Automatic Candle

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Abstract

Many house fires start with candles due to its dangerous open flame, yet candles are a widely used and loved item. The first group approached this problem by placing candles in a 1-gallon jar with an automatically closing lid attached to a timer. When the timer finishes the lid would close and suffocate the flame. Our group designed a candle management system that automatically extinguishes and ignites the candle based on user setting and national safety regulations. It uses a camera and flame sensor for automatically finding the wick, along with minor user guidance. It uses a snuffer and arc lighter for extinguishing and ignition, positioned by an arm driven by precise stepper motors for 3-dimensional movement. Our solution improves on the previous one by taking up less space, operating with a wider variety of candle types, and enforcing stricter safety regulations.

Contents

1 Second Project Motivation

The main engineering problem that we are trying to solve is how to safely light and extinguish a candle, with the limited precision available to us. This is not the first time this problem has been addressed, but we believe this is the first time a solution has been proposed at this scope.

1.1 Updated Problem Statement

Unattended candles cause large amounts of damage to people and property every year. The NFPA (National Fire Protection Association) reports that, in recent years, candles caused approximately 2% of household fires [1]. Of those cases, roughly 11% are due to the user falling asleep with the candle still burning [1]. Annually, damage from candle accidents result in property damage totaling around $268 million (USD) [1]. Candles often start these fire by burning for longer than 4 hours, where they become very hot with a large flame, and ignite nearby items, or the surface it is place on. To combat this, candles have directions with proper usage printed on its packaging and fire protection agencies often run campaigns to spread awareness about candles safety, and promote flame-less alternatives such as electric candles. Despite the risk, people still use candles and likely, always will.

1.2 Updated Solution

Our goal is to reduce the danger of candle use by designing a candle management system which follows candle safety guidelines. To use our device, the user places a candle in our holder, and then they download our app and connect to the device via Bluetooth. Once connected, they can control the lighting and extinguishing of the candle through a phone application. Through the app, the user sets a timer for automatic extinguishing, and then lights the candle remotely. If the user wanders out of Bluetooth range, remotely extinguishes through the app, or the timer expires, the candle will automatically be extinguished. This means that the candle cannot stay on too long, or stay on without someone nearby, eliminating two common mechanisms for candle fires. With our solution, candles still require supervision, but if the user forgets about the candle, or is careless, they won't have to deal with the consequences.

The previous solution to this problem was a one gallon glass jar with a lid that closed after a set amount of time. The closing lid suffocates the flame, extinguishing the candle. This jar has the benefit of working for multiple candle sizes, and is simple to use. However, our solution is superior because it encompasses much more than just the timed extinguishing of the candle. We also handle the other dangerous part of candle use, lighting it. The user never interacts with the flame, which eliminates burn risk. Although the glass jar keeps the flame and candle more contained, it is bulky and potentially aesthetically displeasing. Our solution has a heat-resistant base, and moving arms, which take up minimal space, and look decorative. Also, our solution uses proximity tracking with Bluetooth, making it safer all around.

Other products eliminate candle risks through alternatives that mimic characteristics such as wax warmers and electric candles, however, those products don't have the same light or strength of scent as normal candles. The previous solution is similar to the CandleWatch device, currently on the market [2]. Our solution is novel since it works with many types of candles and ignites the candle. This provides people who want to use real candles, with a convenient and effective way to practice safe candle usage.

1.3 Updated High-Level Requirements

- Must be able to detect if the candle is lit with less than 1% false negative rate.
- Must be able to extinguish a lit candle with a 90% success rate, given an accurate wick position.
- Must be able to light an unlit candle with a 90% success rate, given an accurate wick position.

