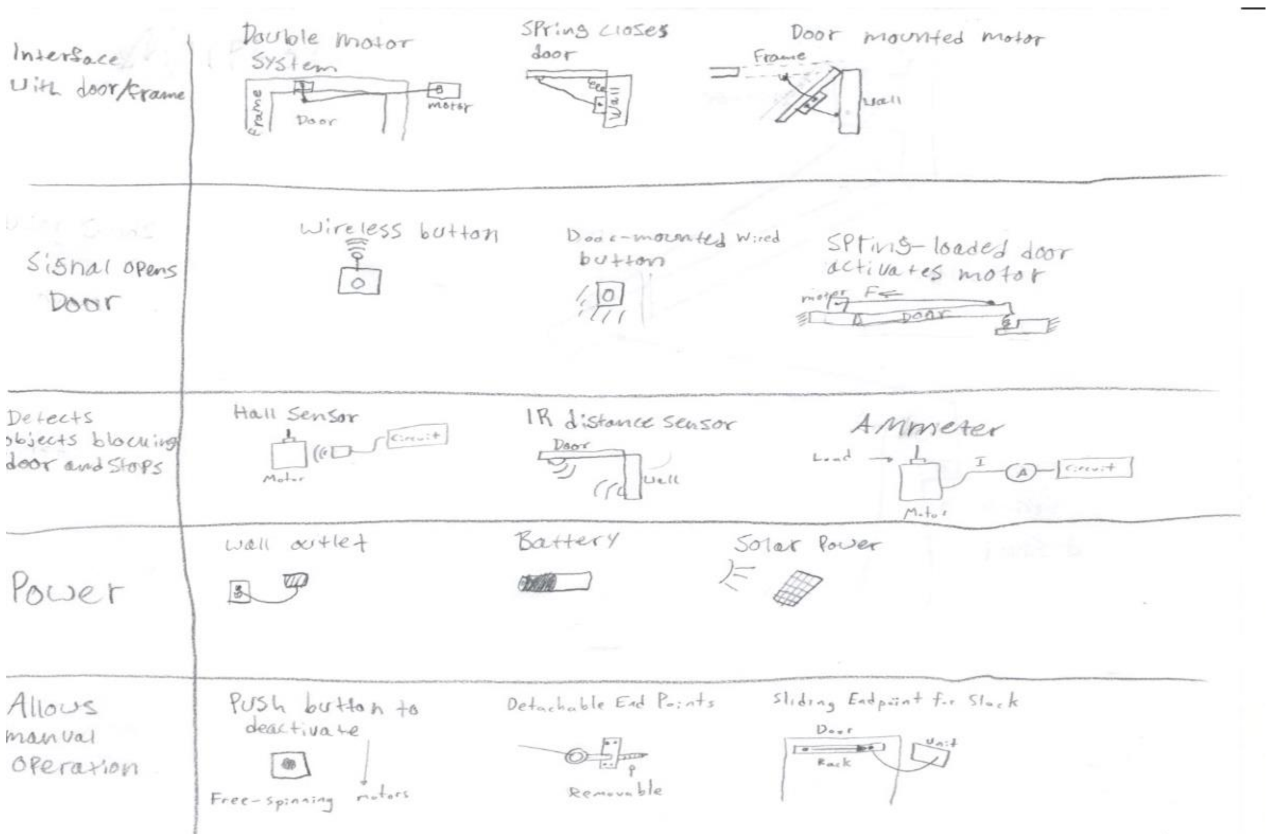


Figure 9 A morphological chart for the door opener

3.3 ALTERNATIVE DESIGN CONCEPTS

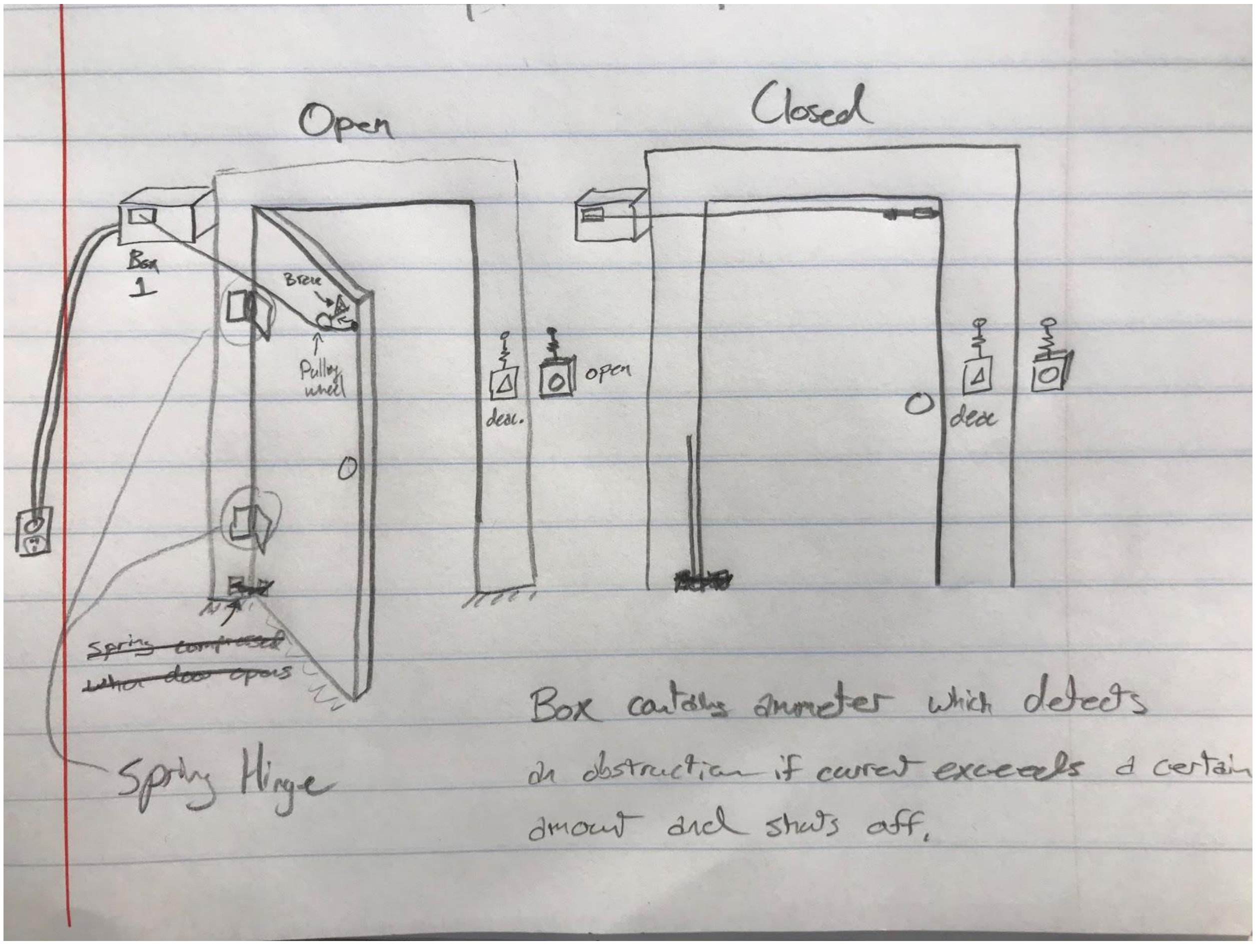


Figure 10 A design concept that uses a single motor with a spring at the hinges. Drawn by Ethan Bredemeier

The design in Fig. 10 uses a device that uses AC power from a typical 120V wall outlet. The motor has steel wire connected to the door via a pulley and an anchor for the wire. The pulley is designed to adjust the resultant force on the door and thus create a better angle for the motor to work with. The spring hinges are used to close the door when the motor deactivates and unwinds. Two buttons are used in this system and both talk to the device. The circular button is wireless and initiates the door opening mechanism whereas the triangular button deactivates the device for manual operation. These shapes are more just to differentiate them from one another, but the buttons don't have to be those shapes exactly.

Concept List: 1- Spring Closed Door 2-Wireless Button 3-Ammeter 4-Outlet 5- Button Deactivation

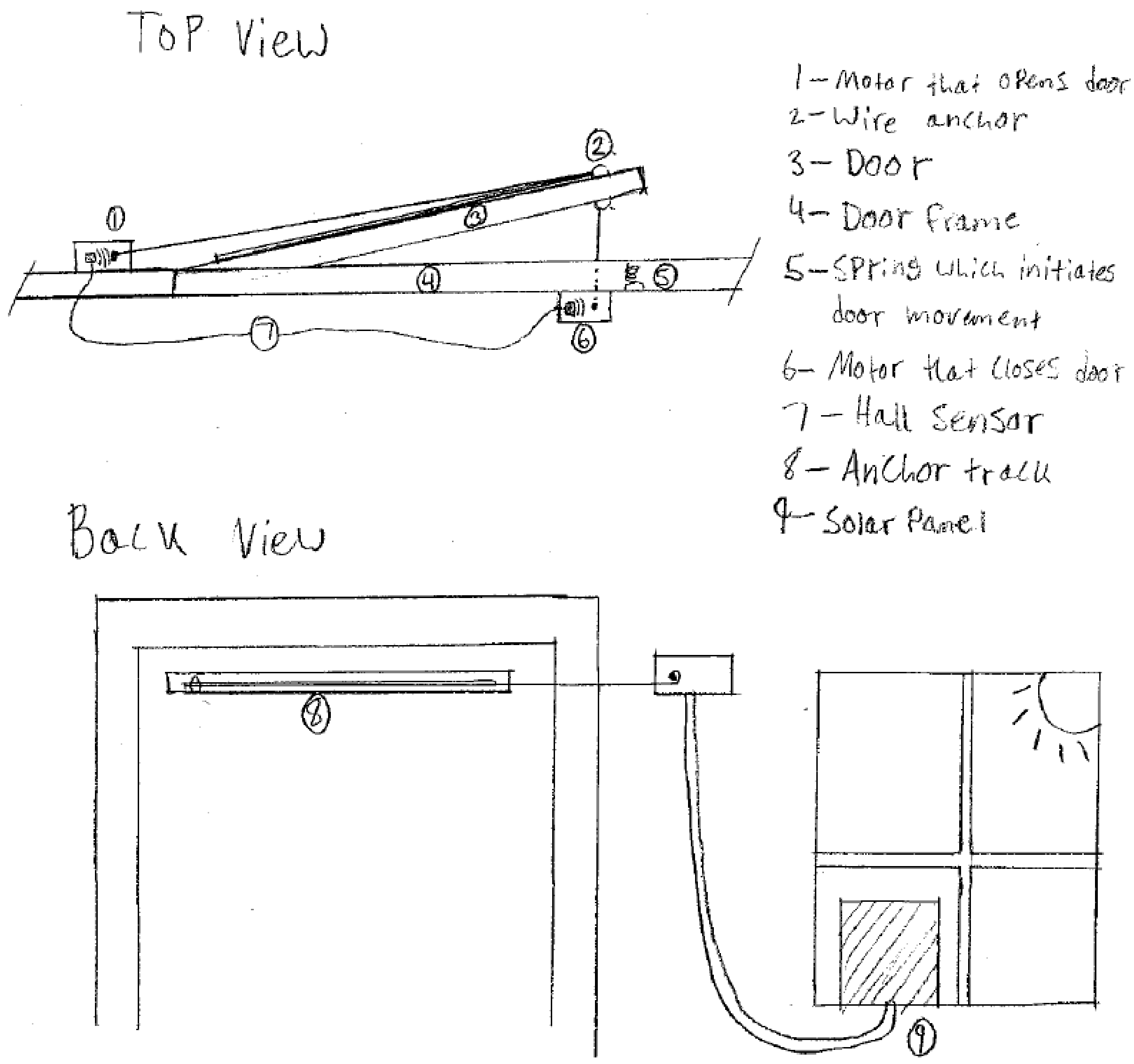


Figure 11 A design concept using a two-motor system. Drawn by Steven Downs

The design in Fig. 11 features two motors, one to open the door and one to close it. For the former action a motor is placed on the wall, and for the latter a motor is on the door frame on the opposite side of the door. The anchor to which the wire is connected is set within a track to allow the anchor to be moved aside and locked in place, allowing the door to be used manually; the anchor for the closing motor can be detached. A spring is placed within the frame such that it pushes the door to initiate its movement once the handle has been turned, which obviates the need for a mechanical arm and pulley to redirect the force. Hall sensors are in place to detect fluctuations in the motor indicative of something obstructing the door. Lastly, power is supplied via solar energy, the depiction of which serves only to convey the concept rather than the intended setup.

