FINAL REPORT: POWER TOOL SAFETY ZONE ENFORCER

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Abstract

There is no defined method put in place by the Occupational Safety and Health Administration (OSHA) for monitoring the area immediately surrounding a power tool operator. In this report, the development of a configurable, low-cost sensor array that monitors human activity within a 1.2 m by 1.8 m safety zone in front of a workbench is discussed. The system can determine if there are zero, one, or more than one individuals in the safety zone and react in real time to enable or disable the ability for a connected tool to be powered. The power state of the tool will simultaneously be indicated to the user through a three-LED status indicator. If fewer than two individuals are in the safety zone, power will be enabled to the device and a green LED will be illuminated. If the tool is currently in use and a second person enters the zone, the power will not be cut and a yellow LED will be illuminated. Otherwise, the tool will be disabled and a red LED will be illuminated. This report outlines the research, design, and verification of all hardware and software aspects of the sensor array.

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1. Introduction

1.1 Purpose

When working with heavy machinery in places such as a lab or a machine shop, one of the first concerns is worker safety. Despite standards put in place and enforced by the Occupational Safety and Health Administration (OSHA), there are still many safety incidents that result in serious injury. For example, in 2007-2008 alone, the number of injuries treated at emergency rooms from table and bench saws was 79,500[1]. In order to address this high accident rate, the objective of our product is to minimize workplace injuries from table-mounted machinery which will increase shop productivity and efficiency due to fewer injuries.

Our proposed solution is to design an automated system that will monitor a specified area around the power tool, identify potential hazards within the area, and then react in the safest manner possible. Since our product must be compatible with a variety of tools to properly address the objective, the system will interface solely with the tool's power source. In this configuration, if an immediate hazard is detected by the system, the tool will not receive power and operation will be inhibited until all hazards have been removed. Once the tool is powered, it will not be disabled until the user stops using it in order to prevent potential risks caused by cutting power mid-task if a new hazard is detected. This implementation will eliminate some of the involved risk in operating power tools and help to automate worker supervision, adding reliability and efficiency to often cumbersome safety procedures.

The effectiveness of our system depends on the physical dimensions of the safety zone. According to a report on recommended safety zones by Podojil Consulting [2] for common machine shop equipment, safety zones for the operator to stand in range in dimension from 1 ft by 8 ft to 3 ft by 6 ft in accordance with ANSI Z535.1-4 standards. The smallest zone that would always provide a standard safety zone for the operator would therefore be 3 ft by 8 ft. However, since the eight-foot width was an outlier compared to the other safety zone widths in the report, we chose a more average value of 6 ft. Lastly, in order to increase early detection of potential risks, we extended the length of the zone to 4 ft. This led us to conclude that a 4 ft by 6 ft zone would be the most effective safety zone for the operator. Converting to meters and rounding, our safety zone was defined to be 1.2 m by 1.8 m.

1.2 Objectives

- When the microcontroller asserts that the machine should be powered, the machine should be powered, and whenever the microcontroller asserts the machine should not get power, the machine shall not be powered. Regardless of whether the microcontroller is asserting the correct signal, the system must be able to respond in this consistent manner.

- The system must be able to detect zero, one, or more than one object in the specified 1.2m x 1.8m rectangular area.

- The system must be able to indicate to the user if the machine will not receive power due to insufficient safety conditions being met.

1.3 Design Overview

At the top level, our system is partitioned into three modules, which are shown in Figure 1.1. The first is the Power Module, which provides power to the rest of our system and contains the relay and current sensor between a regular wall outlet. With these two elements, this module is able to control the power delivered to the power tool and determine if the tool is currently in use. The next module is the Sensor Module, which is comprised of two sensor arrays used in tandem to monitor the amount of people in the safety zone. The two arrays are designated by sensor type and contain either passive infrared (PIR) sensors or ultrasonic range sensors. The final module is the Control Module, which uses data from the Sensor Module and current sensor to count the number of people in the zone and determine if the power tool is currently powered. In response, the Control Module controls the AC relay and uses the status lights to indicate the current status of the system to the user.

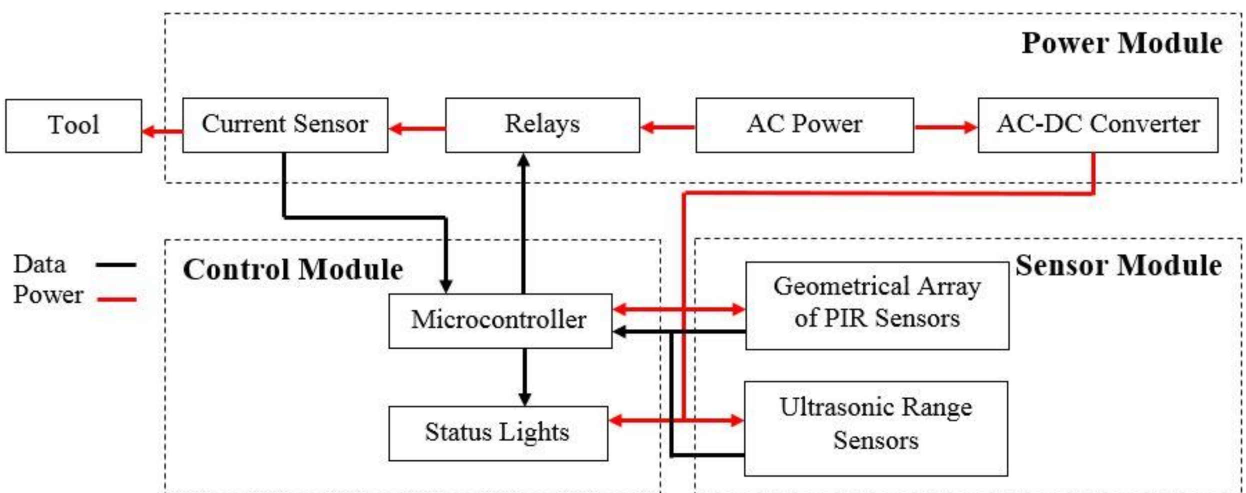

Figure 1.1: Block diagram of overall system

2. Design

2.1 Power Module

Our product is designed to service the largest number of customers in the United States possible. Since most commercially-available power tools in the United States run on a standard 15 A or 20 A wall outlet,[3] our product is compatible with 120 VAC, 60 Hz single-phase wall outlets supporting currents up to 20 A. The complete power module is shown in Figure 2.1. The PCB layout can be seen in Appendix B.

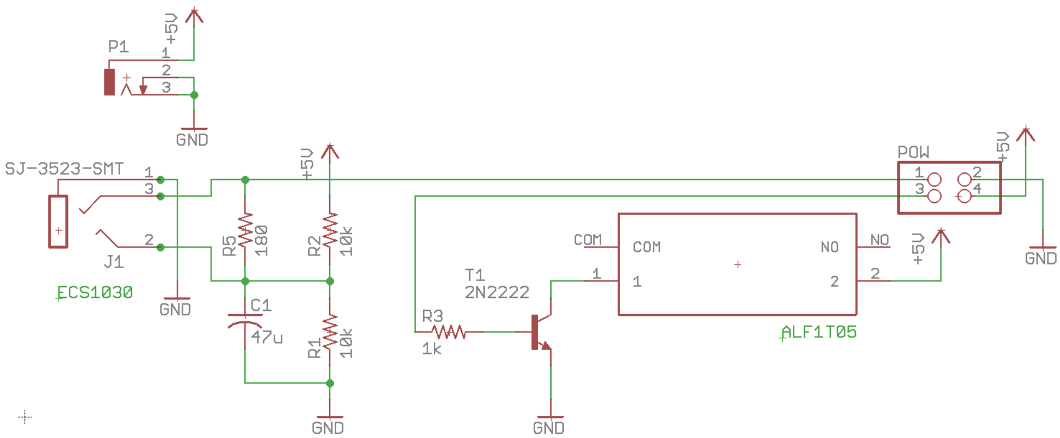

Figure 2.1: Power module circuit schematic

2.1.1 AC/DC Converter

The EA1024CU AC/DC converter was selected to provide a 5V, 4000 mA supply line to the microcontroller circuit.[4] During the design phase, the current specification for the AC/DC converter was determined by summing the maximum current draws for each device, totaling 2842.2 mA. Factoring in a comfortably large margin, our maximum current requirement was set at 4000 mA. During assembly, design changes such as increasing the number of ultrasonic sensors from five to twelve and decreasing the number of PIR sensors from seven to two decreased the current requirement significantly. In total, the maximum current draw is 592.2 mA with a nominal current draw of approximately 300 mA.