1.4 Updated Visual Aid

Figure 1: Physical Design

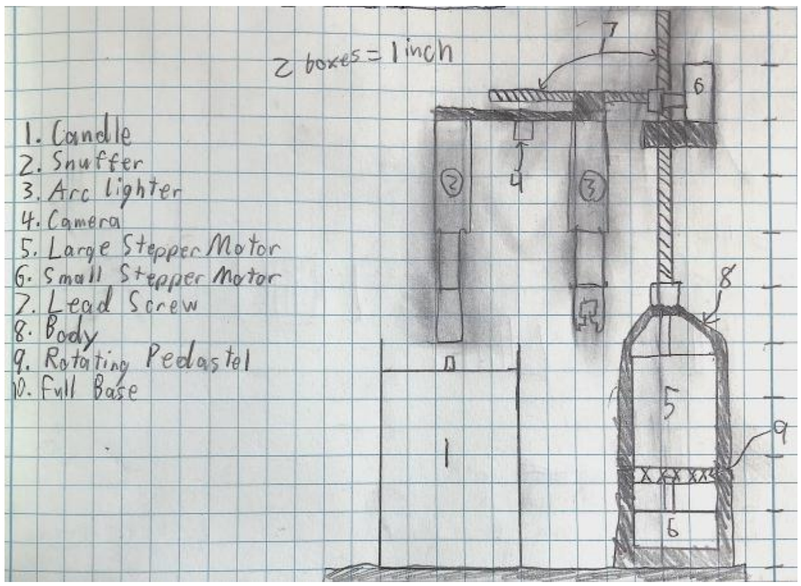


Figure 2: Telescoping Action

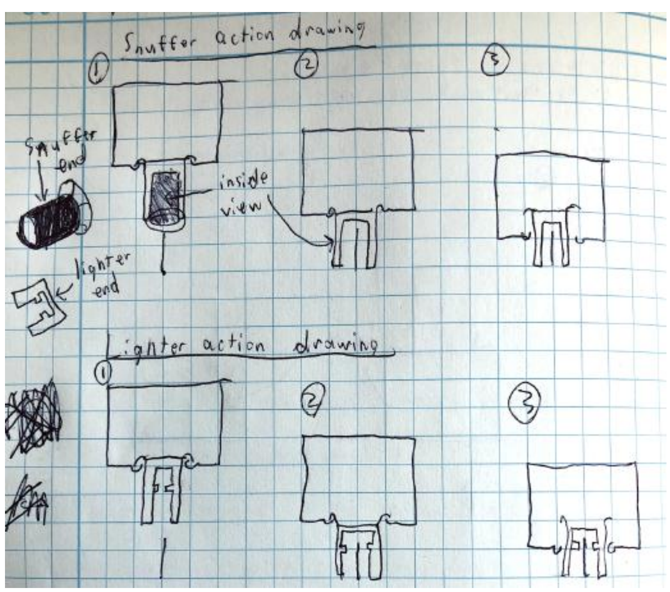
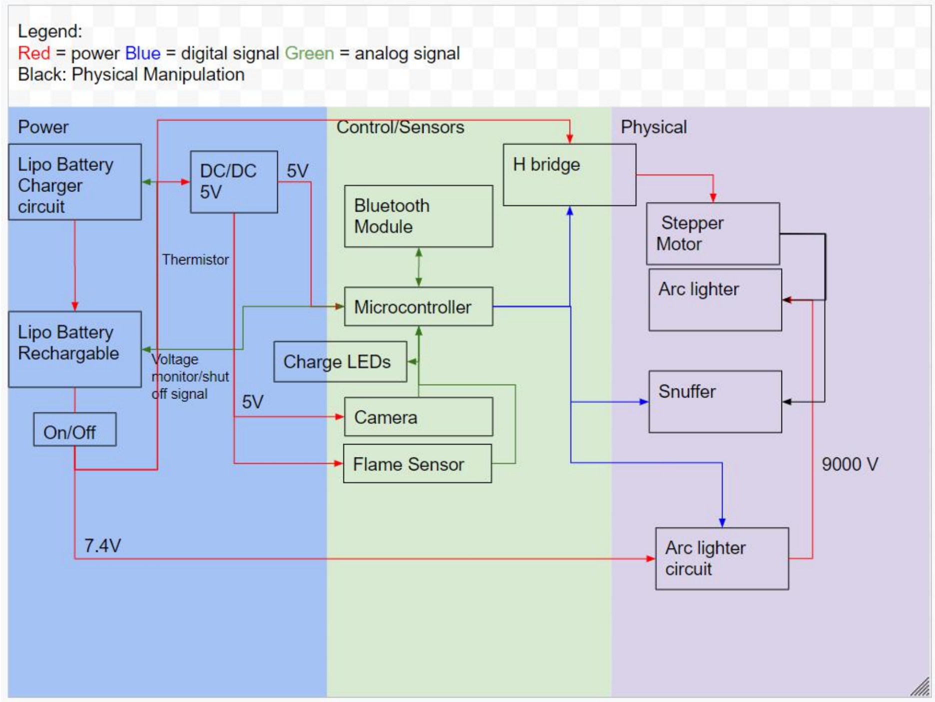


Figure 3: Android App User Interface

1.5 Updated Block Diagram

Figure 4: Block Diagram



2 Implementation

In order to meet our high level requirements, we designed our snuffer and lighting attachments to allow for reasonable error tolerance, should our estimates of the wick position be imperfect. As discussed in the tolerance analysis below, these design choices give us high confidence that this proposed solution will meet all of the high level requirements, as outlined above. A carefully designed power subsystem and arm architecture also ensures that our system stays online and operates to the degree of precision we need, while our control subsystem provides the user with monitoring of the candle and the ability to light and extinguish the candle remotely, through a Bluetooth connection.

Requirement and verification tables for all components are found in Appendix A.

2.1 Power System

2.1.1 Battery

The battery will provide the power needed to the rest of the system. The battery will be a 7.4V lithium polymer(LiPo) battery. The reason for this is that LiPo batteries have superior energy density and current capabilities compared to other types of batteries. The battery we have selected has a discharge rating of 30C and an energy capacity of 2200 mAh. This means that it is capable of discharging up to $2.200 * 30 = 66 Amps$ at any time, well within our circuits needs.The total amp hours per 4 hour run of the system was calculated to be .163 Ah. This took into account the operation of the motors, the sensors, micro-controller, and arc system. The peak current drawn will be during arc operation and top out at 36 A according to simulations. Taking into account that only the micro-controller will be operating at the same time total peak drain is within our 66 A limit. The choice of a battery over a wall power supply is simple, the system should be portable enough to be placed any where a candle can be placed. Being restricted by wall sockets would defeat that. A Lithium polymer battery was selected because it is rechargeable, and has high energy density. Disposable batteries would have been easier to manage, but would not have the energy needed in a reasonable size, and would generate unneeded waste.

2.1.2 Battery Charger

the Battery charger will charge the battery and provide protection to the battery to prevent over charging and imbalance in the LiPo cells. LiPo batteries can be dangerous if charged and discharged incorrectly. To minimize risk a battery management system will be used ensure safe charging and discharging. Two chips will be used, a battery charging chip [3] that will monitor both temperature and charging current, and a cell balancing chip [4] that will ensure both cells in the LiPo are within a safe range of voltages. The micro-controller detailed later will monitor the total voltage of the battery and will shut off the system in the case that the battery is drained to its lower limit, and notify the user to charge the battery. Incorrect LiPo usage can result in the battery igniting or even exploding, that risk makes this battery management system one of the most important circuits in this project from a safety standpoint. While it does not directly contribute to meeting the high level requirement, it is necessary for the battery to operate effectively, which determines if the system as a whole is operational. There was no debate over whether or not to have a battery management system, the selection of the Texas Instrument components was based off of their specifications being within our needs, and the helpful example circuits that are detailed in the data sheets. Unfortunately this circuit cannot be tested, and simulation is redundant since the data sheets provide expected operation.

See Figure 5 for schematic and Figure 6 for PCB

Figure 5: Battery Charger schematic

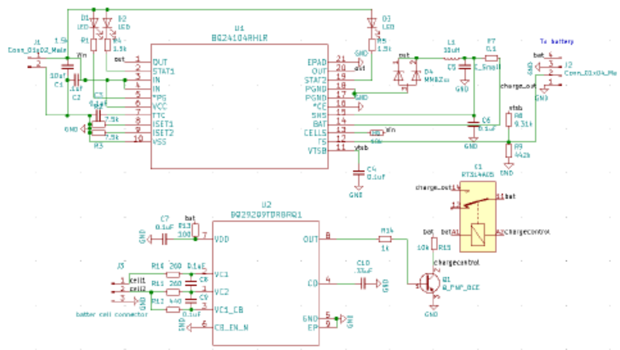
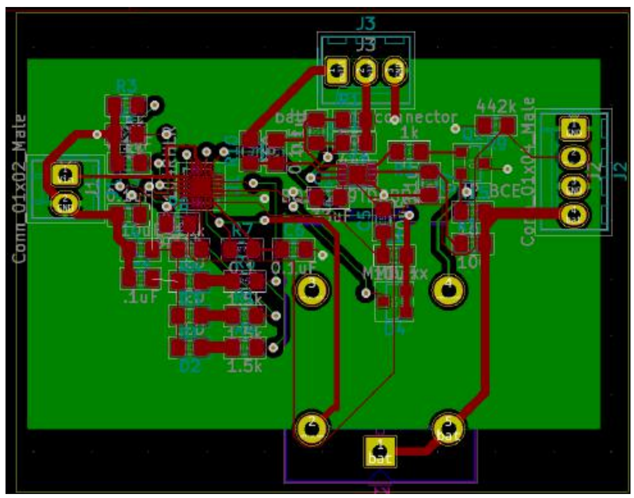


