DESIGN DOCUMENT: POWER TOOL SAFETY ZONE ENFORCER

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Table of Contents

1. Introduction

1.1 Objective

When working with heavy machinery in places such as a lab or a machine shop, one of the first concerns is worker safety. Many standards are in place for what is needed to meet the Occupational Safety and Health Administration (OSHA) requirements. Despite these requirements, there are still many safety incidents that result in serious injury. In 2007-2008, the number of injuries treated at emergency rooms from table and bench saws alone was 79,500[1]. Each time a worker is injured, the company has effectively failed at their primary goal of a safe workplace. Furthermore, companies are typically required to perform extensive paperwork and investigation each time any significant work related injury is reported [2]. Each injury, then, is a failure that results in a loss of efficiency and detracts from the value provided by that workshop. Based on these factors, the objective of our product is to minimize workplace injuries from table-mounted machinery while simultaneously increasing shop productivity and efficiency.

Our solution, therefore, 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 stay powered until the task is complete in order to avoid significant risk of cutting power mid-task if a new hazard is detected. One safety precaution that such a system would successfully enforce is keeping a specified safety zone around a machine clear, protecting the operator from accidental external interference. In precision tasks such as making table saw cuts, any sort of unexpected physical interference can result in the operator contacting the spinning blade, potentially causing amputation or severe muscular or arterial damage. To address this, our system will continuously scan for personnel violating a defined safety zone surrounding the operator and suppress tool operation until the zone is cleared of all but the necessary workers. 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.

1.2 Background

Our product seeks to address the elements of human error. Power tools are typically made with known failure rates, built-in safety switches, and provide detailed instruction on proper use to help prevent injuries. While these factors address operator error, it is much more difficult to build in additional preventative safety measures for accidental human interference. Human error can come in many shapes and sizes, but the source of the wide majority of human error-related incidents comes from direct, interpersonal physical interference. For direct interference to occur, however, the offending party must first be in proximity to the operator. By establishing that only the required personnel are in proximity to the tool before operation, the potential for direct interference can be significantly reduced.

The reduction of the number of workplace accidents caused by human error has significant implications for machine shop safety. According to an article published by NOPSEMA on human error typology [3], "[Human] errors can occur in both the planning and execution stages of a task." In the context of a machine shop, the planning stage includes the preparation steps leading up to using the machine. Logically, the transition between the planning and execution stage occurs when the device is powered, thus initializing execution of the task. Therefore, performing a check prior to the execution stage to verify a successful planning stage is a necessary and effective safety method. In a report on woodworking hazards [4], OSHA categorized location/distance checks and accidental startup prevention as important safeguarding methods. Our system would address both of these methods, providing redundancy in scope of safety verification methods.

Taking this into account, 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 [5], for common machine shop equipment, safety zones for the operator to stand in range in dimension from 1x8 feet to 3x6 feet 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 3x8 feet. 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 six feet. Lastly, in order to increase early detection of potential risks, we extended the length of the zone to four feet. This led us to conclude that a 4'x6' zone would be the most effective safety zone for the operator. Converting to meters and rounding, our safety zone was defined to be 1.2x1.8 meters.

Many common power tools have a 15A current rating [6], so we have decided to design our system to support those power tools that are rated to 15A or less.

1.3 High-Level Requirements List

- When the microcontroller asserts that the machine should be powered, the machine should be powered and whenever it 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.

2. Design

The monitoring system requires three main modules to operate fully. The first of these is the power module. This module ensures that the system can receive power from the wall outlet and also is responsible for the control of the power supply given to the tool that we are monitoring. The second module is the sensor module, which collects data about people or items in our 1.2m x 1.8m zone. The third module is the control module. The control module consists of a microcontroller which is responsible for processing all the data collected by the sensor module and making a decision about the number of people in the zone and indicating this to the user. The block diagram of our monitoring system is shown in Figure 1 below.