Concept List: 1- Double Motor System 2- Door Spring Activation 3- Hall Sensor
4- Solar Panels 5- Anchor Track

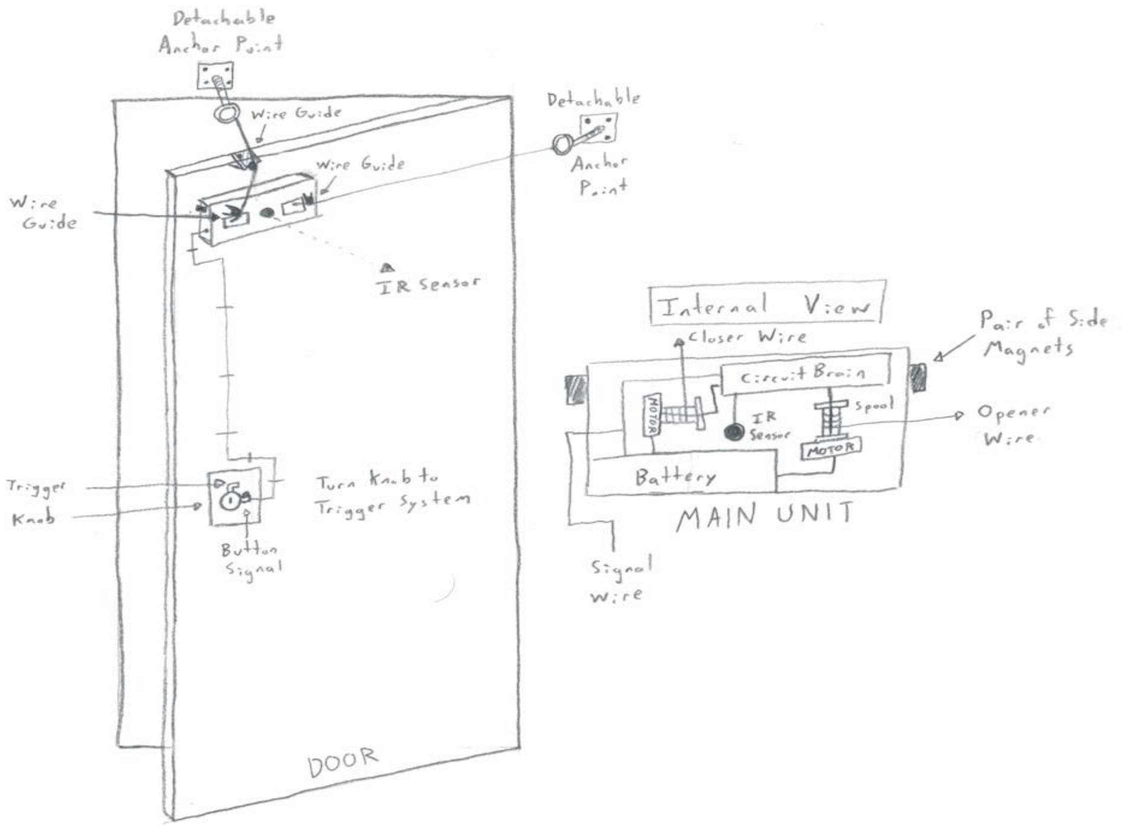


Figure 12 Final Concept Sketch - "The Central Motor Design" by Ardian Pollo

The main feature in Fig. 12 is the incorporation of a central motor unit on the door itself as the interface solution. Inside are two separate motors that winds a spool with a metal wire connected to an anchor point at the top of the frame and the wall next to the door. Along the way is several wire guides to prevent entanglement with the top of door and the holes in the unit. A door mounted button starts the system. The user must turn the knob all the way since attached is a metal hook at the base which presses a button. This signal is carried by wire up to the circuit board above in the main unit. To sense impediment to motion as a safety feature, an IR sensor embedded in the unit. A larger battery powers all of the above including the circuit which regulates the motion of the system. To allow for manual operation, the end points can be unscrewed and attached via magnets to the main unit. This incorporates the following concepts from the morphological chart: door mounted motor and wired button, IR distance sensor, battery, and detachable end points to meet their respective functions.

Concept List: 1- Central Motor System 2- Wired Door Mounted Button 3- IR Sensor
4- Battery Power 5- Detachable Anchor Points

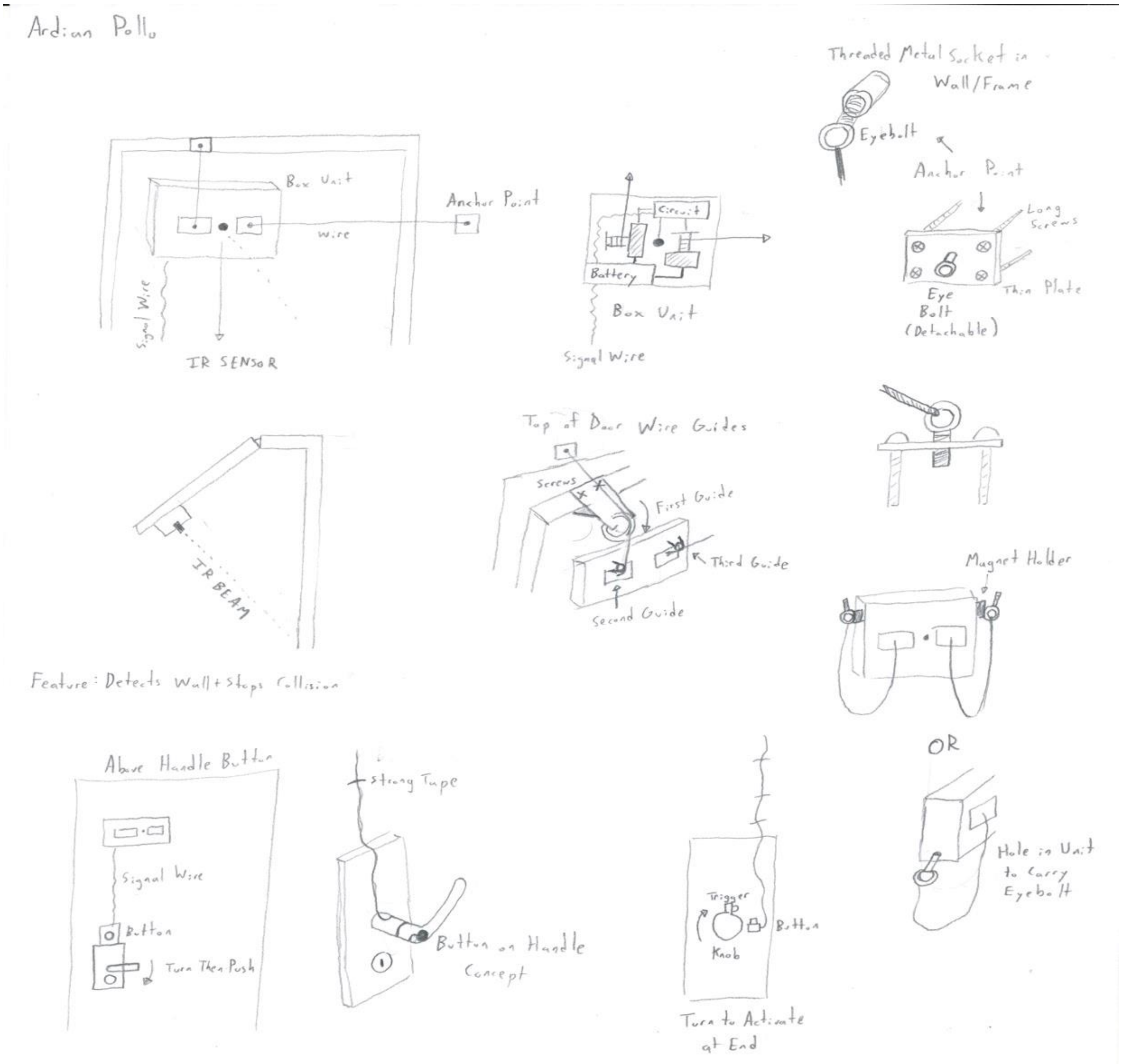


Figure 13 Preliminary Rough Sketches by Ardian Pollo

4 CONCEPT SELECTION

4.1 SELECTION CRITERIA

To help determine which concept is best, an analytical hierarchy process (AHP) was created and is shown in the figure below.

	Visually appealing	Inexpensive	Simplicity	Allows manual use	Opens quickly	Detects obstructions	**Row Total**	**Weight Value**	**Weight (%)**
Visually appealling	1	0.11	0.25	0.14	1	0.2	2.7	0.03	3.19%
Inexpensive	9	1	5	0.25	1	0.25	16.5	0.19	19.48%
Simplicity	4	0.2	1	0.2	0.33	0.33	6.07	0.07	7.16%
Allows manual use	7	4	5	1	9.01	5	31.01	0.37	36.61%
Opens quickly	1	1	3	0.11	1	0.11	6.22	0.07	7.35%
Detects obstructions	5	4	3	0.2	9	1	22.2	0.26	26.21%
						Column Total:	**84.7**	**1**	**100%**

Figure 14 An analytical hierarchy process for the chosen criteria

4.2 CONCEPT EVALUATION

Using the results from the AHP, a weighted scoring matrix was created to rank the concepts overall.

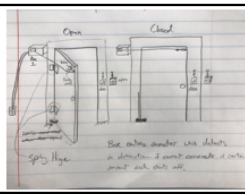
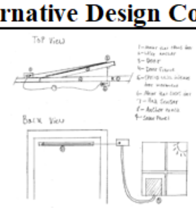
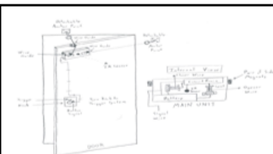
		Alternative Design Concepts					
							
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Visually appealing	3.19	3	0.1	4	0.13	2	0.06
Inexpensive	19.48	4	0.78	3.25	0.63	3	0.58
Simplicity	7.16	5	0.36	4	0.29	3.5	0.25
Allows manual use	36.61	5	1.83	3	1.1	3	1.1
Opens quickly	7.35	1	0.07	4	0.29	4	0.29
Detects obstructions	26.21	2	0.52	3	0.79	4	1.05
	Total score	**3.661**		**3.226**		**3.339**	
	Rank	**1**		**3**		**2**	

Figure 15 A weighted scoring matrix ranking each design concept

4.3 EVALUATION RESULTS

The results of the weighted scoring matrix show that the single-motor system is the best design concept. Due to having one motor instead of two like the other designs have, it is much simpler and will cost less. The obvious advantage of lower cost, we consider to be the differentiator between our device and existing ones. Additionally, the advantage of a simpler device lies in the fact that there are less parts to fail, and more time and effort can be spent on each part in a simpler design. The deactivation button was deemed unnecessary because nothing prevents the door from opening without the device being activated and the wire will simply go slack when opened manually. This ease of manual operation is not present in the other designs due to the second wire that closes the door, which would need to be detached from the door first to prevent the wire from unwinding and staying unwound. The area in which it performed the worst is time to open, which is a result of having springed hinges that add additional resistance. It also scored poorly in detecting obstructions because no measure was put in place, but this shall be corrected. Regarding aesthetics, the concept is relatively compact and thus should not be bothersome.