Figure 6: Battery Charger PCB



2.1.3 Voltage Regulator

The voltage regulator is in place to regulate the 7.4 V of the battery to a voltage usable by the sensors, and the micro-controller. A linear regulator provides a smoother signal at the cost of some efficiency which turns to heat in higher draw environments. Our power draw through the voltage regulator is low enough where losses are negligible. A stable signal is also important when powering a microprocessor and so a linear regulator was chosen over a switching regulator which would have minimized losses. The linear regulator allows the system to meet the high level requirement by powering the control module with a steady voltage necessary for accurate measurements and calculations.

2.1.4 Arc Lighter

The arc lighter circuit uses a fly-back transformer to generate a high voltage arc across the spark gap. Electric arcs can be anywhere from 1000 degrees C [5] to hotter than the sun. The arc generated should have more than enough heat to light the wick. The circuit converts the 7.4 V of the battery to a voltage of 9000 V. The micro controller will provide a 500 kHz 70% Duty cycle signal to drive the primary coil. The variable voltage induces a higher voltage in the much larger secondary coil which overcomes the breakdown voltage of air and creates a plasma arc across the spark gap. While we could not test this circuit due to not having lab access it was simulated on LTSpice, Figure 7. Using equation (1) a primary inductance and secondary inductance were calculated, those values are shown in the simulation. A coupling coefficient of .95 was used, this is relatively high, but with high voltage systems losses tend to be lower due to the low current of the output. The simulation also used a resistor simulating a 100 W output. 100 W is the estimated power needed to light a candle, there was no documentation online of the exact energy needed to light a standard candle. Looking at the result (Figure 8) there is a spike of 9000 V that then falls to -8000 V. The 9000 V will cause a arc across the 3 mm spark gap due to the voltage breakdown of air being 3000 V/mm. The input current was higher than calculated with an estimation of 14 A and a peak in the simulation of over 35 A (Figure 9). Luckily the 10 gauge wire selected for the primary coil is capable of handling the higher current, especially since it is only an instantaneous pulse and not continuous.

$$L_{loop} \approx N^2 \mu_o \mu_r (\frac{D}{2}) * (\ln(\frac{8 * d}{d}) - 2) \tag{1}$$

where N = number of turns, D = diameter of coil, d = diameter of wire

Figure 7: Simulation schematic

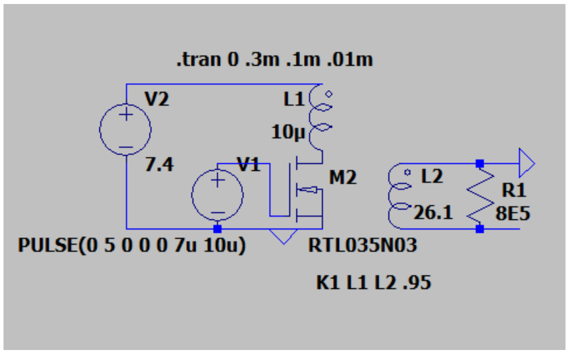


Figure 8: Voltage output of Arc simulation

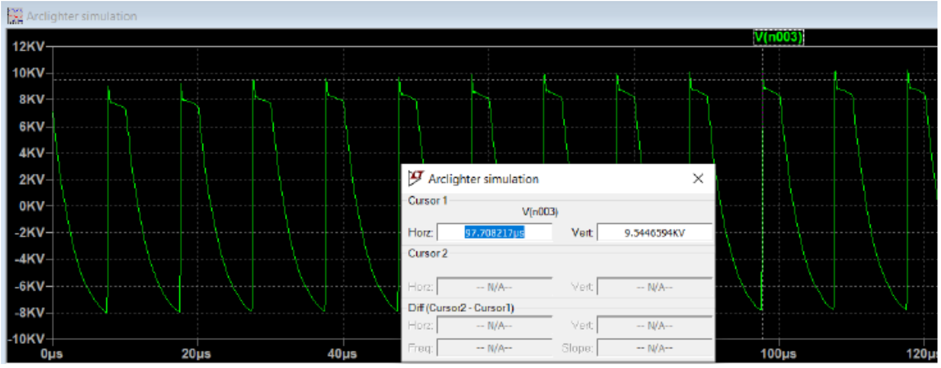
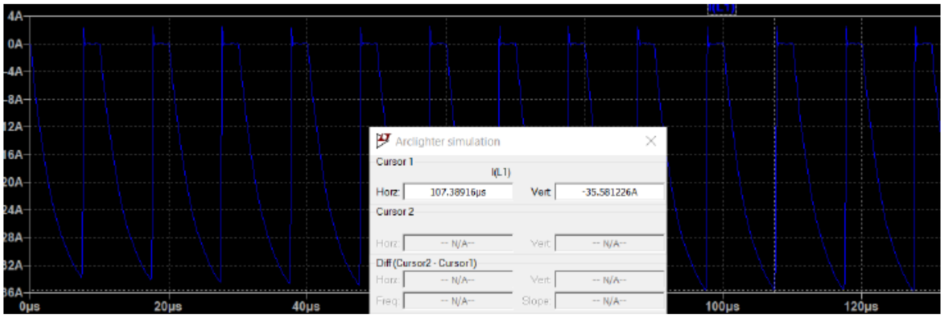


Figure 9: Current input of Arc simulation



2.2 Control System

2.2.1 Micro-controller

The micro-controller interfaces with the Bluetooth module to send sensor data to the user and receive inputs from the user. The user input provides the logic for controlling the motor arms in order to perform the lighting and snuffing actions. The micro-controller uses a multiplexer (Figure 10) to control one motor at a time though an H bridge(Figure 11), precisely setting the Φ-angle and then the horizontal position to place the camera directly above the wick. The micro-controller is responsible for snuffing the candle if the connection to the user is dropped or the timer expires, and must therefore be able to do so without any other external computation. The micro-controller we chose for this project is the ATMega328P-PU, mainly because it has many available pins, and even with the motor-multiplexer we have barely enough pins for all of the sensor and the motors.