2.1.2 AC Relay

The Panasonic ALF1T05 AC relay in the power module electrically connects or disconnects the connected power tool from AC power in response to a 5 V digital control signal.[5] As seen in Figure 2.1, the AC relay consists of four terminals: two terminals to drive the relay coil, a normally-open contact (NO), and a common contact (COM). The relay coil is driven using a common-emitter stage BJT transistor biased in the saturation region, providing sufficient current to drive the relay coil. To generate this current, we designed a BJT current amplifier to provide a current of 180 mA in response to an input current of approximately 4 mA from the microcontroller. When driven with 180 mA at 5 V, the relay is closed, allowing current to flow. Otherwise, the relay is open, allowing no current to flow.

2.1.3 Current Sensor

The current sensor monitors the power state of the power tool by measuring the current flowing through the live wire of the AC power supply. Chosen for its ease of installation, the ECS1030 sensor is a Hall effect sensor that generates an output voltage proportional to the current vector flowing through the center of a split-core current transformer.[6] When measuring an AC power source, the output of the sensor is a small-amplitude AC signal with 60 Hz frequency.

Since we are reading AC voltage, we need to bias the output of our current sensor circuit at 2.5 V to avoid negative voltages at the microcontroller and to ensure that the full range of currents up to 5 V peak to peak can be read. One potential risk occurs if the output amplitude exceeds 5 V peak-peak. However, we can see from the relationship $V_{out}(mV) = 90I_{sense}(A)|_{R_L=180\ \Omega}$ that for a load resistance of 180 Ω, the maximum safe current that can be read is approximately 28 A, well above the 20 A limit of the power tool input.

2.2 Control Module

2.2.1 Microcontroller

The microcontroller module, shown in Figure 2.2, acts as the central control interface for the system. The microcontroller board reads in data from the ultrasonic sensor array, PIR digital logic, and current sensor to determine the current state of the safety zone. Based on these inputs, the microcontroller controls the state of the status lights and the AC relay as described by the software algorithms in Section 2.4. The system uses an ATMega328-20P [7] chip to drive the system. Using an external 16 MHz crystal oscillator with this chip provides a runtime advantage over the built-in 8 MHz crystal. The reset switch allows program execution to be restarted if necessary, and the programming header allows bootloading of the microcontroller for debugging. The PCB layout for the microcontroller can be seen in Appendix C.

2.2.2 Status Lights

The status lights serve as immediate feedback to the power tool operator. A red light indicates that there is more than one person within the safety zone and the tool will not be powered until the risk is mitigated. A yellow light indicates that though the tool is currently in use, there is more than one person in the zone and a potential hazard is present. A green light indicates that less than two people are in the safety zone and the power tool can be operated. The status lights are packaged in a clear plastic box, making them viewable by both the power tool operator and individuals near the safety zone.

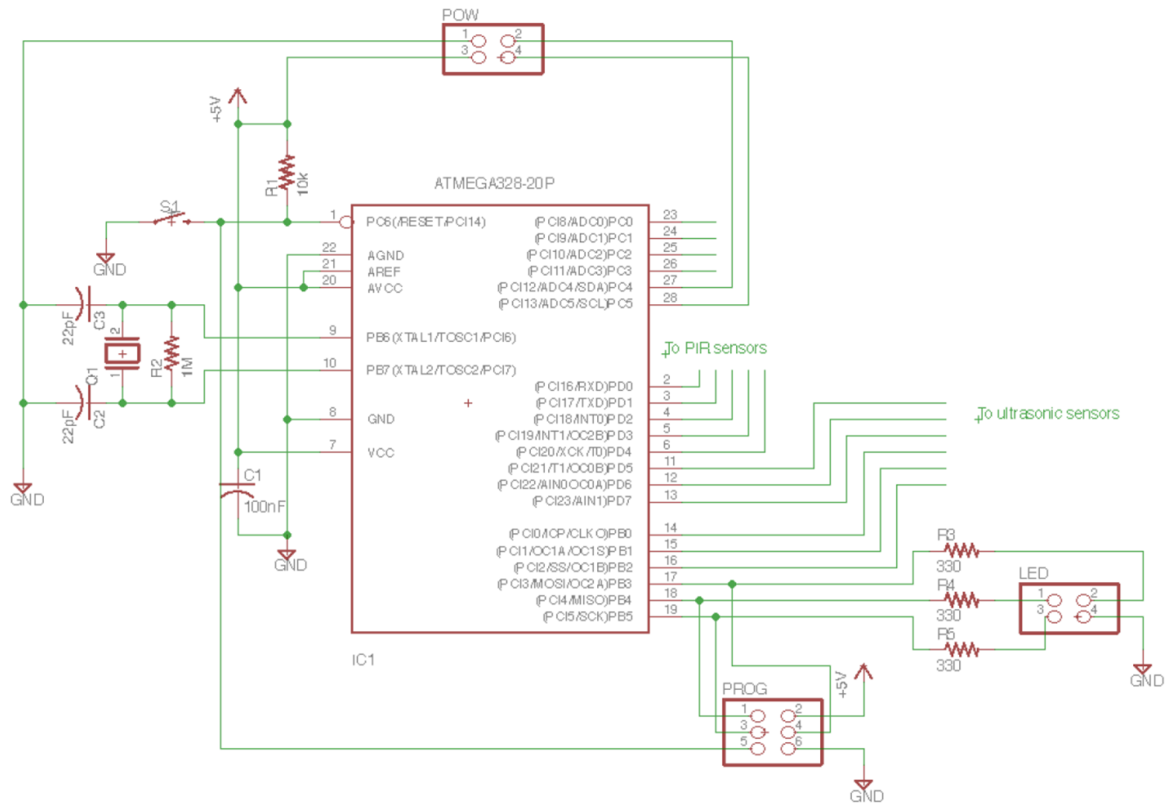

Figure 2.2: Schematic of microcontroller sub-circuit on microcontroller board

2.3 Sensor Module

2.3.1 Ultrasonic Sensors

The HC-SR04 [8] ultrasonic sensors are used to gather the bulk of the information about our safety zone. We chose this sensor because it is easily interfaced with a microcontroller, able to give accurate data when an object is present in its FOV, and is very cost effective. Each sensor is easy to use because it only has four pins: power, ground, trigger, and echo. The trigger pin is an input to the sensor that the microcontroller sets high for 10 µs, signaling the ultrasonic sensor to emit a sonic pulse. The sensor will then set its echo pin high, and once it receives the return sound wave it sets the echo pin back low. We are able to use the microcontroller to time how long the echo pin is high which, based on the speed of sound, will tell us how far away the object it detected is located. The distance is calculated using the equation $d = t/58$, where d represents the distance the object is from the sensor in centimeters and t represents the duration in microseconds that the echo pin was held high.

2.3.2 Ultrasonic Control Circuit

The ultrasonic control circuit increases efficiency of microcontroller pin usage and software runtime. As opposed to direct connections, a 2:4 decoder is used to control the A-line, B-line and AB-line trigger pins, allowing us to trigger the ultrasonic sensors using only two digital input-output (DIO) pins from the microcontroller as opposed to three. The echo pins of the sensors are fed into OR gates in order to cut down on microcontroller DIO pin density by a factor of two.

Since only one sensor per OR gate will be active at a time, the integrity of the sensor data is maintained. A schematic for this circuit is shown in Figure 2.3.

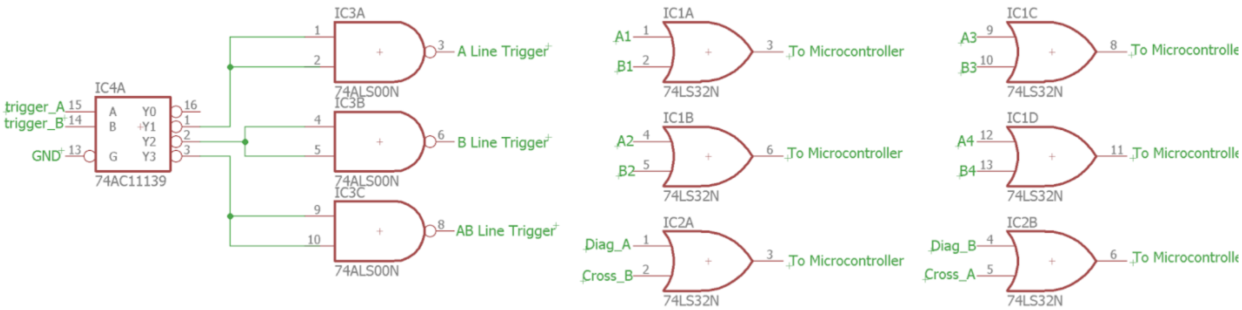

Figure 2.3: Schematic of ultrasonic control circuit

2.3.3 Passive Infrared (PIR) Sensors

We use PIR sensors for side entry/exit detection since they are very good at detecting motion across their field of view. The PIR sensor we chose is the Murata IRA-S210ST01, which outputs an analog voltage corresponding to changes in infrared light (IR) detection and is specifically designed for detecting humans.[9] The output of the sensor is also directional. When someone crosses the FOV from left to right, the voltage increases and then decreases before leveling out whereas when someone crosses from right to left, the voltage decreases then increases. The schematic for the PIR sensor and circuit is shown in Figure 2.4. The design for the PIR PCB can be seen in Appendix D.