4.4 ENGINEERING MODELS/RELATIONSHIPS

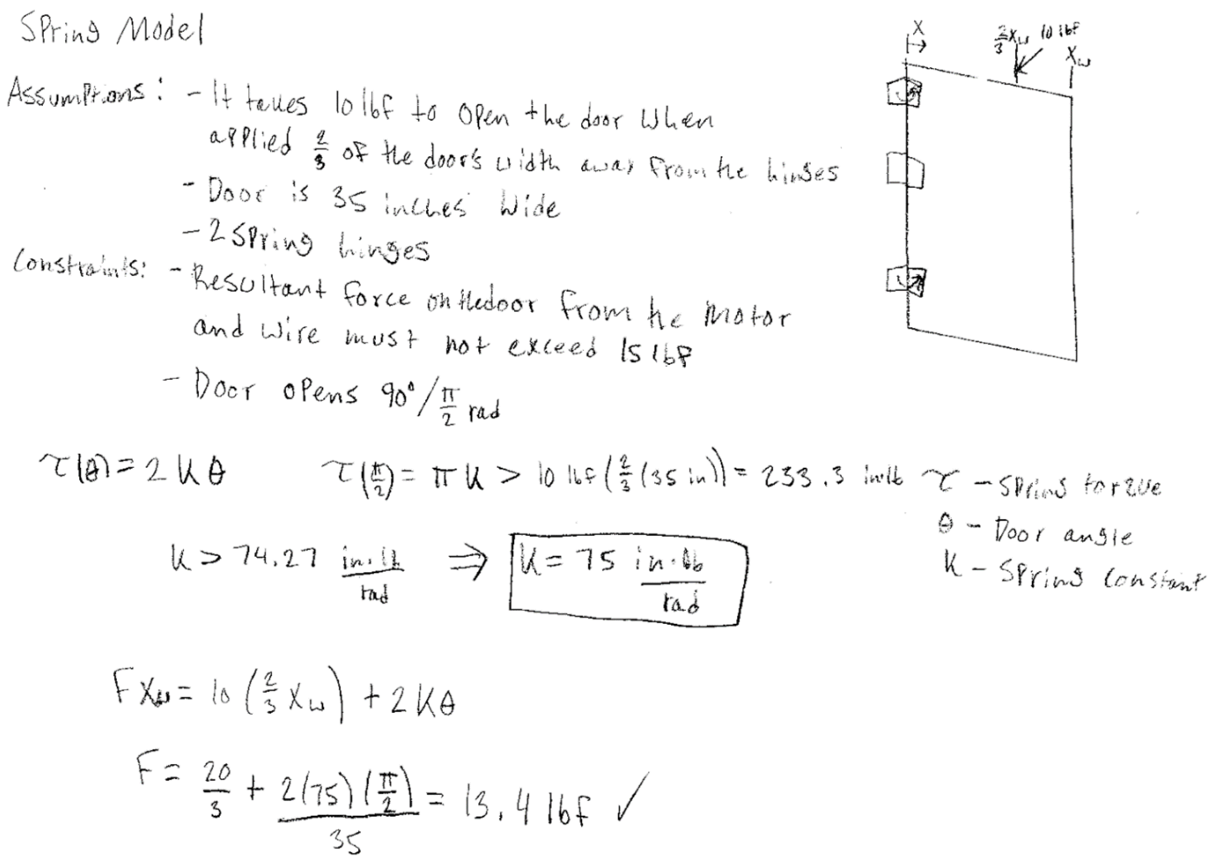


Figure 16 Spring hinges force calculations

This model proves the motor can open the door without exerting more than 15 lbf, as required by the safety standard, despite the additional resistance provided by the springs. Assumed values were taken based on common figures and the springs' material was chosen based on existing products [4]. An older model calculated the dimensions of the spring, but springed door hinges were later decided on to use and made them unnecessary. In that model, either the spring diameter or the spring arm length could have been prescribed a value, but the former was chosen due to the smaller size and thus higher degree of precision needed during manufacturing. In addition, this value was chosen based on available size ranges.

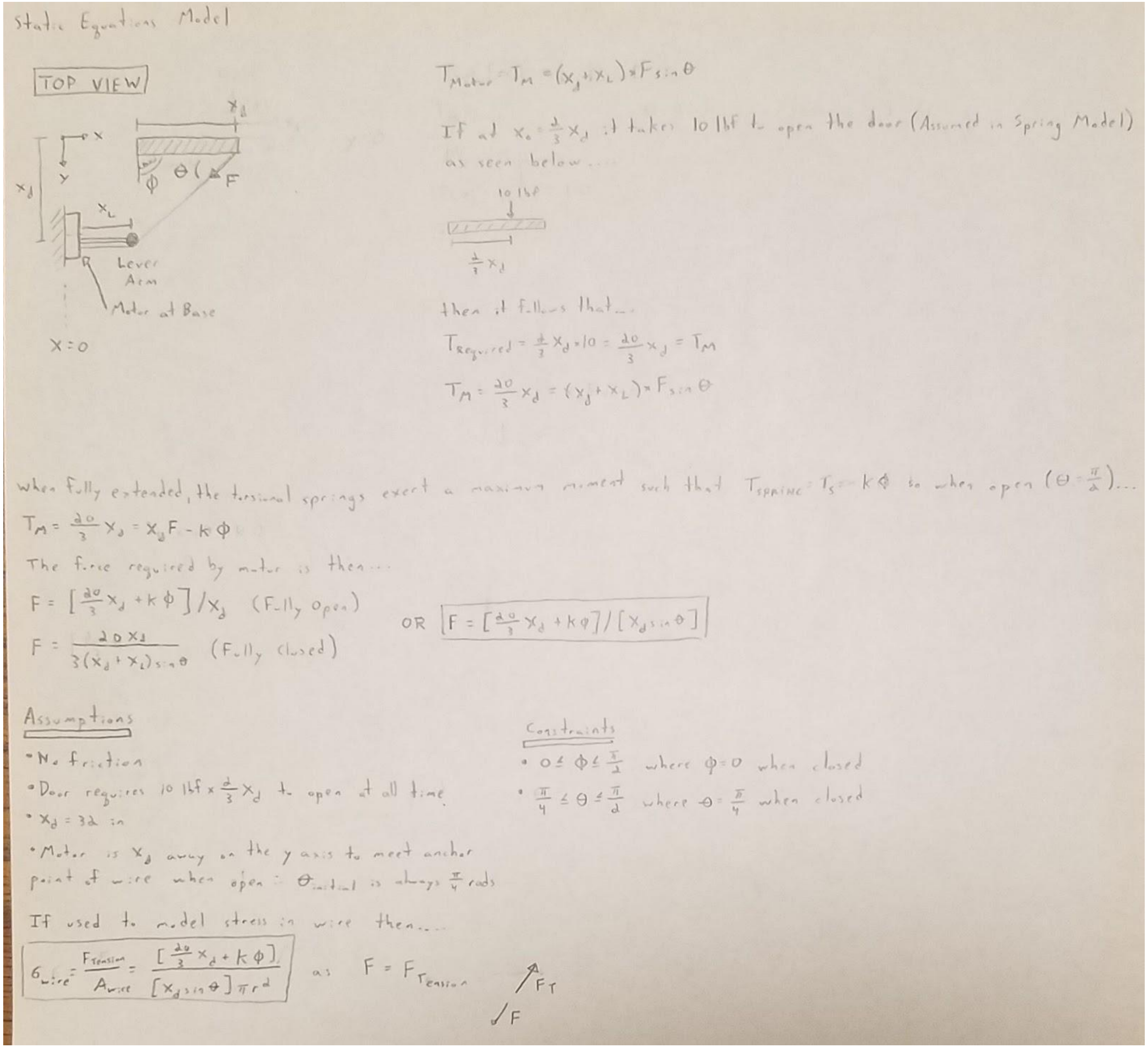


Figure 17 Static Equations and Wire Stress

What this model can show is how the force exerted by the motor depends especially on the geometry the wire and the stiffness of the springs in the hinge. Crucial is the detail that sin(θ) should be maximized in order to reduce the required motor force for the same torque. The ideal angle is thus $\pi/2$ radians with the anchor point and motor unit the same distance from the origin when closed. This will minimize the impact from the springs. One important note is that the end free body diagram assumes the tension of the wire to be equal to this motor force in the model. This gives a simple formula for the wire stress σ which relates the motor force and area of wire. For the same maximum stress, the force will dictate how thick a wire of a given material must be to avoid failure. It also shows that it would be a mistake to assume only tension due to the motor. What must be considered is the possible maximum force exerted by a person trying to slam the door while in operation in addition to the motor.

In addition to the above model, a second was made for a different configuration.

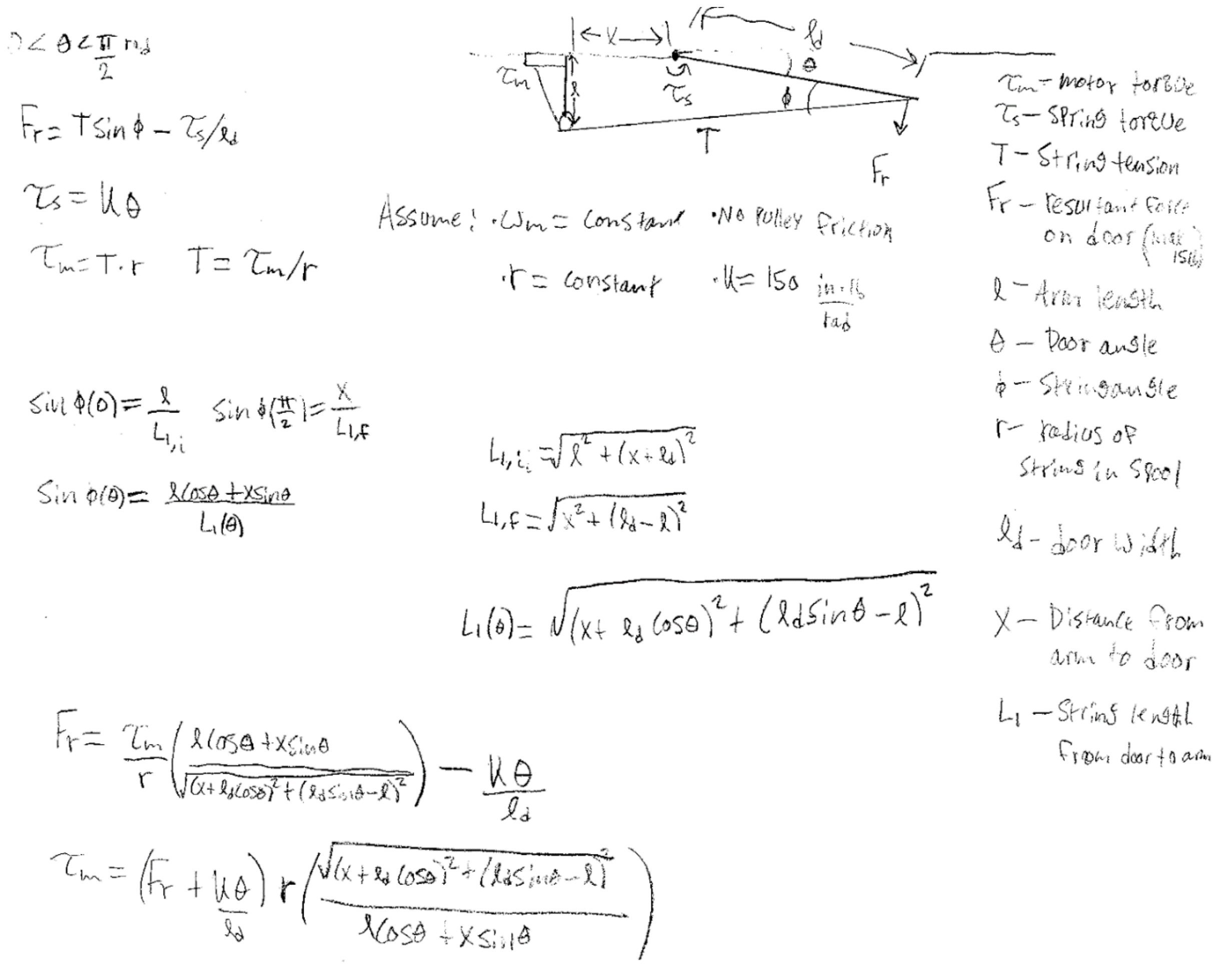


Figure 18 Secondary static analysis for wire tension

		day		
Average times door opens per day?	*day*	5	1825	times per year
duration of motor running during run? (s)	*Seconds*	5	0.0014	hours to open door
			2.53	hours operated/year
According to Engineering Toolbox (kW)	*kW*	3.7	**9.38**	kWh/year
Electric Rates in STL	*Dollars*	$ 0.1258	**$ 1.18**	Electrical Cost per Year (STL)