Figure 10: 3:1 Mux schematic

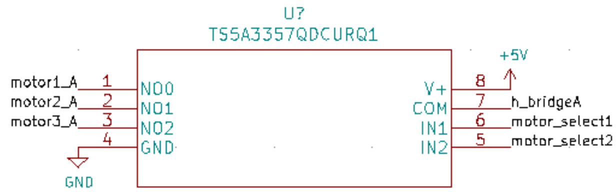


Figure 11: H Bridge schematic

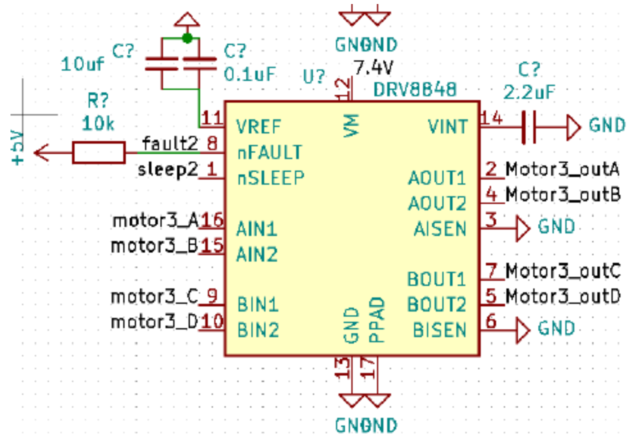


Figure 12: micro-controller schematic

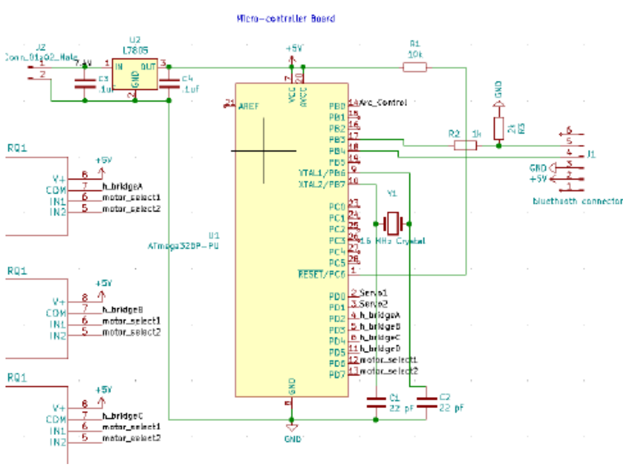
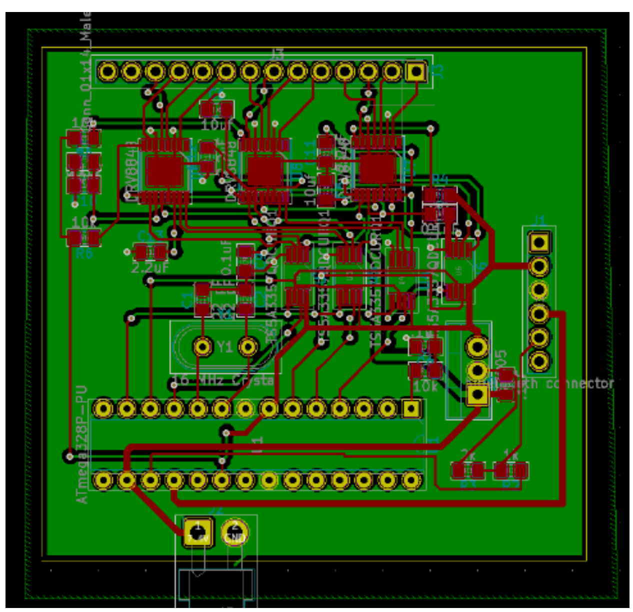


Figure 13: Micro-controller PCB



2.2.2 Bluetooth

Bluetooth was chosen as the method for communicating between the device and the user, since this technology is available in all smart phones and our use case only needs to operate within the same range that Bluetooth supports. Part of the Bluetooth subsystem is the code that controls it. This software must be able to detect when the connection to the user is dropped, since this most likely indicates that the user has left the room. If this is the case, the candle is no longer burning safely, and must be extinguished.

2.2.3 Camera

The camera subsystem will mostly be used to interface with the user, and to allow us to precisely locate the wick on the candle. It will be controlled with our micro-controller, and therefore must be controllable via GPIO pins and a relatively simple communication protocol. The camera device that we chose is designed for use with an Arduino, which guarantees easy control through the GPIO pins, as desired. However, in order to effectively use a camera for these applications, the resolution must be good enough to see the candle wick. The camera that we chose has a relatively low resolution of 640x480, but this is more than enough resolution to see a wick at the close range that we need. The tolerance analysis below shows how this camera's specifications allow for a fairly large error in wick detection. As discussed in future applications, we believe that implementing computer vision and image processing would become more important as the state of this project proceeds, but at this point we have not implemented any such measures.

2.2.4 Flame Sensor

Flame sensors are photo-detectors which are modified to specifically detect mid-length infrared beams. Many of these are designed specifically for Arduinos, which would work well with our project. The main purpose of this component is to ensure that after the snuffing routine has executed, no flame should be detected. Similarly, if the lighting routing has executed, a flame should be detected. If failure is detected in either case, it is of high importance to immediately inform the user. The successful implementation of this component is directly connected to the third high-level requirement described above.

2.3 Arm Assembly

To achieve three dimensional motion, we have 3 motors that move position the arm at its correct position. the motors move through space in cylindrical coordinates: s (radius), z (height), and Φ (angle). We chose stepper motors due to their easy control methods and precise position control, necessary for accurate wick sensing, extinguishing, and igniting. The motors drive quarter inch lead screws that convert rotational motion to linear motion [6].

2.3.1 Components Cart

The snuffer, camera, and arc lighter reside on a cart connected to the horizontal lead screw for positioning.

2.3.2 Vertical (z) Stepper Motor

This stepper motor drives the vertical motion of the arm. It drives the most weight, and thus is the largest with the highest torque and power consumption. This positions the arm components at their proper heights for operation depending on the component in use, and the size of candle used.

2.3.3 Horizontal (s) Stepper Motor

This stepper motor drives the horizontal movement of the arm. It moves the cart carrying the arm components horizontally to position the desired component directly over the wick.

2.3.4 Rotational (Φ) Stepper Motor

This stepper motor drives the rotational movement of the arm. It does not require much power since it does not bear weight. The weight of the device rests on a rotating base, with angular position decided by the motor.