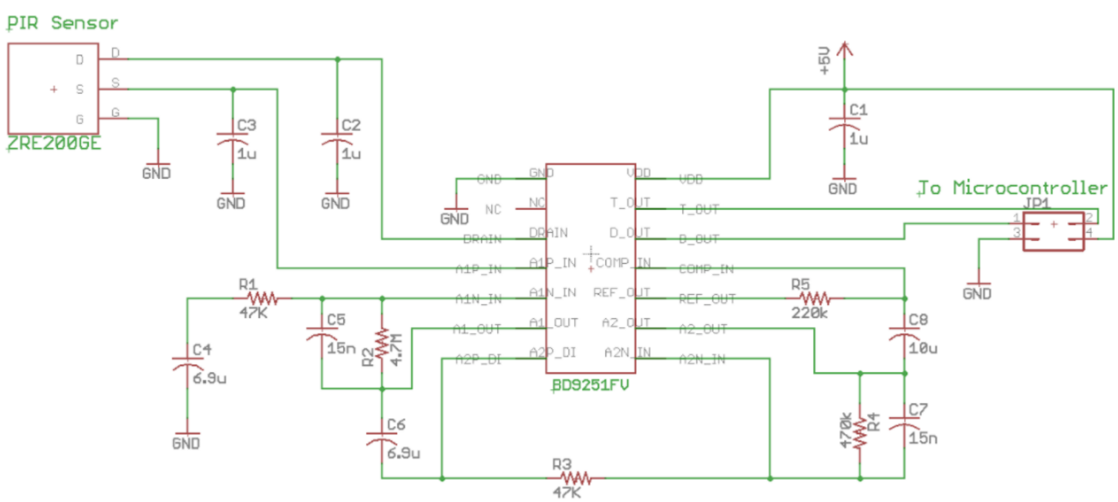

Figure 2.4: PIR circuit board schematic

2.3.4 PIR Amplifying Circuit

Since this output is only in the millivolt level, we need to amplify and filter the output to be able to be read by digital pins on the microcontroller. We use a gain of about 1,000 and a bandpass filter centered at around 2 Hz which approximately corresponds to the period it takes someone to walk through the sensor's FOV. We found a premade IC chip , the BD9251FV, that has a two-stage amplifier along with a bandpass filter that was designed for use with PIR sensors [10].

While the amplifier chip contains the exact framework needed to interface with the PIR sensor, it leaves the choices for the values of the resistors and capacitors that determine the gain and bandwidth of the frequency response up to us. The gain of each stage of amplification is

$$A = 1 + \frac{R_1}{R_2} \tag{2.1}$$

where R_2 is the feedback resistor and R_1 is the resistor connected to the negative terminal of the op-amp in each stage. The way the amplifier chip achieves a bandpass filter is by using a lowpass and a highpass filter at each stage. The equation for the cutoff frequency of both the lowpass and highpass filters is

$$f_c = \frac{1}{2\pi RC} \tag{2.2}$$

where R is the feedback resistor and C is the feedback capacitor in each stage for the lowpass filter. For the highpass filter, R and C are the resistor and capacitor that go from the negative terminal of the first stage op-amp to ground. The datasheet for the amplifier chip lists typical values for each of the resistors and capacitors. The resulting frequency response of the amplifier stages using the typical values is shown in Figure 2.5.

However, after running some tests, we determined R_2 should be reduced. When using the typical values, the gain for our PIR sensor is too large. In order to correct this while minimally affecting the bandwidth of the frequency response, we reduced R_2 in (2.1) for the second stage by a factor of 10, effectively reducing the gain of the second stage by a factor of 10 from 10,000 to approximately 1,000. Based on (2.2) the cutoff frequency of the lowpass filter in the second stage increases by a factor of 10 thereby increasing the width of the bandpass filter. However, the lowpass filter cutoff frequency of the first stage remains unchanged, so the increase in the cutoff frequency of the second stage does not affect the overall bandpass region.

After filtering occurs, the chip uses comparators in conjunction with an OR gate and an SR latch to generate the two output signals. The first is called D_OUT, which pulses twice in response to a person passing through the sensor's FOV. The second is called T_OUT, which transitions from low to high or high to low as D_OUT pulses depending on the direction that a person moved through the FOV.

In order for the PIR sensors to detect activity more precisely, we need to reduce their FOV. In order to do this, we used a Fresnel lens. The lens collimates the sensors previous FOV, and then we are able to use commercially-available metallic tape to cover the lens enough so that only one significantly narrower collimated beam remains.

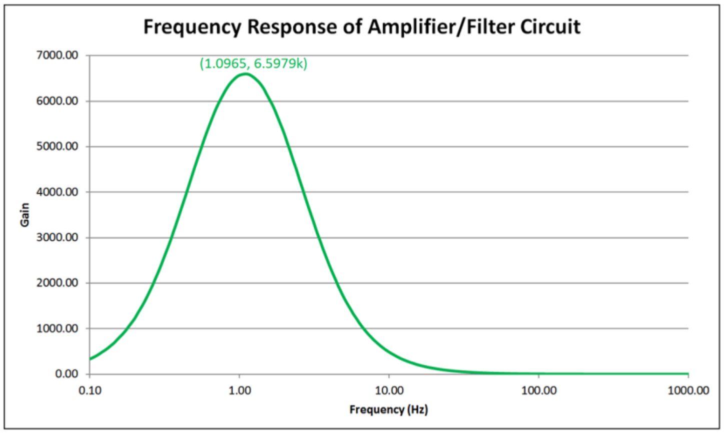

Figure 2.5: Frequency response of two-stage amplifier

2.3.5 Digital Logic Circuit

The digital logic circuit captures and holds PIR sensor information until it can be processed by the software algorithm. Since the PIR sensors are asynchronous, the addition of this digital logic eliminates the possibility of the microcontroller missing a sensor event. As previously mentioned in Section 2.3.4, the PIR amplifier chip outputs two pulses of the D_OUT signal to indicate sensor activity. In addition, a state transition of the T_OUT signal indicates the direction of motion of the object through the sensor's field of view. The D_OUT and T_OUT signals are stored in positive edge triggered D flip-flops until a reset signal from the microcontroller is received. Figure 2.6 shows the schematic of this circuit.

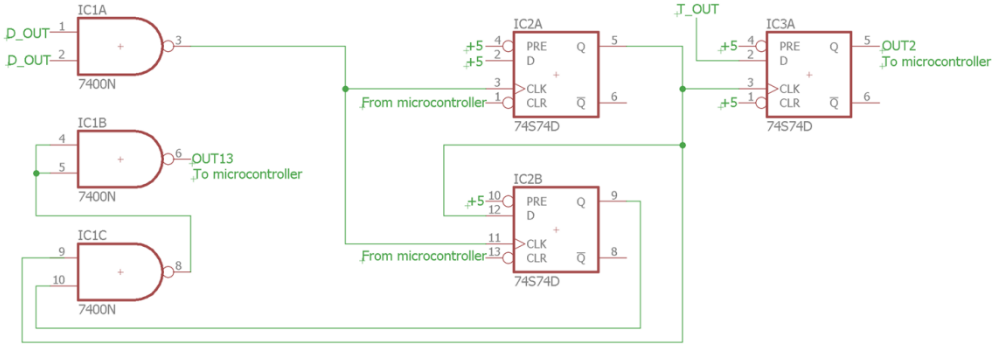

Figure 2.6: Schematic of digital logic circuit

2.3.6 Array Layout

There are two scenarios that need to be considered when monitoring entries or exits from the zone. The first of these is single entry into the zone from the side. Since PIR sensors are good for edge detection, having one of these with its field of view along the edge of the zone should be able to detect if someone enters or exits in a horizontal fashion. To make sure this person is also within the zone and not more than 1.2 m away, there is an ultrasonic sensor along the edge that will be checked if the PIR sensor detects someone to make sure they are within the zone. To account for the case where multiple people might enter the zone at the same time, there is a cross view ultrasonic sensor that is aimed such that its FOV covers only the back half of the zone along the edge where the PIR sensor is located. This way, if two people walk in side by side, the cross view ultrasonic sensor will detect a person, and the edge ultrasonic will detect a person that is closer than where the cross view ultrasonic sensor's FOV intersects the side of the zone. The array layout for side entry/exiting is shown in Figure 2.7.