Figure 19 Power consumption

This model looks at the power consumption required to operate the motor with regards to torque. Additionally, an economic analysis was taken to determine the lifetime operation cost of the device. According to our estimates, the device will be used around 5 times per day 365 days per year. Standard ANSI/BHMA A156.19-2013 requires a 300,000-cycle lifetime which means our device could be passed on for 165 years. Thanks to the previous two models we calculated, we can assume an average power output of 27.6 lbf-ft torque with a maximum torque exerted on the motor of 37.4 lbf-ft. From these values we selected a motor with 3.7 kW of power which can exert up to 53 lbf-ft at 500 RPM. This was determined by using a table relating power and torque to speed [5]. Over time, the cost per year of the device in terms of electrical operation cost will be about $1.18. This was calculated using a standard residential rate of 12.58 cents/kWh from Ameren Missouri [6]. For a more conservative reasonable lifetime of 50 years, the total present value of the electrical cost is $13.28.

5 CONCEPT EMBODIMENT

5.1 INITIAL EMBODIMENT

CAD models of the RADO prototype were made in SolidWorks. An assembly view with a bill of materials is shown in the figure.

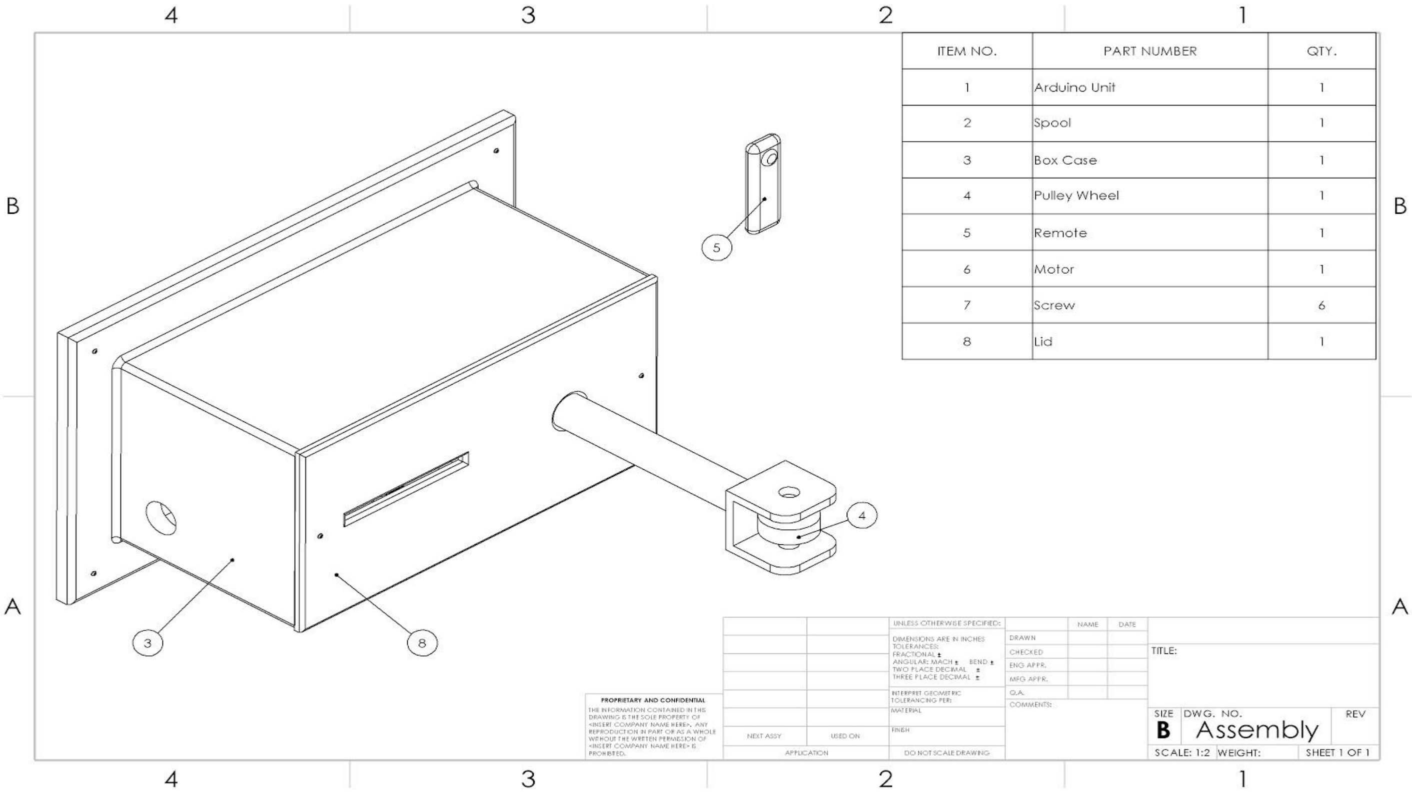


Figure 20 An assembly view of the RADO with a bill of materials

An exploded view is shown in the figure below.

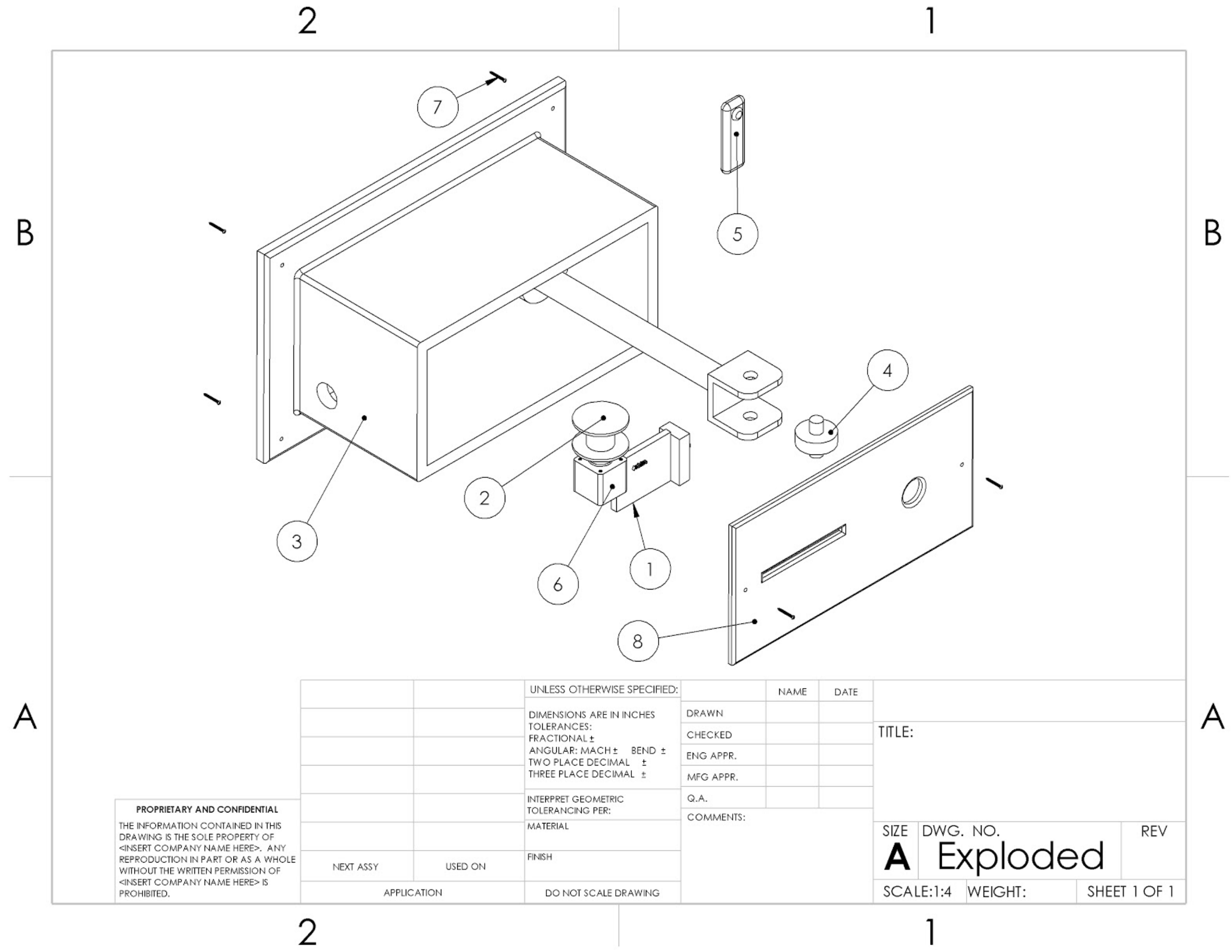


Figure 21 An exploded view of the RADO

The front, left, and bottom views with dimensions are shown in fig. 22. The bottom view was chosen over the top view to show the supports.