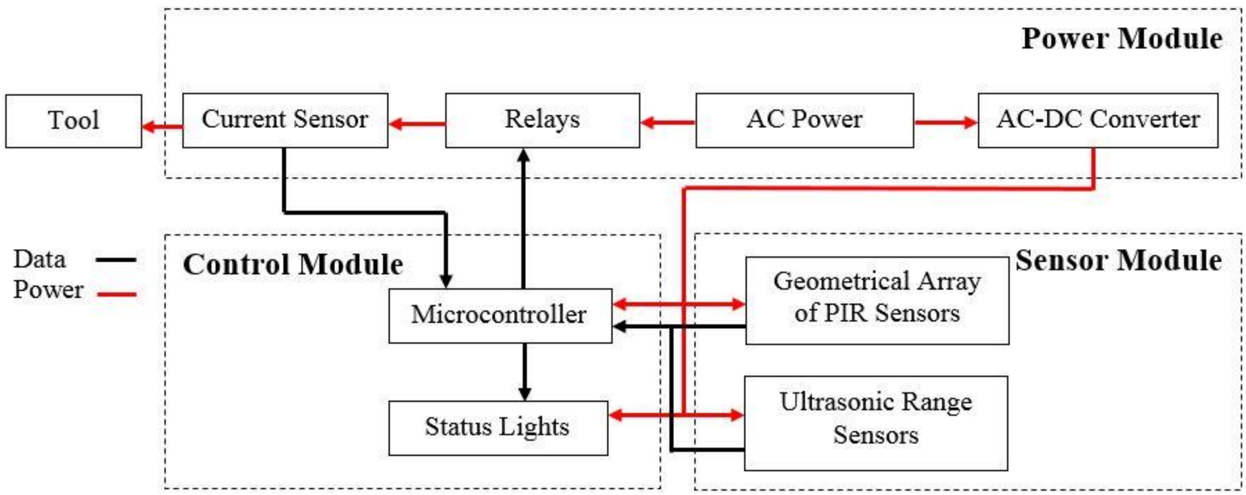

Figure 1: Block Diagram

This system includes a linear array of PIR sensors placed on a variable mounting system that will be placed along the foot of the table that houses the tool. Also on this mounting system will be the ultrasonic range sensor. Since we are monitoring an area that is 1.2m x 1.8m, this sensor array will be placed along the 1.8m side as shown in Figure 2 below.