The second scenario is single entry into the zone from the back. To detect this, the ultrasonic sensors are arranged so that the overlap of neighboring A-line and B-line sensors will be able to determine if there are zero, one or more than one people entering or exiting zone. If only two neighboring overlaps are triggered, then only one person has entered the zone, but if three have been triggered, then two people must have entered the zone since one person should not be able to trigger three at a time unless they are intentionally interfering with the system. In the case that someone is already in the zone, we still must be able to detect if another person enters behind them, so there are two angled sensors looking at the back of the zone as well. The array layout for detecting entry/exiting into the back is shown in Figure 2.8. All other scenarios can be expressed as a combination of these two scenarios.

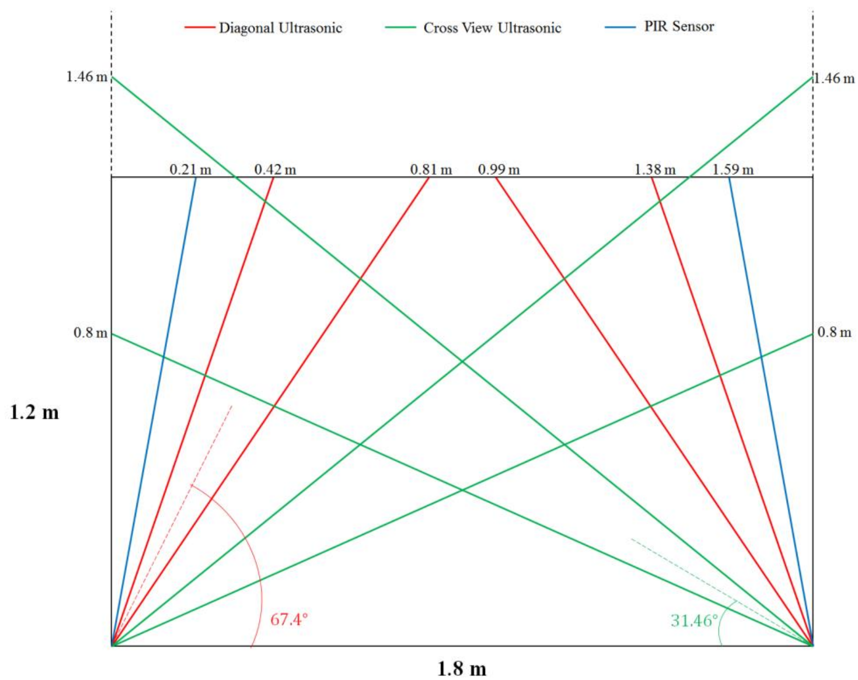

Figure 2.7: Array layout showing sensor arrangement used to detect side entry/exit

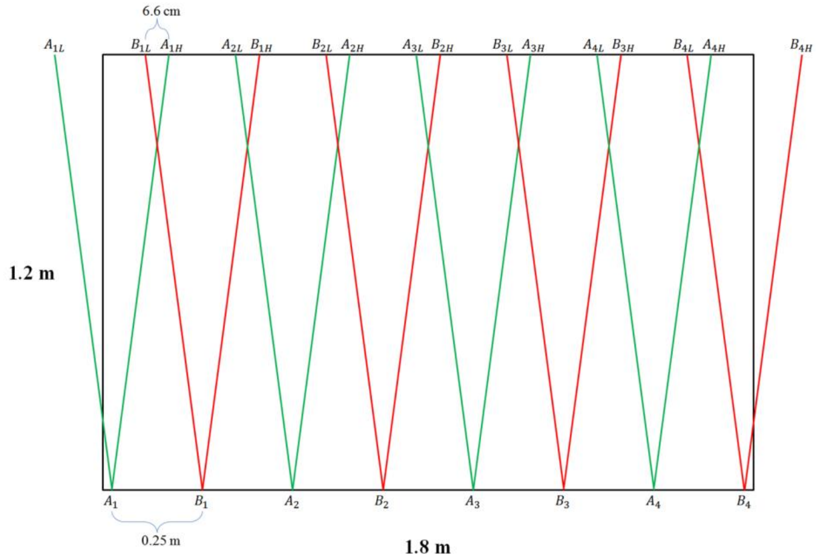

Figure 2.8: Array layout of sensors used to detect back entry/exit

2.4 Software Algorithms

2.4.1 Relay and LED Control

Figure 2.9 illustrates the general algorithm for the main loop. At each iteration, the sensor data is read and then processed to determine if there is zero, one, or more than one person in the zone. If there is more than one person and the tool is not currently powered, the zone is deemed unsafe and the relay will be opened, disabling power to the tool. A red status light will be illuminated, indicating that the tool will not be powered. If there is more than one person within the zone and the tool is currently powered, a yellow status light will be illuminated, indicating a hazard. However, the tool will still remain powered in order to avoid undefined tool behavior due to a sudden loss of power. If there is zero or one person, the zone is deemed safe and the relay will be closed, supplying power to the tool. A green light will be illuminated, indicating that the tool is receiving power.

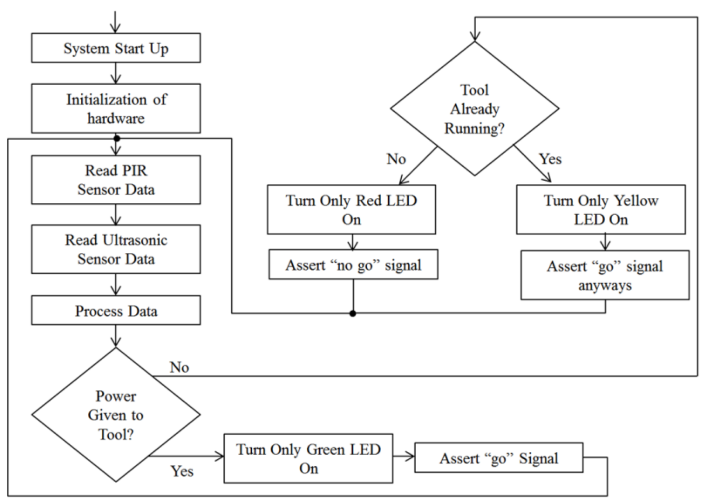

Figure 2.9: Flowchart detailing main control loop

2.4.2 Data Acquisition

There are three different types of data that we must be able to collect. The first is the PIR sensor data. To read the PIR sensor, we first check if there has been activity detected in the sensor field of view using the D_OUT signal. If there has been activity, the direction value from T_OUT is read and stored for later processing. This occurs for both PIR sensors.

The second type of data we must be able to collect is the ultrasonic sensor data. To read the ultrasonic sensor data, each line of sensors is triggered and their echo pins are polled until all pulses for that sub-array have returned. Since the sensors sometimes read spurious values due to sound reflecting off non-ideal surfaces, we implemented a simple averaging filter for each sensor. Then, the pulse widths that correspond to an object's distance to the sensor are calculated and stored for later processing. This process occurs for each of the three sub-arrays.

The third type of data is the current sensor data, which is used to check if the tool is already running. Upon the startup of the system, we assume the tool begins without power, and for a period of a few seconds, we sample the input from the current sensor and find the average value for the unpowered tool. After the average has been set, every time we read the input from the current sensor, we populate an array that stores the four most recent values read from the current sensor.

2.4.3 Data Processing

In order to process the saved data, we first check the side entry detection sensors. If the PIR sensor detects a change, the ultrasonic sensors determine if the change was due to one or two people. The PIR direction information is then used to determine if the change was from an entry or an exit, and the number of people in the zone is changed accordingly. This process is shown in Figure 2.10.

The main ultrasonic array data is used to detect back-of-zone entries and exits. An entry or exit is detected by comparing the current array values with the previous sensor data to determine if the sensor values are increasing (indicating an entry) or decreasing (indicating an exit) across the 120 cm boundary distance. If this distance has been crossed, the number of people within the zone is updated accordingly. When one person is already in the zone, angled sensors are used to detect entrances and exits. This process is detailed in Figure 2.11.

The data from the current sensor is then processed to determine if the tool is in use. To determine whether the tool is currently powered on, we simply check to see if any one of the four most recent values differs from the average value by a certain deviation. We need to check the current sensor like this because the output of our current sensor will be an oscillating voltage signal around a bias point of 2.5 V which means if we just check one value, we may have sampled this wave right when it is near or at 2.5 V. Since 2.5 V is the value the current sensor will report when the power tool is off, this sample will say the tool is off when in reality it is on. Therefore, by checking the four most recent values, the probability that the midpoint is sampled four times in a row is very low and we are reliably able to determine when the tool is on. This does not cause any false positives when the tool is off because when the tool is off, the current sensor output will always be within the specified tolerance.