2.3.5 Snuffer

The snuffer is a long tube that extends downward from the horizontal section of the arm. It lowers onto the lit wick to suffocate and extinguish the flame. It is designed to have 2 inches of telescoping action, to allow for a 1 inch of error tolerance in vertical positioning in either direction. Figure 2 in Section 1 demonstrates the telescoping action of the snuffer.

2.3.6 Arc Lighter Assembly

The arc lighter assembly is a long tube that extends downward from the horizontal section of the arm. It lowers onto the unlit wick to position the arc lighter around the wick, where the generated arc ignites the wick. It is designed to have 2 inches of telescoping action, to allow for a 1 inch of error tolerance in vertical positioning in either direction. Figure 2 in Section 1 demonstrates the telescoping action of the arc lighter assembly.

2.4 Cost

As shown below, the estimated parts cost of our prototype is $121.99, so the estimated development cost is $48,121.99. If we were to produce a large number of such devices, the bulk pricing options we could find would bring this down to $92.04 per unit. This would lower substantially if we are able to get bulk prices on motors.

2.4.1 Parts

Table 1: Parts Costs

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)
Bluetooth	Amazon	7.99	1.00
Camera	Amazon	10.99	1.00
Flame Sensor	Newegg	1.99	1.00
Microcontroller	Digikey	2.08	1.00
Large Stepper Motor	Amazon	15.99	1.00
Small Stepper Motor	Amazon	13.50	1.00
Small Stepper Motor	Amazon	13.50	1.00
Battery	Amazon	15.95	1.00
Assorted resistors, capacitors, ICs, crystals, sockets	Digikey	20.00	1.00
Mechanical Components and Housing	Amazon	30.00	5.00
Total		**121.99**	**92.04**

2.4.2 Labor

Our fixed development costs are estimated to be $40/hour, 10 hours/week for 3 people. We expect this to account for approximately 50% of the final design this half of the semester (8 weeks):

$$3 \times \frac{\$40}{hour} \times \frac{10hours}{week} \times \frac{8weeks}{50\%} \times 2.5 = \$48,000 \quad (2)$$

2.5 Tolerance Analysis

Locating the position of the wick in three dimensional space is critical for this project. It is also the part which we considered most likely to cause the project to fail. However, given the precision of our motors and our purposeful design decisions, we have ensured our ability to consistently find the position of the wick in three dimensions with a high accuracy.

At the beginning of the lighting or snuffing phase, we are assuming that the camera is located directly above the candle wick. We are allowed to make this assumption because the user is responsible for setting the candle wick position in the app prior to lighting. This will ensure that the camera has been centered over the wick at the beginning of the lighting routine. We can also use some basic image processing to fine tune this positioning.

With the camera initialized directly over the wick, we begin the lighting process. First, we position the lighter directly above the wick. This requires us to move the length of the horizontal arm a fixed distance of 1.25 inches. The motor that we are using for the horizontal driver is a stepper motor with 1.8° steps, which means it is accurate within 0.000315 inches. The arc lighter we designed is 0.1 inches across, which ensures that the wick will be positioned directly under our arc lighter, as long as our distances are calibrated correctly.

This gives us the position of the wick relative to the lighter in the horizontal plane, but we must also determine the vertical position of the wick in order to accurately predict how far down the arm must lower in order to light the wick. We could do this by adding extra cameras or sensors, but in order minimize costs and hardware complexity, we will take advantage of the camera we already have.

When the lighter has been positioned over the wick, the camera has changed viewing angles. By comparing the difference in position of the wick in the two views, we can compute the height of the wick. In Figure 14, P1 is the original position of the camera, P2 is the new position of the camera, P3 is the position of the wick, P4 is the farthest point which camera can see from P2, and P5 is the point on the table directly below P2. P3, P4, and P5 are all in the same horizontal plane. The distance between P1 and P2 is 1.25 inches. The angle between P4 and P5 is 12.5 degrees, which is half of the field-of-view (FOV) of the camera [7].

The angle between P3 and P5 is given as θ. h is the distance between P2 and P5, which is the vertical distance from the candle to the wick, and the value we want to solve for.

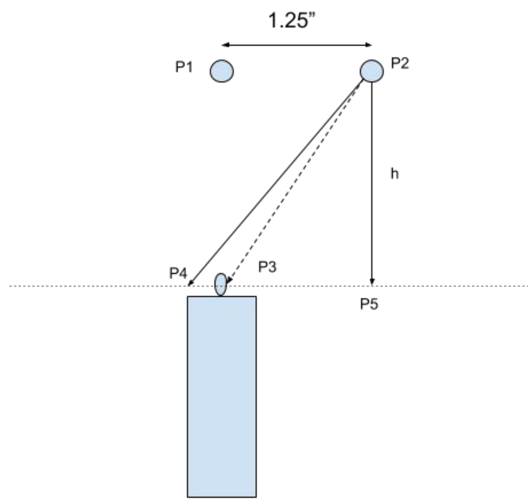
We can immediately express h as a function of θ, as:

$$h = \frac{1.25}{\tan(\theta)} \tag{3}$$

The camera can only give us the distance between P3 and P5 in pixels, so we must compute θ using this distance and our knowledge of the camera's FOV. The distance between P3 and P5 in inches is given by $h\tan(\theta)$, and the distance between P4 and P5 in inches is given by $h\tan(12.5°)$. The distance between P4 and P5 in pixels is 320 for a 640x480 resolution camera, so if the distance between P3 and P5 in pixels is x, then the following equality must hold:

$$\frac{h\tan(\theta)}{h\tan(12.5°)} = \frac{x}{320} \tag{4}$$

Figure 14: Wick Height Prediction Diagram



Using this to solve for h in terms of x, we get:

$$h = \frac{320 \times 1.25}{x \tan(12.5)} \tag{5}$$

This simple equation is all we need for our basic height prediction. However, we need to ensure that even with slight variations in x, that our height prediction falls within our allowable tolerances.