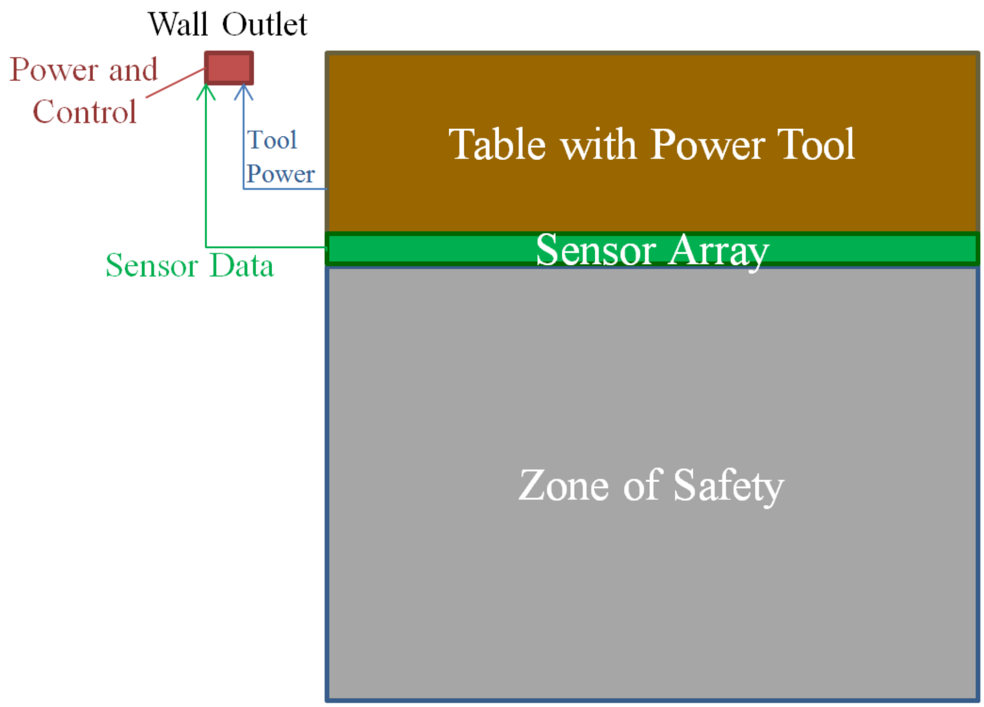

Figure 2: Diagram showing physical layout of system

The processing and control unit will be housed next to the wall outlet for the tool being monitored. The device will plug into the wall outlet and then the power tool's cord will plug into our device. The bulk of our system will be physically housed within a metal box containing everything except for the physical sensors themselves and the status lights. Our status lights will be on a removable sticky patch so that the user can place them in an optimal location, such as the wall behind the tool, or on the edge of the work bench. This allows for a measure of configurability and customization of the system layout. Our sensor array will be mounted on a 1.8m long piece of metal with an angled cut used to contain wires and sensor backends, so that we will not have extraneous wires running to and from our array. The mounted array will be placed in front of the base of the tool bench. We are assuming that the bench is not open at the bottom, so this should not be too much in the user's way, however it does produce a hazard for system in the event one of the sensors is kicked or stepped on and broken. The geometric layout for the PIR sensors in the zone of safety is shown in Figure 3.

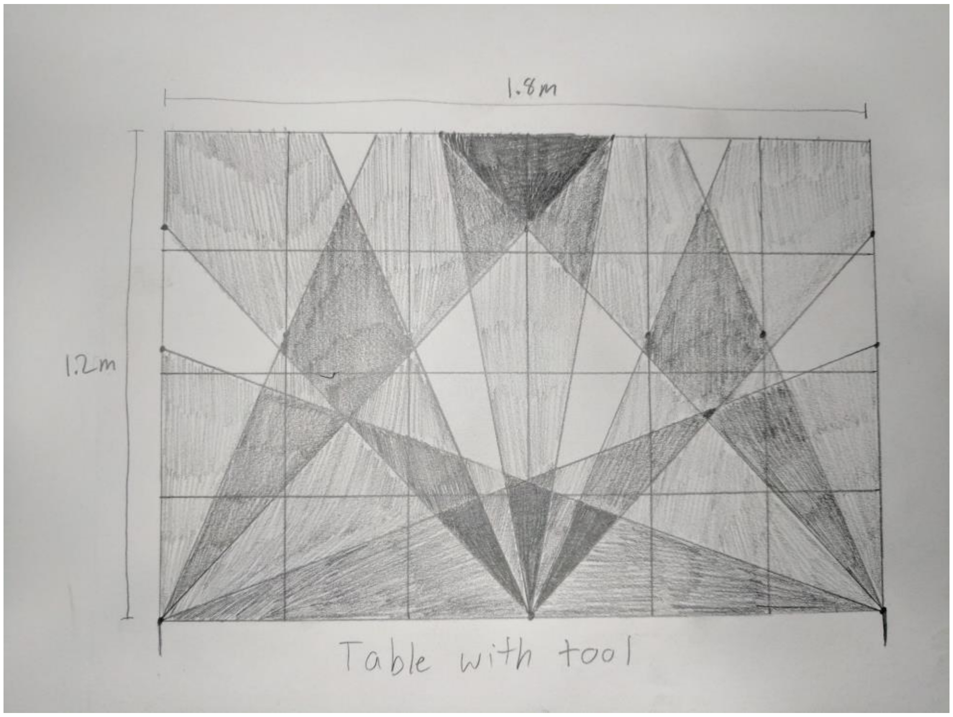

Figure 3: Geometry of PIR Sensor Array

2.1 Power Module

This module contains the power supplies for our system as well as the power connection to the tool itself. We will take the power input from a typical wall outlet that will go along two paths. The first path will go through a relay to power the attached tool. The second path will pass through an AC/DC converter that will transform the input power supply voltage to a DC supply voltage as described in Section 2.5.

2.1.1 Relay

The Panasonic Electric Works ALF1T05 relay will mechanically connect or disconnect the AC Power Input to the power cord of the tool based on a 5VDC input signal supplied by the microcontroller. The relay will support a maximum current throughput on the signal terminals of 20A [7], which should be more than sufficient given the 25A slow-blow fuse present at the input of the contacts. By having this relay, we will be able to control whether the tool gets power or not based on the processing of data that occurs in the control unit. The relay will serve as the functional output of the microcontroller system such that all supporting sensor data will be synthesized to control the state of the relay. The relay will be located near the AC input power supply along with the AC/DC converter in order to isolate high-power circuit components from the user.