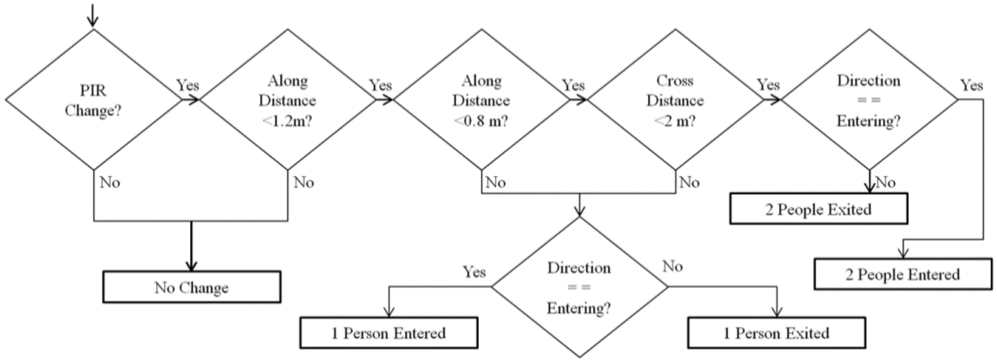

Figure 2.10: Flowchart detailing side entry/exit detection algorithm

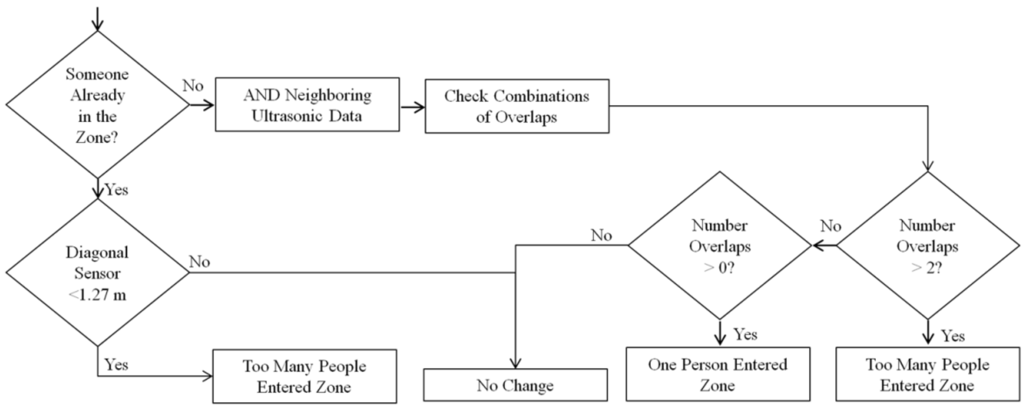

Figure 2.11: Flowchart detailing back entry/exit detection algorithm

2.5 Physical Design

The power module case is designed to be as unobtrusive as possible. It consists of a 4 inch by 4 inch by 3 inch metal box with a single 20 A outlet on the front that the power tool can plug into. The dual-outlet cover plate on the rear panel serves as a feedthrough for the AC power line and AC/DC converter, which plug directly into any two-outlet wall outlet rated to 20 A. Inside this box are all the components mentioned in Section 2.1. The mounting system we are currently using for the array is a pair of gutter siding lengths that form a rail with a slit in the side so that our sensors can see into the zone. Additionally, there are vertical side rails for the PIR sensors so that they can have better visibility. Inside the sensor rail, we have our microcontroller and other logic circuits that connect to the sensors.

3. Verification

Our design verification was done in two stages. The first was the individual component level verification, which helped ensure that when the system was put together, the individual components would function as desired. The second stage was the system-level verification, which allowed us to test the entire module and also further confirmed individual component functionality. The full Requirements and Verification table is attached in Appendix A.

3.1 Power Module

In order to verify that our AC relay functions correctly, we first check to make sure the impedance through the relay when open is greater than 1 MΩ and less than 1 Ω when closed. We test this by using a DC power supply to place a range of voltages across the relay coil and a current-reducing resistor and then measure the impedance across the normally open (NO) and common (COM) pins of the relay. When we ran this test, the impedance was 0.052 Ω for voltage levels between 4.0 V and 5.5 V. The impedance was measured as "overload" when we supplied 0 V and 0.5 V across the relay coil. Based on these results, our relay is well within the requirements.

We also need to make sure the circuit to drive the relay coil is capable of opening and closing the relay. In order to test this, we connect one end of the relay coil to 5 V and the other end to the collector of the BJT in the current driving circuit. We supply 0 V and then 5 V to the base of the BJT and measure the current through the relay coil and to the base of the BJT. When 0 V is supplied, the BJT is off and 0 A of current flows through the relay coil and the base of the BJT, opening the relay. When 5 V is supplied, the BJT is on, the relay is open, the current through the relay is 176 mA, and the current through the base of the BJT is 4.182 mA. Based off this test, we have verified our microcontroller will be able to open and close the relay using the BJT current amplifying circuit.

Next, we check to see that the current sensor is able to read AC current through the power tool. The current sensor has a linear current response proportional to the measured current. In order to characterize this relationship, two current measurements are made for AC-powered devices with low and high current draws. The linear relationship is established by noting that the origin must be crossed and the slope of the line will approximately be one half of the bias resistance. Figure 3.1 gives our characterization results.

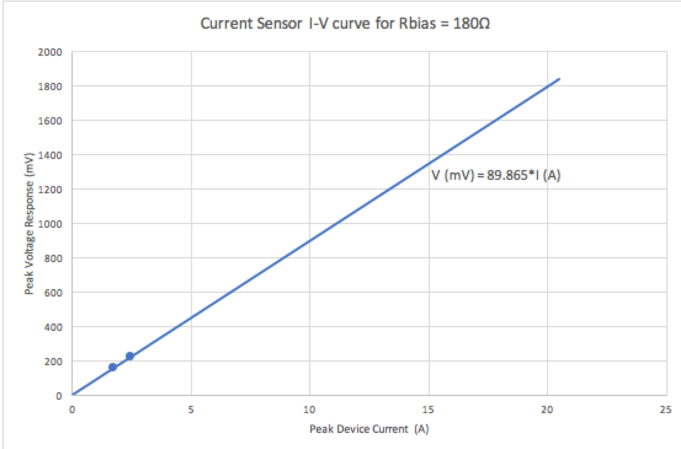

Figure 3.1: Current sensor I-V relationship

3.2 Ultrasonic Sensors

In order to verify the accuracy of the ultrasonic sensors, we placed a flat object at many different distances from the sensor. We then measured the difference between the actual distance of the object and the distance calculated by the ultrasonic sensor at 10 cm increments. These errors are shown in Figure 3.2. All error uncertainties are well within the 10 cm allowed error, verifying that our sensors are accurate enough to use.

In order to verify the timing constraint on the settling of the output of the averaging filter, we connected one ultrasonic sensor and ran the averaging filter on the output. By causing an abrupt change in what the ultrasonic sensor would see in its field of view and comparing the time of this change with the time that the output of the averaging takes to reach that value, we were able to determine that the worst-case latency is approximately 500 ms. The plot used to calculate this latency is shown in Figure 3.3.