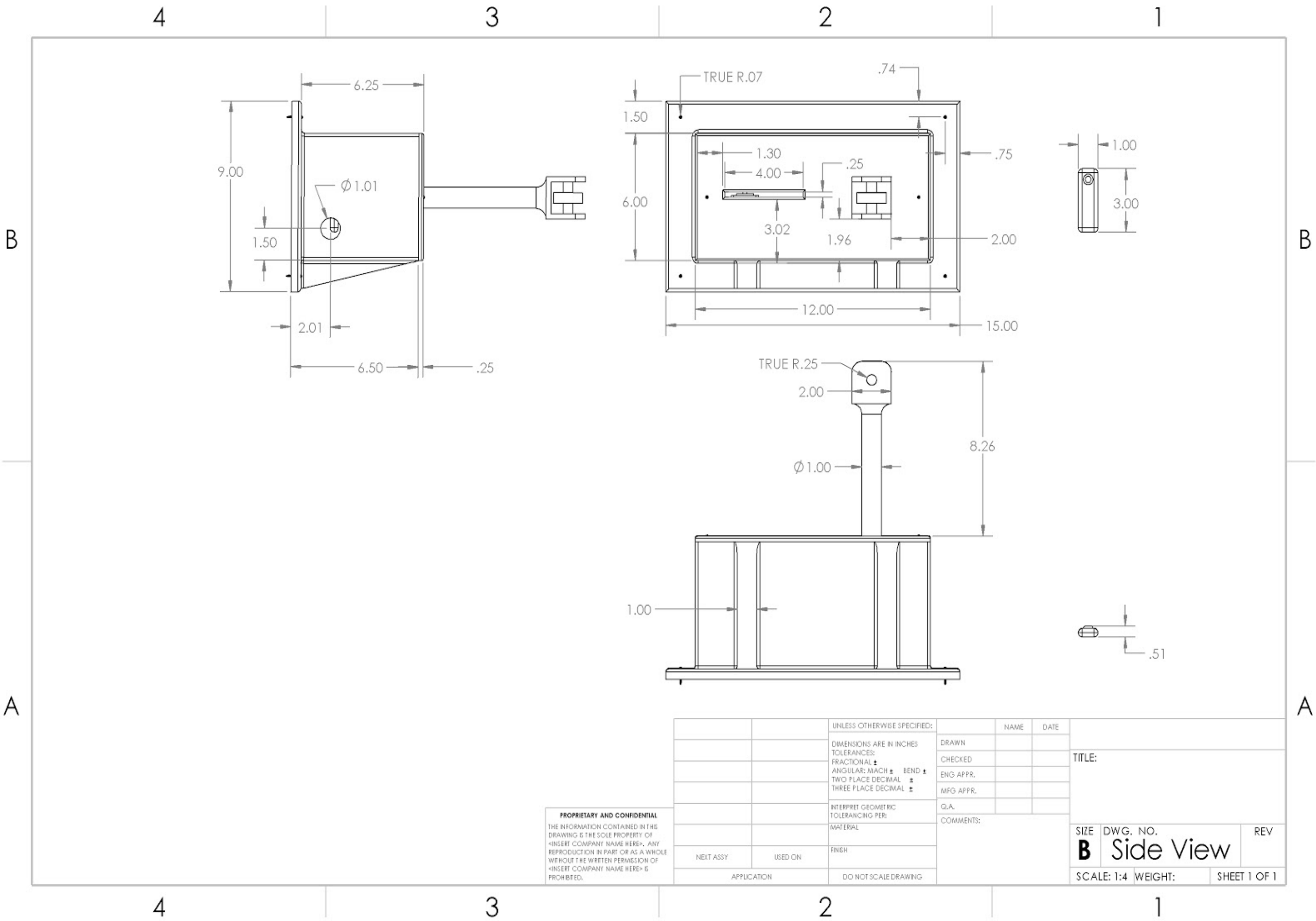


Figure 22 Front, left, and bottom views of the RADO with dimensions in inches

The parts used for the proof-of-concept prototype are listed in the following table.

Table 4 Initial parts list of components

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit Price	QTY.	Total Price
1	Drill Motor	Amazon	B0791T26VD	280W, includes slip clutch	$32.09	1	$32.09
2	Spring Door Hinges	Amazon	B00JS31K9A	Gray, 4"x4"	$24.56	2	$24.56
3	Arduino	Amazon	A000066	3.1"x 2.2"x 1" Blue	$22.69	1	$22.69
4	String and Spool	Jolley Basement	N/A	Green string, gray spool	Estimate ~$5	1	$5
5	Pulley Wheel	Jolley Basement	N/A	2.5" Diameter, silver	Estimate ~$5	1	$5
6	Wireless Button	RobotShop	DFR0107	Black and white, RB-Dfr-92	$12.02	1	$12.02
						SUM:	$101.36

[1] https://amzn.to/2A7UOU3
[2] https://amzn.to/2QNpeQT
[3] https://amzn.to/2QLJtyp
[4] https://bit.ly/2IUCHDU

5.2 PROOF-OF-CONCEPT

Three performance goals that the prototype will be expected to meet are as follows:

1. RADO will open the door within 10 seconds.
2. RADO will complete 10 cycles without maintenance.
3. Total weight is below 7.5 lb.

Many design choices went into the RADO, several of which were determined using our models above. The types of parts within the system were split into three different categories: mechanical, electronic, and aesthetic. The mechanical components are important for the support and function of the RADO whereas the aesthetic pieces can use cheaper, lighter, and materials that are easier on the eyes. First, the product must work before we can worry about the aesthetics of the product. Some critical design features for support include the braces on the bottom of the box, a reasonably large diameter support at the base of the pulley arm, and strong lightweight materials such as wood or aluminum for the mechanical pieces. All of the specific dimensions were determined using our first two models involving the spring force and the force required to open the door. Other pieces included in the mechanical components are the pulley arm, pulley, and the anchor point on the door. Electronically, we chose to use a DC drill motor with a slip clutch and an AC/DC converter so that the RADO can be operated without a battery. This was decided on because we were unable to find a AC Drill with a slip clutch. Our second highest rated feature was detecting obstructions, so it is necessary to use a drill motor with a slip-clutch attached. This feature adds a safety benefit to the design as the clutch will prevent the string from breaking and the door from harming anything that may obstruct its path. Another electronic design choice is using an Arduino to control the motor and manage the signal inputs. This component will require coding to allow the motor to rotate fast enough to meet our performance requirements.

6 WORKING PROTOTYPE

6.1 OVERVIEW

The following changes were made going from the proof of concept to the working prototype:

- The string was replaced with steel wire that could withstand the tension it would experience from the weight of the door, the strength of the spring hinges, and the torque from the motor.
- A solenoid locking system was implemented as a safety feature that functioned as an external automated deadbolt lock. The solenoid was paired with a spring attached to the bolt. When the solenoid was activated it would unlock the door, and when the solenoid was deactivated, it would lock the door by allowing the spring to decompress.
- The spool was replaced with a long screw containing a cap at one end to better contain the stiffer wire. Additionally, the spool was widened to fit the thicker wire.
- The Battery was replaced with an AC to DC converter which provided more consistent power to the motor. This is a key component of our design where a daily battery change would no longer be necessary.
- A small wire was placed around the pulley wheel to keep the wire from falling off the pulley.

6.2 DEMONSTRATION DOCUMENTATION

We took some images of our working prototype as can be seen in the figure below.

Figure 23 Images of the working prototype

6.3 EXPERIMENTAL RESULTS

The first performance goal of having the RADO take 10 seconds or less to open was met with relative ease as the rotational speed of the motor can be programmed. For the working prototype, the motor was programmed to open the door in exactly 10 seconds. In future work, this could be made faster bearing in mind that the force normal to the door must not exceed 15 lbf as required by safety standards. For faster speeds, a door stopper would be needed to halt the movement of the door, which for the working prototype was not necessary due to the adequate deceleration provided by the spring hinges.

The second of running for 10 cycles without the need for any adjustments was also met, albeit with less ease. The one problem was that the wire would not stay wrapped around the small radius of the spool and would try to straighten out if the wire slacked at all, which meant that the door would not close back to its initial position and ended up slightly more open with each run. To compensate for this, the motor was programmed to close for a slightly different amount of time from the time to open. This can be eliminated by using the minimum amount of wire needed for the RADO to function.

The last goal of having the box unit weigh no more than 7.5 lb was also achieved relative ease, with the final weight being about 7 lb. This could have been even lower because the box dimensions were intentionally made larger than necessary as a precaution against unexpectedly needing more room inside the box with which to work. This led to having more than a third of the volume being empty and unused. Additional work could be put into consolidating the internal components to a more efficient configuration, thereby reducing the necessary dimensions even further. This would then allow for sturdier and thus heavier materials to be used in the unit.

7 DESIGN REFINEMENT

7.1 FEM STRESS/DEFLECTION ANALYSIS

Below is a FEA simulation created in SolidWorks which captures the typical conditions and constraints the unit endure in its operation. The focus was the displacement of the lever arm, subject to an imposed force of 60 lbf located at the pulley wheel perpendicular to the arm. This value is realistic as it is theoretical calculated maximum tension the wire on the pulley will experience and transmit to the pulley. It does factor in external forces such as human interference, so it would not represent a normal operation. The only constraint was a fixed bottom since the device will be mounted to the wall via bolts, limiting its movement in all directions. The mesh used was a medium mesh which is enough to model the displacement of the lever arm.

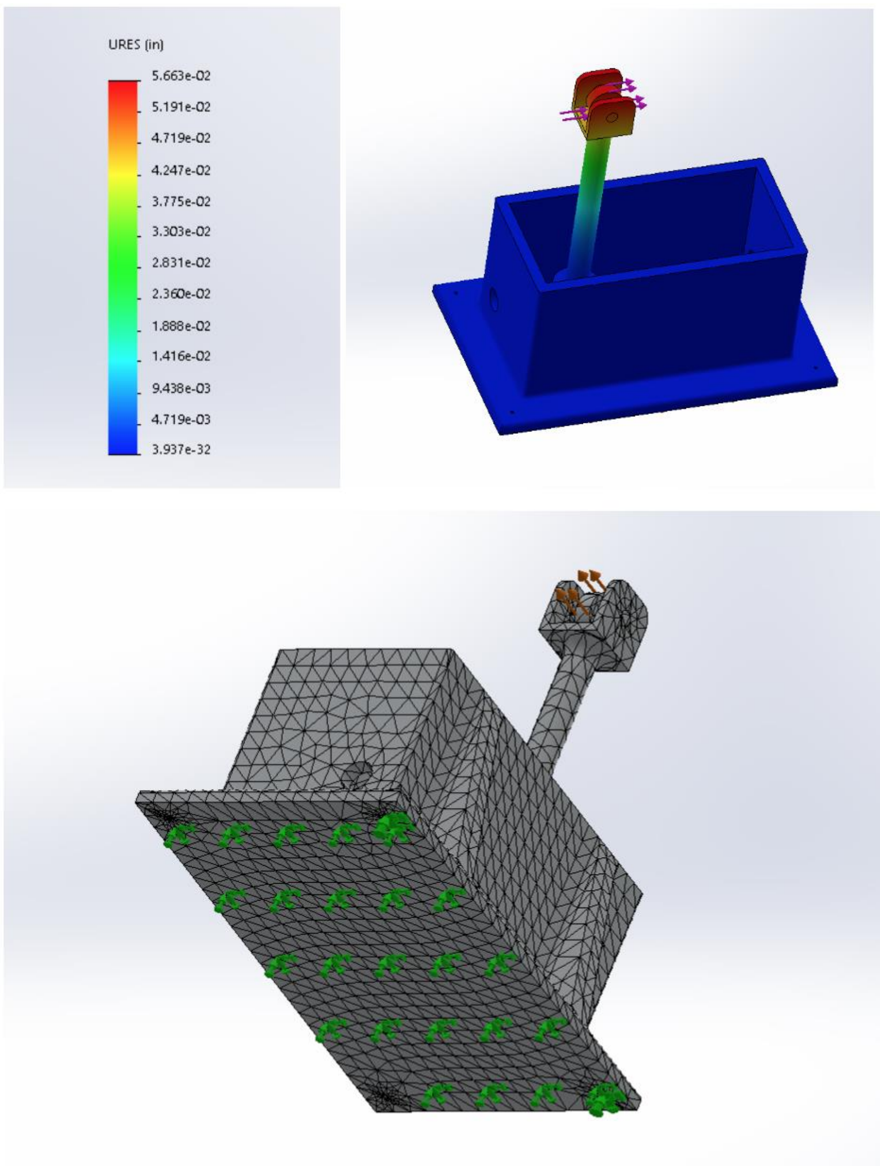


Figure 24 Loaded deflection simulation and unloaded medium mesh model

As seen in Fig. 24 the maximum deflection occurs at the pulley towards the door. The maximum deflection is approximately 0.053”. This minimal deflection will cause no problems to the functionality of RADO. This maximum deflection it would take to cause a significant problem is when the RADO arm would start to deflect. This will never happen as other parts such as the wire will fail before the arm does.

7.2 DESIGN FOR SAFETY

In the interest of safety, several risks have been analyzed based on likelihood and severity to prioritize efforts in mitigating them.

7.2.1 Electrical Fire

Risk: Electrical fire
Description: A short circuit or exposed wire ignites flammable material.
Impact: 5. This has the potential to burn down a house and cause serious injuries.
Likelihood: 1. Using power rated wires, removing any flammable materials, and covering any exposed wires or connections, this can easily be avoided.