Let $\hat{x}$ be the interpreted horizontal distance in pixels to the wick, and let x_e be the error in that distance. Similarly, let $\hat{h}$ be the predicted vertical distance to the wick, and let h_e be the error in that prediction. Using the derived equations above, we get:

$$h_e = |\hat{h} - h| = |\frac{320 \times 1.25}{\hat{x} \tan(12.5)} - \frac{320 \times 1.25}{x \tan(12.5)}| = |\frac{1}{(x - x_e)} - 1|\frac{320 \times 1.25}{\tan(12.5)} = |\frac{x_e}{x(x - x_e)}|\frac{320 \times 1.25}{\tan(12.5)} \tag{6}$$

Our lighter and snuffer appendages allow for 1 inch of tolerance in either vertical direction. To ensure that this is enough, we will consider $h_e \leq 1$. For $x_e > 0$, this gives us:

$$1 \geq \frac{x_e}{x(x - x_e)} \frac{320 \times 1.25}{\tan(12.5)} \tag{7}$$

From our use case, we know that $x > 0$ and $x - x_e > 0$, so we can solve for x_e as:

$$x^2 - x x_e \geq x_e \frac{320 \times 1.25}{\tan(12.5)} \tag{8}$$

$$x^2 \tan(12.5) \geq (320 \times 1.25 + x \tan(12.5)) x_e \tag{9}$$

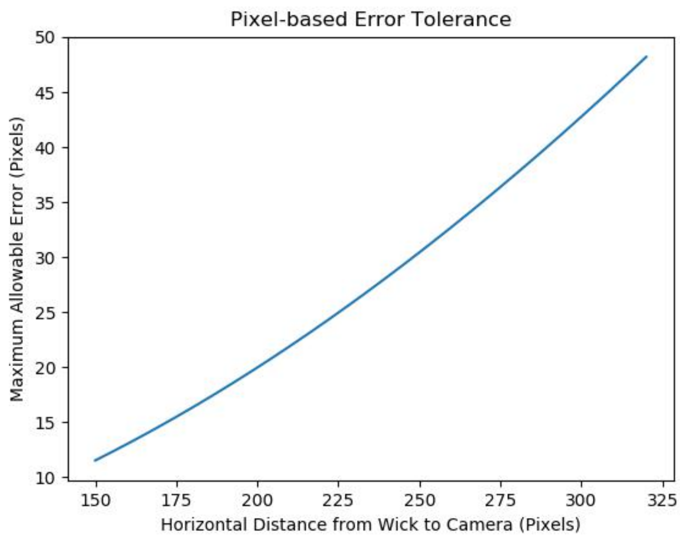
$$\frac{x^2 \tan(12.5)}{320 \times 1.25 + x \tan(12.5)} \geq x_e \tag{10}$$

If $x_e < 0$, then the inequality is flipped but the values stay the same:

$$\frac{x^2 \tan(12.5)}{320 \times 1.25 + x \tan(12.5)} \leq x_e \tag{11}$$

Evaluating these inequalities for all possible values of x gives us a plot of the allowable error in pixels for wick detection, as shown in Figure 15. The most strict case allows for 11 pixels of error. We ensure that we always fall within this tolerance by selecting the wick in a circle of radius 10 pixels, and requiring the user to verify the wick position before the lighting process can be initiated.

Figure 15: Allowable Wick Detection Error



3 Second Project Conclusions

In the second half of this semester, we were able to design a better solution to a previously solved problem. While we weren't able to build a physical prototype, we are satisfied with the design decision that we made and the final proposal that we have put together. We believe that given more time and resources, this project has the potential to scale effectively for more real-world applications.

3.1 Implementation Summary

While we were able to get a successful design together, we of course were not able to implement the system due to external circumstances. We were able to simulate wick detection error bounds using the results from the tolerance analysis. However, we were not able to perform any tests with real images, due to the fact that we didn't have the camera module which we had picked out. The same height prediction algorithm could be derived for any camera, but the results wouldn't satisfy our testing needs, due to the differences in resolution and field-of-view between the cameras we had available to us. We also had considered building an Android application for a proof-of-concept, but without any of the components we could do little more than build a user interface, as show in Figure 3.

Anders was in charge of the Power subsystem, Armando was in charge of the Arm Subsystem, and Kevin was in charge of the Controls subsystem.

3.2 Unknowns, Uncertainties, and Testing Needed

The largest unknowns are testing and verification of physical components and systems. This applies to the entire project, but it most greatly effects the drive systems and wick locating system. Extensive modeling shows that the chosen motors and lead screws can precisely move our desired load at a reasonable speed; however, motors often have lower torque capability than stated. We planned for this tolerance, but the only true verification of our chosen motors is lab testing. Lower torque capability can cause many problems, including under-sizing batteries and moving the load too fast. Another issue in the drive system comes from weight estimation. Predicting weight is always difficult without extensive mechanical modeling. Underestimating weight can lead to higher power consumption by the motors or even damage to the motors. We prefer to overestimate weight, but severe overestimation leads to aggressive and fast movement of the load, lowering safety and requiring more extensive control.

There are also a variety of unknowns surrounding the software implementation of this project. The control logic is imperative for the implementation of this system, but we were not able to implement this without all of the motors and sensors to control. Without the physical devices to test, there is some uncertainty around the ability of the micro-controller to handle all of the motor control logic effectively. Additionally, we would have liked to test the candle height detection algorithm to confirm the tolerance analysis results, but without the camera module this is not possible, as described in the Implementation Summary. Testing the wick detection using the intended camera is one of the most critical tests for the success of our high level requirements, and would be one of the first components we would have verified given the chance.

3.3 Ethics and Safety

3.3.1 Ethics

This project has ethical considerations dealing with its function of improving safety. This project claims to reduce the risks of using candles by both eliminating the direct user interaction with the flame, and by providing a safeguard against the dangers presented by forgotten lit candles. This can lead to violations of 2 different IEEE codes of ethics, #3: "to be honest and realistic in stating claims or estimates based on available data;" [8], and #9: "to avoid injuring others, their property, reputation, or employment by false or malicious action;" [8]. Addressing #3, our claims can easily be overstated to be the all inclusive candle management system which requires no oversight. This also addresses #9. These claims can give people the impression that they are completely safe if they just use our project. This can lead to potential injury and damage by false impressions. We will ensure that claims are clearly stated. We will emphasize that candles still require oversight, and are dangerous when used improperly. We will also reference the NCA guidelines throughout our user manual and packaging to promote safe candle usage.

3.3.2 Safety

This project has little danger alone, but it is meant to be used with candles, a common household item that presents danger to both property and person. We will analyze the safety of our project when attached to a candle to get the most realistic sense of our project's hazards and how we combat them.

All types of candles have open flames. Although jar candles and certain candle holders contain the flame and reduce danger, all candle still have potential to start home fires or burn people. The National Candle Association has safety guidelines directed at customers to prevent the many hazards associated with candles. We help address the crucial NCA guidelines [9], "do not burn a candle for longer than four hours and cool for at least two hours before relighting", and , "never leave a burning candle unattended." If a candle burns for too long, it's flame becomes large and hot, possibly leading to combustion of the surface it rests on, or nearby items. Our project has timers that will automatically extinguish candles after 4 hours. This both stops the candle from getting too hot, and ensures the candle is put out after four hours, reducing the dangerous consequences of forgetting about a lit candle. We also will put a timer on the candle that doesn't allow it to be re-lit by our project until 2 hours have passed after it was last put out. Another cause of fires is the method of extinguishing the candle. Most people blow out candles with air. This is not safe due to the possibility of blowing the hot wax onto something flammable. We follow the NCA recommendation, "Usa a candle snuffer to extinguish a candle." Our project uses a small snuffer to extinguish candles.