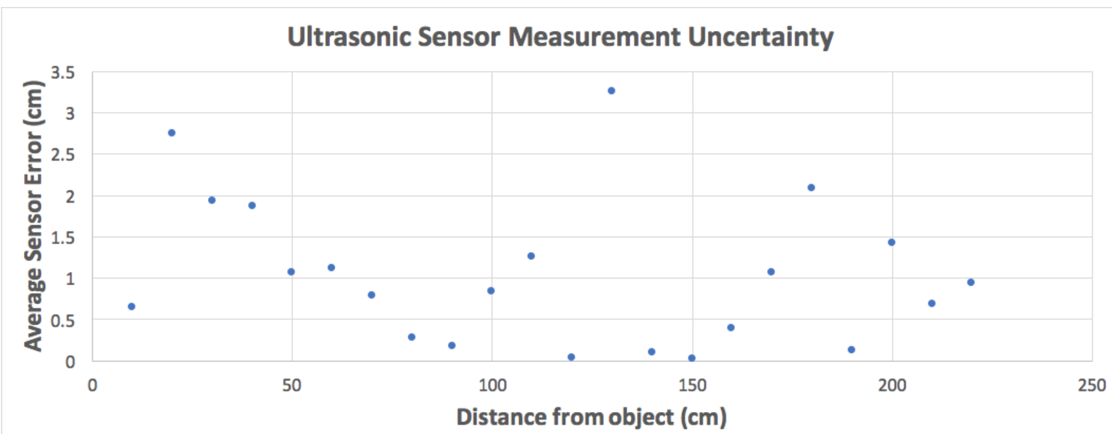

Figure 3.2: Ultrasonic sensor uncertainty characterization

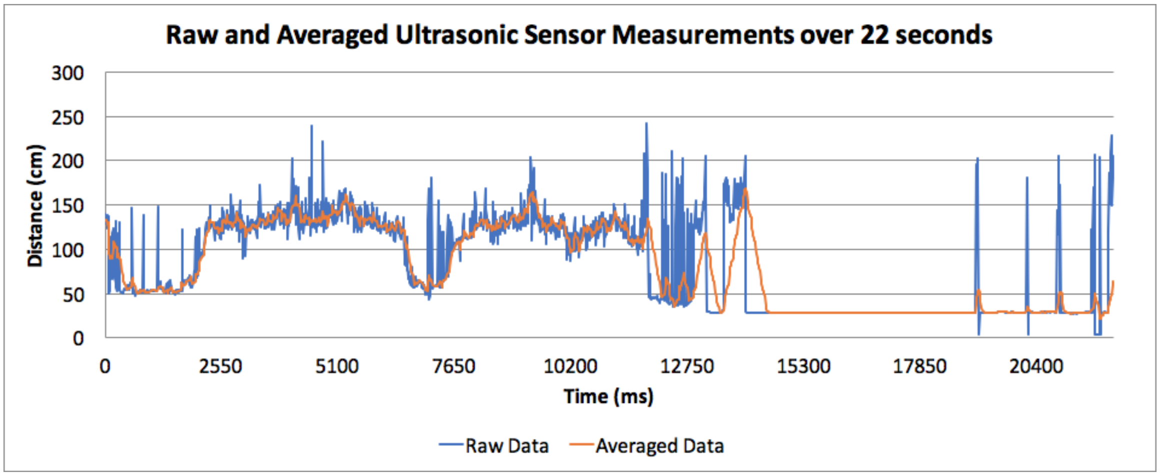

Figure 3.3: Comparison of raw and filtered ultrasonic sensor measurements

3.3 PIR Sensors

In order to verify that the output of the PIR sensor's amplifier chip was above our 4 V requirement, we connected the sensor up to an oscilloscope and looked at the output signals D_OUT and T_OUT. From this, we could see that the maximum voltage seen on the oscilloscope was 4.71 V, indicating that the PIR sensor amplifier output is above the required voltage.

In order to verify the modified FOV of the PIR sensor, we connected the output of PIR to the oscilloscope and walked in front of the sensor. We marked the approximate position we were at when each of the two D_OUT pulses occurred to mark when we entered and exited the FOV. Since our bodies do not have a negligible width, we marked where the front of our body was for entering the FOV and where the back of our body was for exiting the FOV. We did this for a few different distances to create two lines that approximate the sensor's FOV. Lastly, we used basic trigonometry to calculate the FOV. Based on these tests, our modified FOV measured approximately 22 degrees.

The output of the digital logic was verified using both an oscilloscope and using the microcontroller. On the oscilloscope, we can see the activity bit goes high on the second rising edge of the inverted D_OUT signal. In addition, the direction bit goes from low to high, indicating a left to right direction of travel, as seen in Figure 3.4. Similarly, using the microcontroller to run a serial monitor, we verified that the software was getting the correct values based on the activity and direction of the person triggering the PIR sensor.

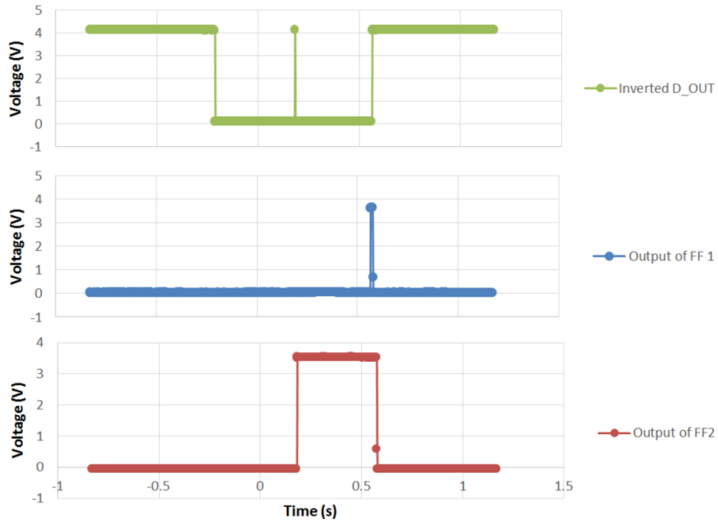

Figure 3.4: Output of digital logic where FF1 holds activity and FF2 holds direction

3.4 Array Side Entry/Exit Detection

Side entry was verified by setting up the array and determining where PIR sensor boundaries lay. By watching the change in LEDs when entering the zone, we were able to verify that the sensors were aligned properly and that the field of view was sufficiently narrow. Combined with the side entry algorithm we were able to successfully determine when there were too many people in the zone, indicating that the activity and direction outputs of the PIR were correct.

3.5 Software Requirements

The reading of sensor data was tested by connecting the microcontroller to the PIR and ultrasonic sensor arrays. For the ultrasonic sensors, objects were placed at measured distances and their values were recorded using a serial monitor. These values were accurate and only had small errors that were verified to not affect the functionality of the rest of the system. By putting timers around the ultrasonic read data function call, we were able to determine the maximum function call time of 0.05 s, and an average time of 0.03 s. For the PIR sensors, people would enter the zone in a known manner and the software results were verified via serial monitor again.

The processing of ideal sensor data was verified by creating arrays with known values that represent certain entry/exit scenarios and then running the code while watching for the correct output of the function regarding the number of people in the zone. The main relay control was verified by having people walk in the zone to create certain known scenarios and by watching the LEDs change and seeing if the tool was powered or not. These tests were run multiple times each with a set of ideal data and the output was verified to be completely accurate. The runtime for the entire algorithm was determined by using a in program timer that prints the time before and after the function call. By printing this value each iteration, we were able to verify that the system can respond to a change in the zone in less than three seconds.

4. Cost

4.1 Parts

For a complete Bill of Materials, refer to Appendix E.

Table 4.1: Bill of materials (BOM)

Part Name	Part Number	Unit Cost	Quantity	Total
Microcontroller	ATMega328-20P	$5.50	1	$5.50
Ultrasonic Range Sensors	GP2Y0A60SZLF	$1.71	12	$20.52
Power Module	Custom	$26.84	1	$26.84
PIR Module	Custom	$6.92	2	$13.84
Cabling	AWG 22	$26.68	200 ft	$24.68
PCB Fabrication	PCBWay	$10.00	3	$30.00
Structural Components	N/A	N/A	N/A	$25.93
Surface Mount Components	N/A	N/A	N/A	$7.50
Total				**$154.81**

4.2 Labor

Table 4.2: Estimated labor costs

Name	Hours Invested	Hourly Rate	**Total Cost** = Rate*Hours*2.5
Nick	200	$30	$15,000
Kristina	200	$30	$15,000
Channing	200	$30	$15,000
Total	600	N/A	$45,000

4.3 Grand Total

Table 4.3: Grand total of costs

Parts	Labor	Total Cost
$154.81	$40,500	$40,654.80

5. Conclusions

5.1 Accomplishments

We were able to design a fully functioning power control module that could effectively supply or cut off power from the tool. We were also able to design software algorithms that could consistently and accurately process the data. The PIR sensor and digital logic circuit were successfully integrated into the system to allow us to detect side entries as well. We were also able to create a viable product that was non-invasive for workers and has use in the real world at a low cost.

5.2 Uncertainties

The biggest issue we had was with our ultrasonic sensors. According to the datasheet [8], they are supposed to have a range resolution of 2 cm to 400 cm; however, when there were no objects in front of the sensor, the values returned were incorrect. We attributed this issue to the manufacturing techniques used to make the product cheaper, which resulted in inconsistent behavior. In order to fix this, we arranged the sensors in such a way that the value returned would be outside the sensors desired accuracy range so it they would not affect the data used to determine if the tool should be powered.

5.3 Ethics and Safety

Since this project involves creating a product that will increase worker safety in machine shops, it is important to consider the requirements put in place by the Occupational Safety and Health Administration (OSHA), the regulatory body for workplace safety. The requirement enforced by OSHA that is most relevant to this project discusses guarding for power tools. According to these requirements, if there is a part exposed that could cause harm to a worker such as gears or hinges, then guarding must be in place so that the operator does not have “any part of his body in the danger zone during the operating cycle”.[11] While this regulation accounts for the operator’s whereabouts during the operating cycle, it does not account for other people that could be potentially in harm’s way during operation of the power tool. While OSHA does not have any specific requirements about a zone of safety, many machine shops implement this type of regulation themselves to protect their workers and avoid workplace injury. Serious workplace injuries must be investigated by OSHA and could result in negative consequences for the particular shop.[12]

One of the largest concerns for safety with our design is the actual power tool that our system is interfacing with. When working using our system in conjunction with a power tool, users must still be aware that even with the added safety measure we are creating, the tool is still dangerous and must only be used with proper training. Another safety concern is the location of our device. Since it will be a ground mounted sensor system, the possibility of tripping on it is a potential safety hazard. We minimize the risk of tripping by placing our sensor array right up against the base of the power tool and minimize the distance that the array protrudes into the work zone.