7.2.2 Falling off of the wall

Risk: Falling off of the wall
Description: The entire unit falls to the ground and damages both the RADO and the floor.
Impact: 3. The RADO could break completely and require replacing. Floorboards may also need replacing.
Likelihood: 2. This is easy to avoid if the RADO is secured with long bolts into a strong wall and is light.

7.2.3 Slip clutch fails or is improperly calibrated

Risk: Slip clutch fails or is improperly calibrated
Description: The slip clutch fails and the door opens with too much force.
Impact: 2. Excessive force may be applied to the door by the motor, potentially hitting the user or damaging the RADO.
Likelihood: 1. This is only likely if there is a manufacturing error or it was improperly set at installed.

7.2.4 Wire breaks

Risk: Wire breaks
Description: The wire is put under too much tension and snaps, making the door close and hit the user.
Impact: 1. Injuries are unlikely to occur from the door hitting the user.
Likelihood: 2. This is most likely to occur by an external force acting on the door during operation. Design considerations will be put into the wire selection, making sure a reasonably strong wire is chosen. Cost considerations may require compromise on the lifetime of the wire, meaning the wire will be expected to last a certain number of cycles until breaking or replacing.

7.2.5 Electrocution

Risk: Electrocution
Description: The user is electrocuted when performing maintenance on the wall unit.
Impact: 5. This can result in serious injury or death.
Likelihood: 1. No exposed wires or connections should be present in the RADO, and if the user disconnects the power before performing maintenance this will not happen. Ideally, the RADO should not require maintenance.

7.2.6 Risk Assessment

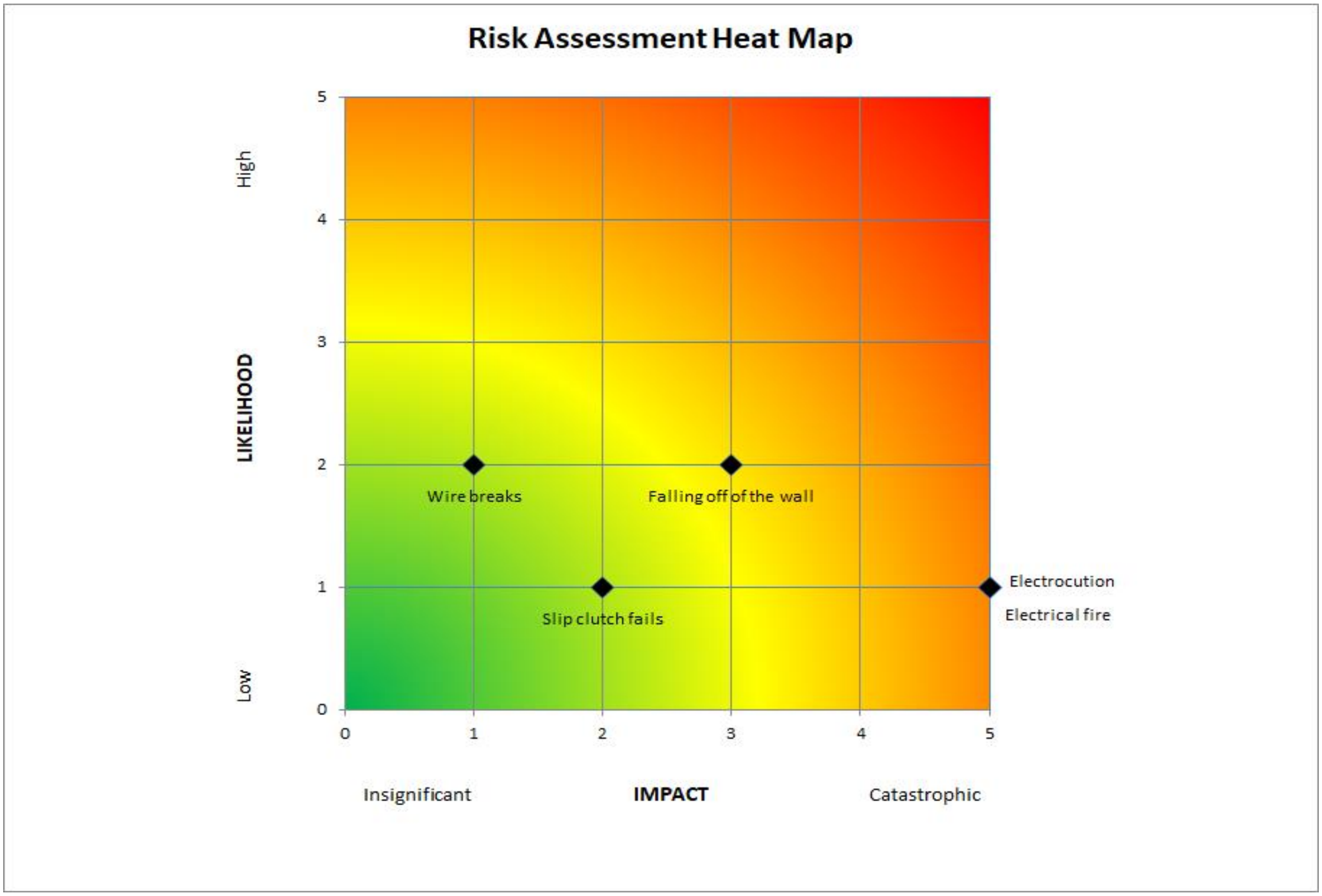


Figure 25 A risk assessment heat map visually representing what risks should be prioritized

Electrocution and electrical fires are shown in fig. 25 to be the highest priority risks that should be dealt with despite the likelihood being very low. This is reasonable because these are risks that should not just be "unlikely" to occur but almost impossible to occur. The second highest priority is ensuring the RADO does not fall from the wall, which would require repairs to be made or replacement of the unit, wasting the user's money due to a relatively easy to avoid issue. Tied for the lowest priority are the wire breaking and the slip clutch failing. The former will depend on the quality of wire chosen and the latter merely requires the proper settings to be in place.

7.3 DESIGN FOR MANUFACTURING

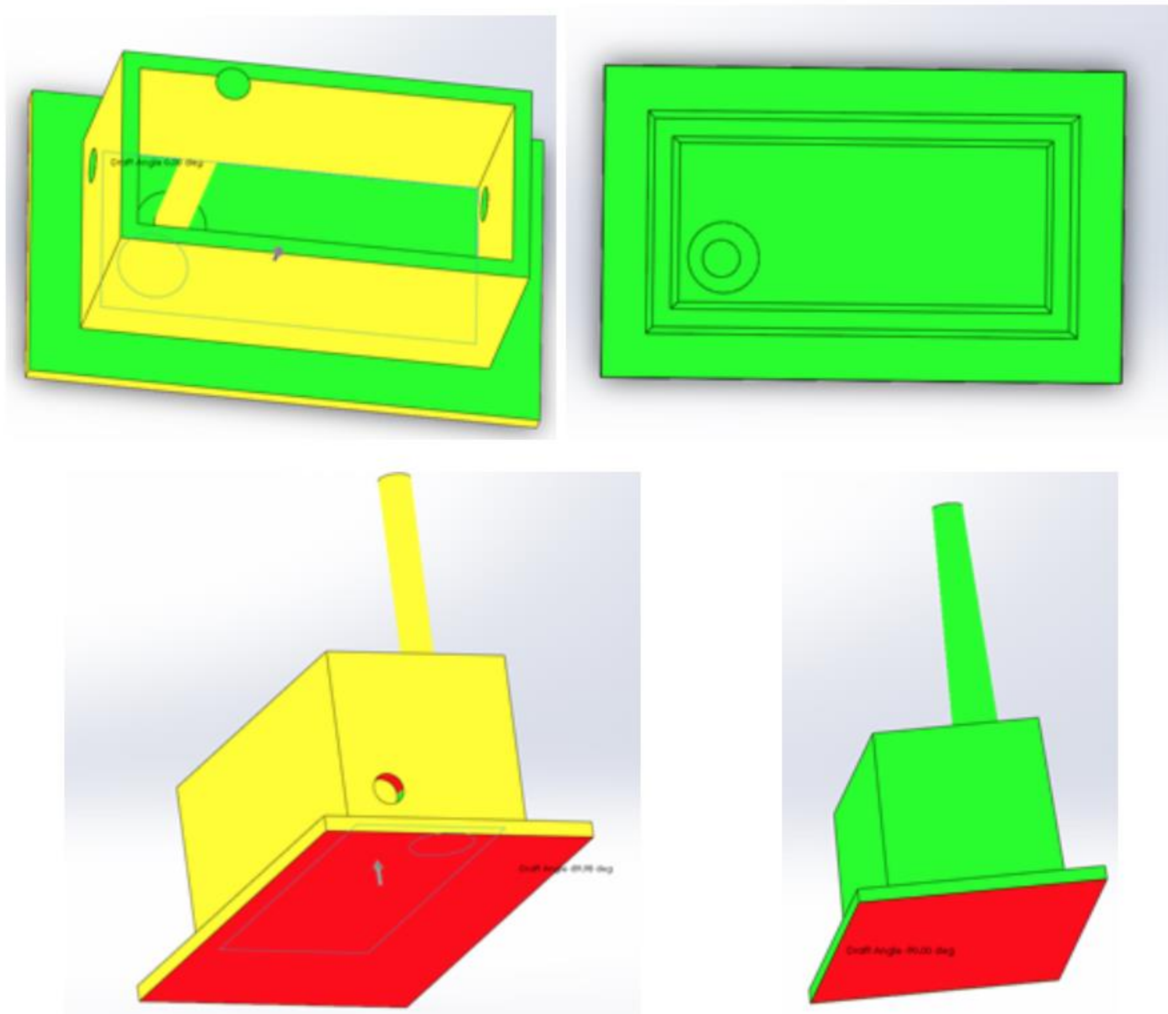


Figure 26 Draft analysis of box component of RADO

For our first DFM analysis, we decided on using injection molding. Our base and walls can be made more quickly and cheaply with a plastic material rather than a metal. Additionally, the product can be made out of lighter material. A few changes that we made to our original model is we removed the two parts of the pulley arm and made it into one long arm with a 2-degree chamfer. The reasoning behind this was that adding two separate chamfers to the two parts resulted in a smaller diameter at the top of the pulley arm which sacrifices structural stability. Combining the parts and adding one large chamfer of 2 degrees allows us to keep stability and makes it easier to manufacture. Another change we had was removing the two holes on either side of the housing unit. These horizontal holes added unnecessary complexion to the injection molding process. Instead of adding this complexity, we decided to work smarter and not harder and add a step of drilling into the housing after it has been molded. This makes it faster, cheaper, and easier to manufacture.