Open flames can also injure people directly when lighting and extinguishing a candle. Even when following the NCA guidelines of using long lighters or matches [9], a user could still burn themselves by accidentally touching the source of ignition on the lighter. People could also burn themselves on a snuffer since the snuffer usually gets hot when extinguishing a candle. Our project eliminates all that risk igniting the candle automatically with an arc lighter attached to a robotic arm. The user only needs to press a button to ignite the candle remotely, eliminating proximity of the user to the flame or heat. Another risk of injuring when using candles is the heating up of the candle holder during usage. Our project does not directly address this since the point of a candle is to heat wax and provide light. This safety will be left to the user to follow NCA guidelines.

Our device uses an electric arc lighter to ignite a candle wick. This leads to a shock hazard if a user touches the arc of the device when in use. We will address this by including warnings to keep away from the candle wick during ignition. We also will not start the arc lighter until it is in position to ignite the wick.

There is a danger associated with the moving arms of the device. They can knock over nearby objects and things can get caught in the spinning motors. We will address this by having all motors moving at very slow speed, and having covers. We will also limit the amount of required proximal clearance the device needs to operate.

3.4 Project Improvements

If given a longer time to work on this project, we would the improve the project's scalability, devise a new method for monitoring negligent use, and improve drive system's weight and energy requirements.

This project provides the greatest benefit to the restaurant business. High-end restaurants use real candles to enhance the ambiance and attract high income customers across the world. Lower-end restaurants may opt for electric candles or nothing at all due to the maintenance and safety hazards of candles. Our project makes candles safe and easy to manage, but it must be connected to a single person's phone and can only control one candle. This makes our project impractical for most restaurants, which can have over 50 tables in a single establishment.

In the future, we imagine that these challenges could be overcome by deploying the devices in a small IoT network. By replacing the Bluetooth node with a ZigBee node, a collection of these devices would automatically form a mesh network. Introducing an extra ZigBee node connected to a WiFi proxy would allow us to send data over the internet to a cloud-based IoT service, such as AWS IoT Core. This service would be responsible for processing data from each device and responding back to each device in the network individually. The user would be able to control all devices at once through this service, therefore improving the ease of use.

In order to improve scalability and ease of use, it is also necessary to implement better image recognition, so that the user does not need to manually select each wick. AWS offers an image recognition tool called AWS Rekognition, which would fit this use case well. If the AWS IoT Core is added to the project for managing multiple devices, then the AWS Rekognition service can be seamlessly integrated. Neither of these AWS implementations would require any extra cost per device, but would add overhead costs for the use of AWS and the labor costs for developing the infrastructure.

We would also improve the drive system. The current system is larger and consumes more power then necessary for our uses. This is due to necessary design choices in the motors previously stated in section 3.2 of this report dealing with unpredictable weight. Torque testing on motors and weight verification for arm components would likely allow us to select smaller, cheaper, and lighter motors since we potentially overestimated the weight. These verifications would also allow us to potentially lower the speed our loads are driven at, reducing power consumption.

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Appendix A Requirement and Verification Table

These are the Requirements and Verifications for each of the components and subsystems detailed in section 2, separated by sub-block.

Table 2: Power Supply Subsystem Requirements and Verifications

Requirement	Verification
Battery 1. Provide enough power for voltage regulator, controller, and motors. 2. Provide adequate power for at least 10 operating hours.	1. Connect the battery to a resistor and LED. Monitor over time to verify that adequate power is provided. (a) Calculated amp hours needed for 4 hours of operation should be around .11256 Amp-Hours. 2. Connect battery to electronic load and test maximum amperage out of battery at rated voltage.
Battery Charger / Balancer 1. Charge battery safely [10] to at least 8V. 2. Balance battery cells to within 1%.	1,2. (a) Connect the battery charger to a correctly rated resistor and verify output voltage and current are within safe charging parameters of the battery (will be provided by the battery manufacturer). (b) Connect battery to battery charger and measure voltage and current to ensure safe battery charging through multiple cycles. (c) Apply inconsistent voltage to battery cells within safe limits and measure voltage of cells when plugged into circuit to verify equalization.
Voltage Regulator 1. Provides 5v +/- 5% to all low voltage* components. 2. Can provide rated power to each low voltage* component while all components are operating. *low voltage = less than 5V	1. Verification (a) Connect to power supply set to 12v to input. (b) Connect electronic load to output. (c) Connect oscilloscope to output pin. (d) Monitor voltage across a range of currents up to maximum current draw to ensure criteria are met. (e) Will also need to be tested while connected to AC/DC converter to ensure the entire power system is accurate. (f) The same procedure will occur.

Table 3: Control Subsystem Requirements and Verifications

Requirement	Verification
Microcontroller 1. Can both send and receive with the Bluetooth controller through the serial interface at a baud rate of 9600. 2. Must be able to communicate with the camera over I2C at a baud rate of 9600. 3. Must be able to shut off the system if the battery gets too low in order to prevent damage to the battery.	1. (a) Connect the controller to the GPIO pins on an Arduino board, configured for serial reading and writing. Set the baud rate to 9600. (b) Generate and send 9.6 Kb of data from the Arduino to the microcontroller. (c) Echo back the same data from the microcontroller back to the Arduino. (d) Verify that the data transmitted matches the data received. 2. (a) Connect the controller to the GPIO pins on an Arduino board, configured to use the I2C protocol. Set the baud rate to 9600. (b) Generate and send 9.6 Kb of data from the Arduino to the microcontroller. (c) Echo back the same data from the microcontroller back to the Arduino. (d) Verify that the data transmitted matches the data received. 3. (a) Supply monitor pin with a voltage below the operating limit and observe microcontroller measurement. (b) If correct measurement is seen then show the controller controlling the main battery relay disconnecting it from the rest of the system and show that the battery needs charging.
Flame Sensor 1. Must be able to detect if a candle wick, placed up to 12 inches from the sensor, is lit, with $< 0.1\%$ false negatives.	1. (a) Connect the flame sensor to an Arduino. Configure it to poll 10 times per second. (b) Place a candle down and measure 6 inches above the wick. (c) Mount the sensor at this position, and light the candle. (d) Verify that the user flame is detected to the desired accuracy. Adjust thresholds as necessary. (e) Repeat for distances of 8 inches, 10 inches, and 12 inches, until a constant threshold works for all distances.