We must also be aware of the IEEE Code of Ethics.[13] In order to follow #1, our product is specifically designed to reduce the risk of danger to workers, satisfying the first clause. The status lights satisfy the second clause by providing immediate feedback to the worker if endangering factors are present. In a worst-case scenario where the relay was shorted, the tool would function as if our device was not present, adding no additional safety hazards. If the relay was somehow left open, the power tool that interfaces with our device will receive no power which will prevent proper functionality of the power tool but will not add any additional safety hazards.

To ensure we are following IEEE Code of Ethics #3, as part of our sensor characterization procedure, we ensure there is no combination of hazards such that a hazard within the detection zone will not be identified. The range of which our product is effective is explicitly stated and will not deviate from the listed range when physically implemented. Our claims are reasonable, making the key distinction that our product is able to reduce the number of accidents but is not able to prevent all accidents. Our product only identifies certain types of hazards and cannot protect against circumstances outside of the scope of its functionality.

5.4 Future Work

In the future, we would like to be able to refine our design more to be able to more precisely determine the boundaries of the zone. Currently, due to the sensor inaccuracy mentioned in Section 5.2, the boundaries are all approximates, however if we were able to find more accurate sensors, we believe that this issue can be solved. Additionally, we would like to have a more robust sensor mounting system. Our current mounting system was chosen due to cost; however, it is not the most sturdy or durable material. In addition, it does not completely protect the sensors, which is a necessary trait if our product was to actually go to market. Finally, we would like to have a custom designed power supply for our 5V system, instead of using an AC/DC converter that occupies an additional wall outlet. By implementing a custom designed power supply, we will be able to only use one wall outlet for our system, making it more versatile and reducing the space that our power module would need to take up when connected to the wall.

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Appendix A: Requirements and Verification

Component	Requirement(s)	Verification
AC Relay (4 points)	1. *The relay shall provide less than 1Ω of output isolation for a control input of 4.0 - 5.5 VDC.* *(1 point)*	1. Verification for Requirement 1 a. Apply 4.0VDC to the control terminals of the relay. b. Using an ohmmeter, probe the signal terminals of the relay and ensure that a low impedance (<1Ω) condition is present. c. Repeat steps a and b for input voltages of 4.5VDC, 5.0VDC, and 5.5VDC.
	2. *The relay shall provide greater than 1MΩ of output isolation for a control input of 0 - 0.5 VDC.* *(1 point)*	2. Verification for Requirement 2 a. Apply 0VDC to the control terminals of the relay. b. Using an ohmmeter, probe the signal terminals of the relay and ensure that a high impedance (>1 MΩ) condition is present. c. Repeat steps a and b for an input voltage of 0.5VDC.
	3. *The BJT current amplifier circuit is able to amplify an input current of approximately 4mA to an output current of 180mA +/- 10%* *(2 points)*	3. Verification for Requirement 3 a. Apply 5VDC across the base-emitter junction of the relay. b. Using a current probe, measure the input current at the base. Verify that input current is on the magnitude of 4mA. c. Using a current probe, measure the current through the coil of the relay. Ensure that the output current is within +/- 10% of 180mA.
Current Sensor (3 points)	1. *The current sensor shall be able to sense AC currents between 5A and 15A* *(3 points)*	1. Verification for Requirement 1 a. Using a voltmeter, place voltage probes in parallel with the resistive load of the current sensor. **For two or three devices:** b. Connect any device that can be powered from a 110VAC single-phase source to a wall outlet. c. Power current sensor circuit and measure peak amplitude of output voltage waveform.

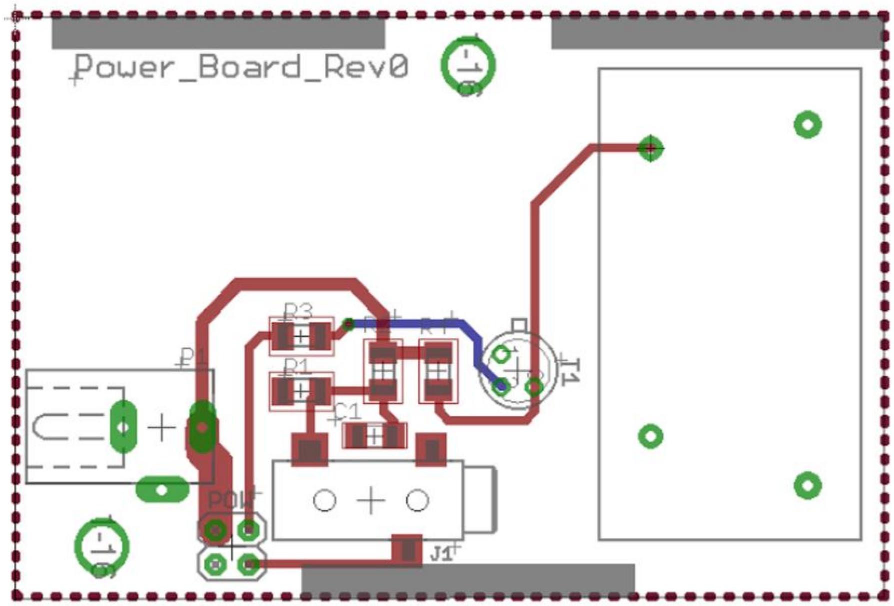
		d. Create a linear plot of output voltage versus input current. The relationship will be given by the measured voltage divided by the coupling resistance plus an offset. e. Extend the linear plot to 15A. Ensure that the corresponding output peak voltage will be less than 2.5V.
AC/DC Converter (1 point)	*1. The AC/DC converter shall output 5VDC with less than 10mV of ripple. (1 point)*	1. Verification for Requirement 1 a. Connect output of circuit to oscilloscope. b. Apply input signal to regulator. c. Measure average signal value and ensure it is within the range of 5±0.2VDC
Microcontroller (18 points)	*1. Microcontroller must use no more than 4A when powered by a 4.5-5.5V source. (3 points)* *2. The microcontroller shall respond to the change in the presence of zero, one, or more than one persons in less than three seconds (3 points)* *3. The microcontroller shall be able to read in sensor data in under 0.1 s. (5 points)* *4. The software, with idealized sensor data , shall be able to process sensor data to determine if there are zero, one, or*	1. Verification for Requirement 1 a. Connect microcontroller to variable voltage source. b. Measure microcontroller current draw for supply voltages of 4.5VDC, 5.0VDC, and 5.5VDC by recording current draw displayed on the voltage source. 2. Verification for Requirement 2 a. Perform a worst-case timing analysis. b. Trace software control loop. c. Calculate maximum time delay for each component. d. Sum all delays in loop and ensure total is less than three seconds. e. Run 100 measurement simulations and average the latency of each. 3. Verification for Requirement 3 a. Connect sensor array to microcontroller. b. Continuously read state of the array. c. Output processor times at the beginning of the execution phase of each data cycle. Ensure the time delay between adjacent cycles is less than 100ms. 4. Verification of Requirement 4 a. Create three simulated cases of entry and exit events. Add in random offset as a noise factor. b. Pass simulated data into algorithm and

	more than one person in the zone 95% of the time. (7 points)	record output. c. Iterate 100 times and ensure that 95% threshold is met.
Status Lights (2 point)	*1. The status LEDs must draw 10-15 mA of current.* *(1 point)* *2. The status LEDs must be visible from 1.8 meters away* *(1 point)*	1. Verification for Requirement 1 a. Set microcontroller to output 5V for red LED. b. Using oscilloscope, measure the voltage drop across the 1kΩ resistor. c. Using the voltage drop and the known value of the resistor, calculate the current through the LED. d. Repeat steps a through c for the yellow and green LEDs. 2. Verification for Requirement 2 a. Set microcontroller to output 5V for red LED. b. Stand 1.8 m away and check if LED is visible. c. Observe the LED under low light, medium light and bright room lighting conditions. d. Repeat steps a through c for the yellow and green LEDs.
Array of PIR Sensors (12 points)	*1. Each PIR amplifier chip must be able to output an amplified pulse with magnitude greater than 4.0V when a person enters or exits its field of view.* *(3 points)* *2. Each sensor must have a modified field of view of 30° or less* *(2 points)*	1. Verification of Requirement 1 a. Set up an alternate program on our microcontroller that simply turns on an LED when the PIR sensor reports that it detects a person. b. Have different people walk through the FOV at different distances from the sensor. c. Determine the accuracy of the detections. 2. Verification of Requirement 2 a. Use the setup from 1a. b. Mark on the floor when a person is detected moving into the FOV from either direction. c. Repeat step b 4 times for each side of the beam. d. Use best-fit line of data to determine