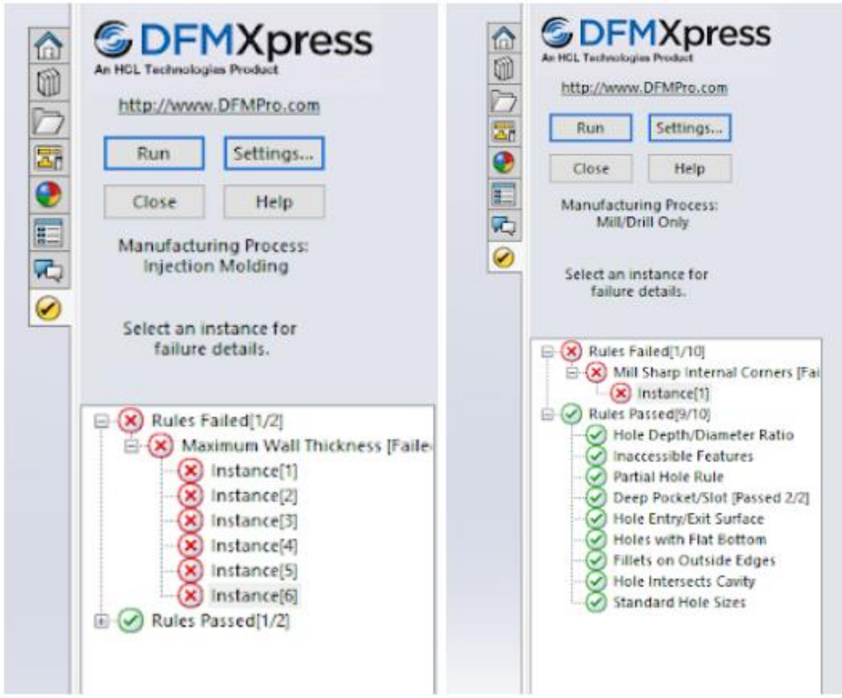


Figure 27 Injection molding and milling manufacturing processes

For our first manufacturing process we chose injection molding. Injection molding is great for mass production and cheap material design. Our one issue with injection molding is that we haven't designed the walls to an appropriate thickness. For the majority of the instances, we could make the walls thinner to comply with the maximum wall thickness parameter. However, the base wall thickness should remain thicker than the maximum wall thickness of 0.12" because it is a force-bearing part that will be mounted to the wall. A base that is too thin could result in failure of the pulley arm. Additionally, the pulley arm has a wall thickness that is too thick, but this is also necessary as it is also a force-bearing part. For our second manufacturing process we chose to use mill/drilling. This is a slower process than injection molding but resulted in fewer problems. The only issue our design faced was that the interior corners were too sharp for a mill to accurately cut. This is an easy design fix as we would simply fillet the interior corners to a diameter that would expedite the milling process.

7.4 DESIGN FOR USABILITY

Certain impairments may require specific modifications to be made to the RADO to make it easy to operate for all users, some of which are addressed here.

Vision - The only component of the RADO which relies upon vision is the activation switch. Having a switch that is large, has writing or a symbol indicating its purpose (eg. "Open," handicap symbol), and has a color scheme which contrasts with the wall would make it easy to use in most cases of vision impairment. Additionally, having lights on the switch would make it easier to see in the dark.

Hearing - The usability of the RADO is not dependent on the user's hearing capabilities, relying only upon the activation of the switch, and thus requires no modifications regarding it. It is, however, a possible that a malfunction that could be detected by sound (such as a motor issue) may occur and go unnoticed, leading to greater damage. A modification that would be helpful is a red light on the RADO which activates when a malfunction is detected.

Physical - The purpose of the RADO is to make it easier for users with physical disabilities to use a door, making it unnecessary to create additional modifications. As long as the activation switch is easily reachable and triggerable, most cases of physical impairments should not prevent the user from operating the RADO. The trigger is simply a button, which takes little work to activate.

Language - As with vision impairments, a large switch with a universal symbol, such as the handicap symbol, indicating the function of the switch should make the required input apparent. Alternatively, including in the manual labels with a selection of languages that can be placed on or near the switch can communicate what the user needs to do. This, however, cannot account for all languages.

Control - As before, a large switch that is noticeable and easy to press will make the RADO simple to operate for users with impaired motor control, who are distracted, or are under the influence of medication. It is highly unlikely for there to be a situation in which missing the button proves an issue as there are no risks directly related to doing so.

8 DISCUSSION

8.1 PROJECT DEVELOPMENT AND EVOLUTION

8.1.1 Does the final project result align with its initial project description?

For the most part, yes; the working prototype met all performance goals to prove it can work well as an automatic door opener. Many features, however, would require improvement for a sellable product, such as an improved locking mechanism that uses the built-in door latch rather than the solenoid workaround. The one feature that did not align with the initial description is the aesthetic quality of the RADO, which was neglected for the sake of finishing the functional components of the prototype.

8.1.2 Was the project more or less difficult than expected?

While the RADO was not expected to be very easy to design, it seemed easier than some of the other project options. However, some initial expectations oversimplified some of the hurdles that had to be overcome or did not account for some hurdles that ended up appearing. For instance, the steel wire used in the prototype did not wind around the spool easily and would attempt to straighten out if the tension was released, which made the door not return to its exact initial position when closing.

8.1.3 On which part(s) of the design process should your group have spent more time? Which parts required less time?

We should have spent more time on the mechanism meant to count the revolutions of the motor which would have accounted for slippage in the code. A proper button wired to the unit would have been nice to implement as well. The case and lever arm, while sufficient at the time, might benefit from a third look especially in choice of material for construction. The door frame should have required less time, but it was essential for the testing of the prototype.

8.1.4 Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

The door frame that was made took longer than anticipated, and one thing that was into accounted for was the weight disparity between the door and frame. Because the door was several times heavier than the frame, the frame ended up being unstable, a problem corrected by weighing down the frame supports with sand buckets and by standing on them. Additionally, the box ended up being too large to 3D print, so it was instead made using wood. In future work, a more condensed product would make it more easily printed.

8.1.5 In hindsight, was there another design concept that might have been more successful than the chosen concept?

The chosen concept performed satisfactorily and met all performance goals, which attests to its success. While other designs have the potential to perform equally as well or better, we are satisfied with the chosen design and believe it to have been the best choice. It is, of course, possible and even likely that better concepts can be made, but we were unable to think of them at the time. With additional time, more research could have been done on possible designs.

8.2 DESIGN RESOURCES

8.2.1 How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

The codes and standards that were relevant to the RADO were ones concerning functionality and safety. Having to meet a 300,000-cycle lifetime, while excessive for the amount of use the RADO will experience, will assure the quality and durability of the product. The standard stating that a door must be opened using less than 15 lb of force for safety reasons established design limitations that were easy to meet and highlighted the need for safety throughout the device.

8.2.2 Was your group missing any critical information when it generated and evaluated concepts?

We faced a critical lack of information and knowledge about circuitry. When generating our concepts we assumed that we could program and have an Arduino act exactly how we planned; however, we quickly learned that troubleshooting would capitalize much of our time. In hindsight, developing our concepts with circuit simplicity in mind could have enabled us to more fine tuning and, perhaps, new features such as a wireless remote. If we practiced better foresight, we could have also taken a course or two regarding electronics and programming.

8.2.3 Were there additional engineering analyses that could have helped guide your design?

For the most part, no. One analysis that could be done is a fatigue analysis because of the requirement that the RADO must withstand at least a 300,000-cycle lifetime, but the actual number of cycles it will undergo is at least an order of magnitude less than that and the stresses involved are not significant enough to cause considerable fatigue damage. The spring and tension analyses were the most important for the design and were helpful in making several decisions.

8.2.4 If you were able to redo the course, what would you have done differently the second time around?

We would have spent less time building a door frame and more time improving our design. We completed this project with a functioning prototype, but with more time available, we could have made many improvements. Our design was aesthetically unappealing, so, using a 3d printer for the outer casing would have certainly helped. Secondly, we would have had more time to fine tune the locking mechanism with the solenoid and bolt. Our bolt simply obstructed the door, but with more time we would have added a sliding mechanism, similar to a bathroom stall lock.

8.2.5 Given more time and money, what upgrades could be made to the working prototype?

Time is everything. If our group had more time we would have used different materials first and foremost. Aluminum was available in the machine shop, but wood was much more accessible, cheaper, and easier to work with. We certainly would have used aluminum as our rod supporting the pulley system and beautified our box using a 3d printer. Additionally, we could design a way to trigger the built-in door latch to obviate the need for the solenoid.

8.3 TEAM ORGANIZATION

8.3.1 Were team members' skills complementary? Are there additional skills that would have benefitted this project?

Our group's skills were very complimentary, but we all lacked experience with Arduino programming and building circuits in this setting. Lots of time and effort went into learning and troubleshooting the Arduino code, and having a team member who had more experience in computer science would have been beneficial. Otherwise, the team worked well together and had a good mix of seriousness and levity. Also important was the mix of knowledge, without which we would likely have not thought of reaching out to the theater department to borrow a door for the working prototype.

8.3.2 Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

At the beginning of the project, other home appliances were under consideration to design retrofitted devices for convenience. One such device was an automatic vegetable cutter to assist with cooking. Another was an automatic water faucet retrofit that could be used on any type of faucet handles to make it easier to wash hands. While these were considered to have several complications in their design, other products related to home improvement would be interesting to pursue.

APPENDIX A – COST ACCOUNTING WORKSHEET

Table 5 Cost Accounting Worksheet

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit Price	QTY.	Total Price
1	Drill Motor	Amazon[1]	B0791T26VD	280W, includes slip clutch	$32.09	1	$32.09
2	Spring Door Hinges	Amazon[2]	B00JS31K9A	Gray, 4”x4”	$24.56	2	$24.56
3	Arduino	Amazon[3]	A000066	3.1”x 2.2”x 1” Blue	$22.69	1	$22.69
4	3/64” Steel Wire	Amazon[4]	sv-10	Silver	$8	1	$8
5	Pulley Wheel	Jolley Basement	N/A	2.5” Diameter Silver Wheel	Estimate ~$5	1	$5
6	Button	Gateway Electronics	N/A	4” Diameter Yellow Button	$2.50	1	$2.50
7	DC Brush Motor Controller	Ebay[5]	2001712008	5.2”x2.9”x1.8” Blue/Green	$24.69	1	$24.69
8	AC to DC Converter	Gateway Electronics	APS99ES-12	4”x6”x2” Black Box (15V/6.6A)	$20	1	$20
9	Solenoid	Gateway Electronics	4600-00057	3” Silver Cube (12V DC 5.3 Ohm)	$4.95	1	$4.95
						SUM:	$144.48

[1] https://amzn.to/2A7UOU3
[2] https://amzn.to/2QNpeQT
[3] https://amzn.to/2QLJtyp
[4] https://www.amazon.com/Ohaha-Grinding-Machine-Stainless-Aluminum/dp/B06XKZSHYH
[5] https://www.ebay.com/i/392018233919?chn=ps