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Table 3 – continued from previous page

Requirement	Verification
Bluetooth 1. Must be able to maintain a connection up to 10 meters away with open space between devices. 2. Must connect to available devices on interrupt signal. 3. Must power down if no device is found within 5 minutes of the interrupt signal.	1. (a) Connect the Bluetooth module to the GPIO pins on an Arduino. (b) Run a simple ping-pong program on the Arduino to monitor the connection status of the Bluetooth device. (c) Connect to the Bluetooth chip via cell phone. (d) Measure 10 meters away from the Bluetooth chip, and place the cell phone there. Ensure that the space between is free of obstacles. (e) Monitor the connection status of the Bluetooth device, and ensure that the connection is maintained for at least 30 minutes. 2. (a) Connect the Bluetooth module to the GPIO pins on an Arduino. (b) Load the Arduino with the code for connecting the Bluetooth chip to another device. (c) Send an interrupt signal to the Arduino. (d) Verify that the Bluetooth module is able to connect to a cell phone. 3. (a) Connect the Bluetooth module to the GPIO pins on an Arduino. (b) Load the Arduino with the code for connecting the Bluetooth chip to another device. (c) Send an interrupt signal to the Arduino. (d) After 5 minutes, verify that the Bluetooth module has stopped trying to connect and powered down.
Camera 1. Must have a high enough resolution that the user can identify the position of the wick in an image taken from 6 to 12 inches away.	1. (a) Connect the camera module to an Arduino. (b) Load the Arduino with the image capturing sketch. (c) Place a candle down and measure 6 inches above the wick. (d) Mount the camera at this position, and use the Arduino to capture an image. (e) Verify that the user can clearly see the wick in the image (f) Repeat for distances of 8 inches, 10 inches, and 12 inches.

Table 4: Arm Assembly Subsystem Requirements and Verifications

Requirement	Verification
Vertical Stepper Motor 1. Must have a stall torque of 6kg-cm ± 15%. 2. Must have a step angle of 1.8° ± 15%. (a) If it has a smaller step angle, we will adjust the control, but it will not negatively affect the performance of the device. (b) Values based on datasheet [11]	1. (a) Program Motor to run constantly by PWM Arduino program. (b) Connect motor to dynamometer or electric brake to provide precise loading of the motor. (c) Run motor at No-Load or low load. Increase the load until the motor is running at approximately half of no-load speed. Record this torque. (d) Take this torque point and the No-load speed and create a linear plot. The Y-intercept is the stall torque. 2. (a) Attach a piece of bright tape to the motor shaft. (b) Mark starting position of the motor. (c) Program Motor to step 200 steps using an Arduino PWM program. (d) Run the motor and mark the ending position of the bright tape. (e) Record this position in degrees relative to the start. position. It should have traveled 360 degrees. (f) Divide the position by the number of steps taken (30), and you have the step angle of the motor.
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Table 4 – continued from previous page

Requirement	Verification
Horizontal Stepper Motor 1. Must have a stall torque of 1.325kg-cm ± 25%. 2. Must have a step angle of 1.8° ± 15%. (a) If it has a smaller step angle, we will adjust the control, but it will not negatively affect the performance of the device. (b) Values based on datasheet [12]	1. (a) Program Motor to run constantly by PWM arduino program. (b) Connect motor to dynamometer or electric brake to provide precise loading of the motor. (c) Run motor at No-Load or low load. Increase the load until the motor is running at approximately half of no-load speed. Record this torque. (d) Take this torque point and the No-load speed and create a linear plot. The Y-intercept is the stall torque. 2. (a) Attach a piece of bright tape to the motor shaft. (b) Mark starting position of the motor. (c) Program Motor to step 200 steps using an arduino PWM program. (d) Run the motor and mark the ending position of the bright tape. (e) Record this position in degrees relative to the start. position. It should have traveled 360 degrees. (f) Divide the position by the number of steps taken (30), and you have the step angle of the motor.

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Table 4 – continued from previous page

Requirement	Verification
Φ Stepper Motor 1. Must have a stall torque of 1.325kg-cm ± 25%. 2. Must have a step angle of 1.8° ± 15%. (a) If it has a smaller step angle, we will adjust the control, but it will not negatively affect the performance of the device. (b) Values based on datasheet [12]	1. (a) Program Motor to run constantly by PWM arduino program. (b) Connect motor to dynamometer or electric brake to provide precise loading of the motor. (c) Run motor at No-Load or low load. Increase the load until the motor is running at approximately half of no-load speed. Record this torque. (d) Take this torque point and the No-load speed and create a linear plot. The Y-intercept is the stall torque. 2. (a) Attach a piece of bright tape to the motor shaft. (b) Mark starting position of the motor. (c) Program Motor to step 200 steps using an arduino PWM program. (d) Run the motor and mark the ending position of the bright tape. (e) Record this position in degrees relative to the start. position. It should have traveled 360 degrees. (f) Divide the position by the number of steps taken (30), and you have the step angle of the motor.
Snuffer 1. Must be able to reliably extinguish wicks, with < 1% error rate after covering the wick for 2 seconds. (a) Must be able to extinguish various wick sizes (< $\frac{1}{8}$ inches).	1. (a) Light a candle, and wait 10 minutes until the wick is in a well-lit state. (b) Put the snuffer over the wick for 2 seconds to extinguish it. (c) Lift up the snuffer and check if the wick is extinguished. (d) Repeat above steps many times to establish an error rate with data. (e) Repeat above steps with different wick sizes, and with telescoping compressed.

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Table 4 – continued from previous page

Requirement	Verification
Arc Lighter 1. Must be able to light wicks of diameters between 1/16 inches and 1/8 inches with at least a 90% success rate	1. (a) Set up a large adequately voltage rated resistor between leads of output and apply voltage to the arc light circuit with power supply to verify that High voltage will occur. (b) Run arc light circuit off of power supply and verify that a arc will occur (c) Set up a wick with diameter 1/16 inches, away from other materials. i. Position the arc lighter with terminals on either side of the wick. ii. Apply voltage across the arc lighter for 3 seconds. iii. Remove the arc lighter and visually confirm that the wick was lit. iv. Extinguish the wick, then repeat using a wick with a diameter of 1/8 inch. v. Repeat above steps many times to establish a success rate with data