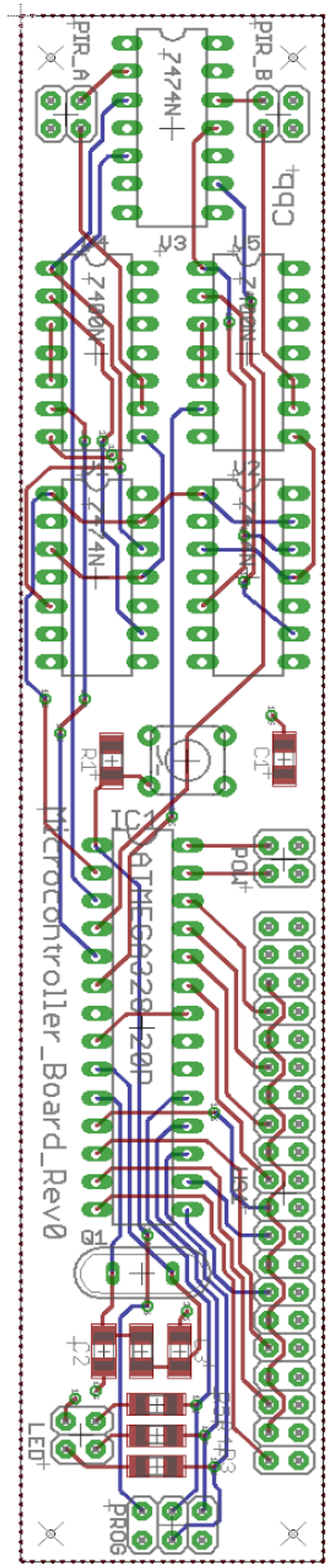
		triangle corresponding to sensor FOV
	3. The digital logic shall be able to capture the output of the T_OUT and D_OUT signals from the amplifier chip and maintain them until the microcontroller has read that data. (3 points)	3. Verification of Requirement 3 a. Set up the microcontroller to output the current state of the PIR digital logic latches of a given PIR sensor after each sensor read cycle. b. Have a person walk across the field of view of the PIR sensor. Ensure that T_OUT and D_OUT latch in the digital logic system to reflect the motion event.
	4. The PIR sensors shall be able to sense a person entering or exiting from the side of the zone (4 points)	4. Verification of Requirement 4 a. Connect the PIR sensor to the array b. Have a person walk across the field of view of the PIR sensor. c. Watch LEDs to determine that PIR sensors function as expected.
Ultrasonic Range Sensors (10 points)	*1. Each ultrasonic range sensor shall return an pulse width corresponding to the nearest object in within its field of view, given that the object is within 75cm (1 point)*	1. Verification of Requirement 1 a. Connect a single ultrasonic sensor channel to the oscilloscope in accumulating mode. b. Have a person walk into the FOV of the sensor at a distance of 10cm. c. Ensure a pulse is emitted from the sensor and is displayed on the oscilloscope. d. Repeat 1a-c in increasing increments of 10cm up to 1.5m.
	2. The microcontroller shall be able to use each ultrasonic range sensor to determine the distance of a moving object with an accuracy of +/-10 cm within 1.5s. (3 points)	2. Verification of Requirement 2 a. Connect a single ultrasonic sensor channel to the microcontroller b. Have a person stand 150cm away from the sensor in the broadside direction c. Have the person walk forward for 100cm and stop. Record the time delay between cessation of motion and the first instant that the ultrasonic reading is within specification.
	3. The ultrasonic sensors used for back of zone entry shall be able to distinguish one or more people entering/exiting at	3. Verification of Requirement 3 a. Arrange ultrasonic array in two-stage configuration. b. Have 1 and 2 people walk into the zone through the back face. Ensure that the

	a time. *(4 points)* 4. *If someone is already in the zone working at the tool, the back entry detection unit can still detect another person entering the zone* *(2 points)*	number of people are reported accurately. 4. Verification of Requirement 3 a. Arrange ultrasonic array in two-stage configuration. b. Have one person walk into the zone from the back. Verify that the person is recognized by the system. c. Have another person walk into the zone and verify that both individuals are recognized.

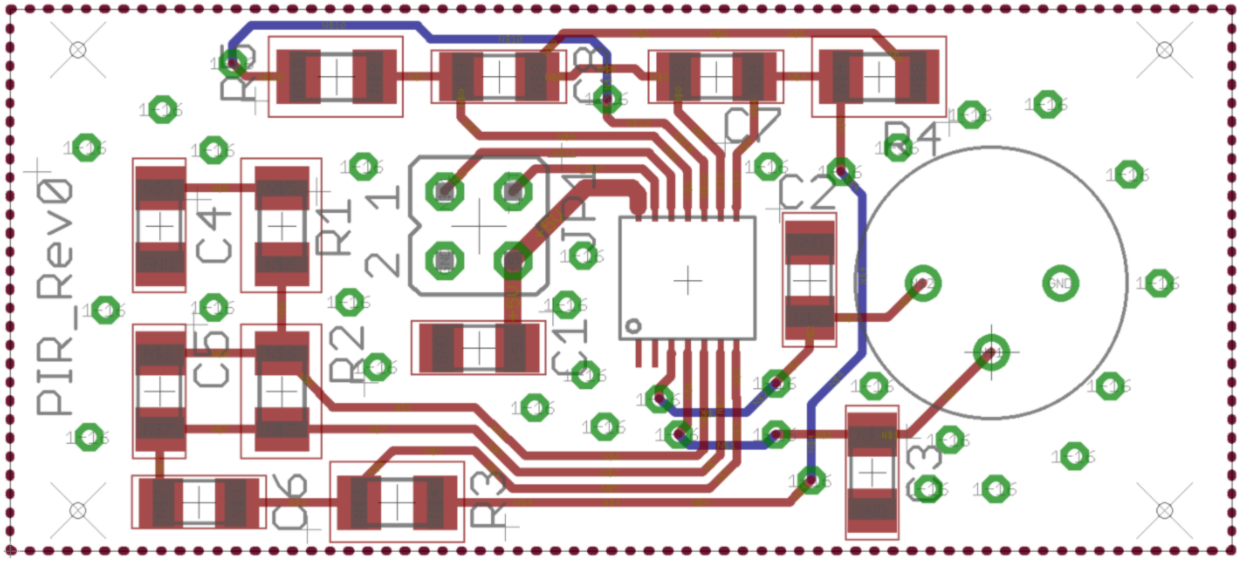
Appendix B: Power Module PCB Layout



Appendix C: Microcontroller PCB Layout



Appendix D: PIR Sensor PCB Layout



Appendix E: Bill of Materials

Part Name	Part Number	Unit Cost	Quantity	Total
Power Tool Outlet	Leviton 20 Amp Tamper Resistant single outlet	$3.62	1	$3.62
Power Cord	Nema 5-15 SJT Power Cord	$6.48	1	$6.48
Single Outlet Cover	Leviton single outlet cover	$1.94	1	$1.94
Vinyl Studs 8-10, AWG 22-18	N/A	$0.20	2	$0.40
Winged Wire Connectors	N/A	$0.16	3	$0.48
#8 Washers	N/A	$0.06	2	$0.12
Machine Screw Nut #8-32	N/A	$0.06	2	$0.12
Flange Mounts AWG 22-18	N/A	$0.30	2	$0.60
Cable Ties, Vinyl	N/A	$0.06	40	$2.36
Aluminum siding	Argent Silver, 1 ft	$0.49	20 ft	$9.80
AC Relay	ALF1T05	$3.94	1	$3.94
Non-Invasive Current Sensor	ECS1030-L72	$9.95	1	$9.95

AC/DC Converter	EA1024CU	$12.95	1	$12.95
PIR Sensors	IRA-S210ST01	$1.81	2	$3.62
Fresnel Lense	IRA-S210ST01 Lens	$3.33	2	$6.66
PIR Sensor Filter-Amplifier	BD9251FV	$1.69	2	$3.38
3M Foil Tape	3381 Silver, 50 yd	$9.21	1yd	$0.19
Microcontroller	ATMega328-20P	$5.50	1	$5.50
Ultrasonic Range Sensors	GP2Y0A60SZLF	$1.71	12	$20.52
Cabling	AWG 22, 100 ft	$12.34	200 ft	$24.68
PCB Fabrication	PCBWay, single board	$10.00	3	$30.00
Surface Mount Components	N/A	$7.50	1	$7.50
Total				**$154.81**