APPENDIX B – FINAL DESIGN DOCUMENTATION

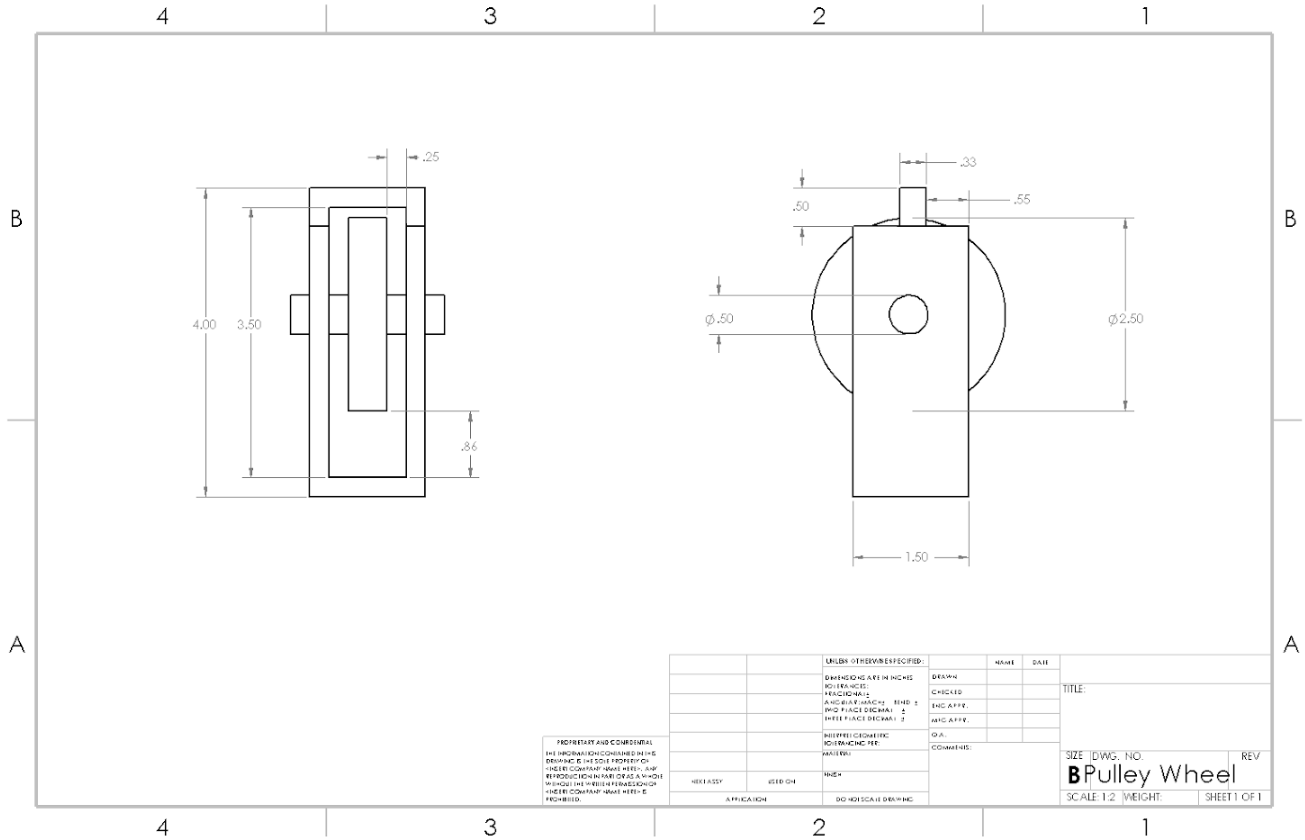


Figure 28 Pulley CAD Drawing

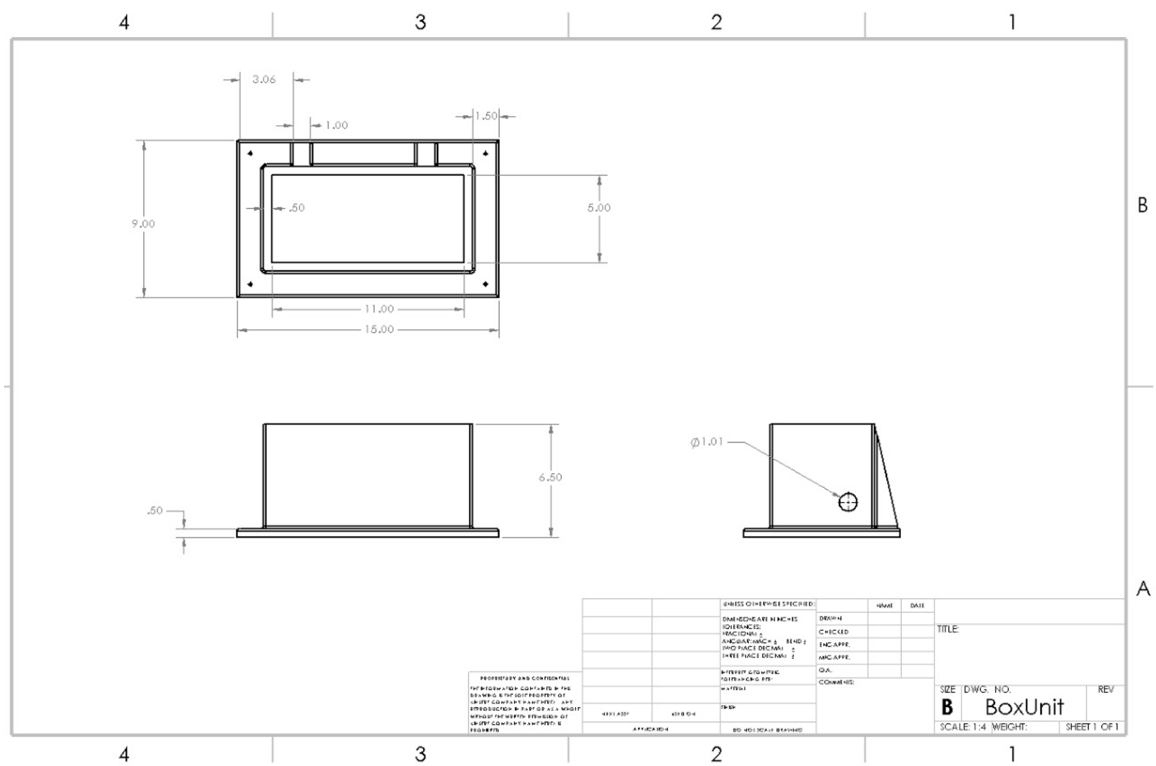


Figure 29 Box Base CAD Drawing

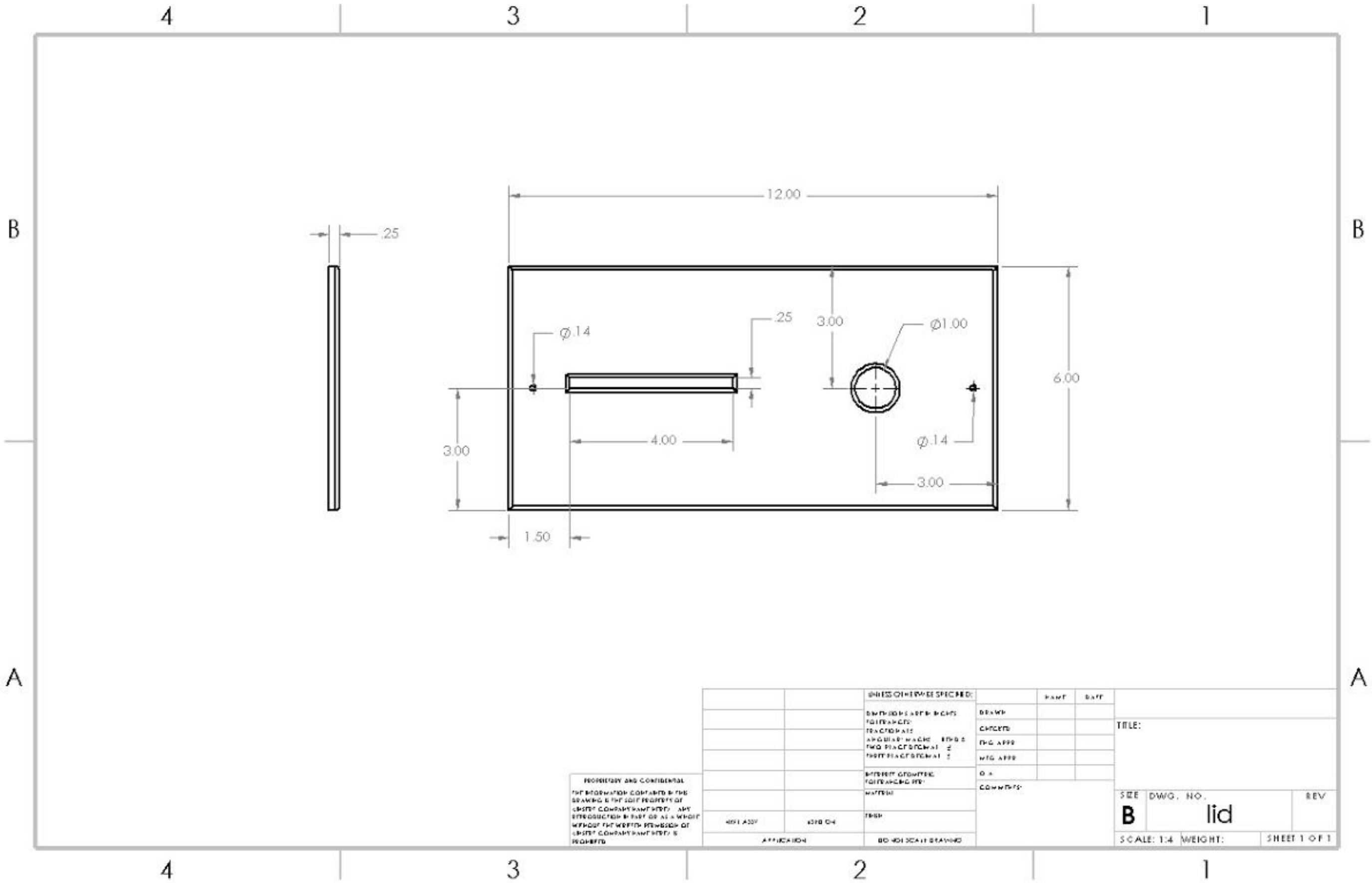


Figure 30 Box Lid CAD Drawing

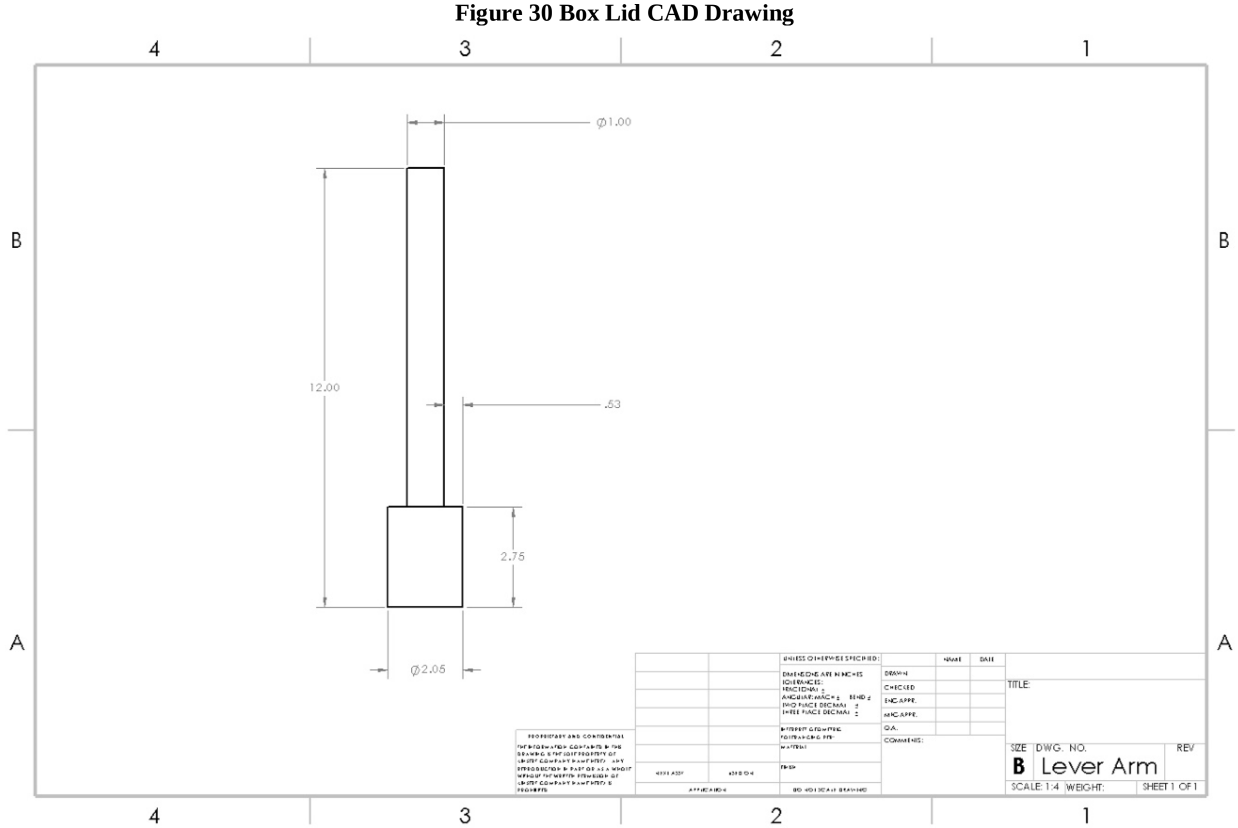


Figure 31 Pulley Arm CAD Drawing

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