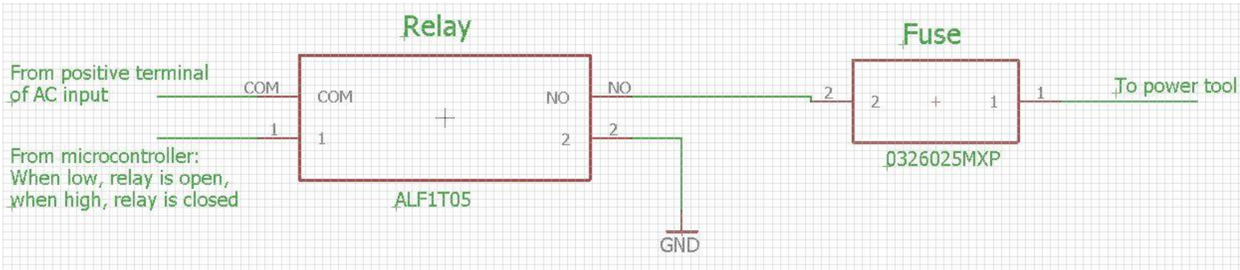

Figure 4: Relay and fuse schematic

2.1.2 Current Sensor

This ECS1030-L72 Non-Invasive Current Sensor will be used to determine if there is current being drawn through our device and into the tool, indicating if the tool is currently in use. Once power is supplied to the tool, we do not want to cut power while the tool is being used, even if someone walks into the zone. Unexpectedly cutting power to the tool during operation can cause unsafe behavior of the machine and potentially cause worker injury. This sensor will clip onto the "hot wire of the AC line connecting the relay to the tool's physical outlet in order to measure the instantaneous current draw of the tool. The current sensor inductively reacts to line current and produces a scaled current as an output. By reading the voltage generated by the signal current across a 10Ω load resistor, the microcontroller will determine how much current is flowing through the "hot" wire. If the current is above the threshold indicating that the tool is running, then the microcontroller will be able to react accordingly. This sensor can detect up to 30A of current flow [8], which is sufficient for detection of the maximum current draw of a power tool supported by this project (15A).

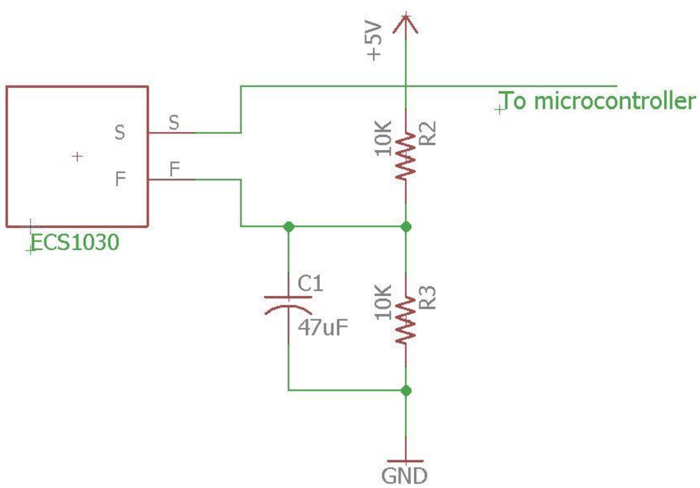

Figure 5: Schematic of Current Sensor circuit used to determine the amount of current flowing to the tool.

We need this circuit because our current sensor will output a scaled current which will be an AC current like the current going through the wire being sensed. We start by setting a bias point of 2.5V so that when we have the AC voltage variation, we can make sure the voltage sent to the microcontroller will be positive. Setting this bias point is done by using a 5V source and two 10k resistors so that the voltage between them will be half the supply voltage, which is 2.5V. There is a 10Ω resistor built into our sensor, and the voltage across that resistor should never exceed 5V or go below 0V because of our adjusted bias point. This necessity and layout of this circuit was outlined by Open Energy Monitor [9].

2.1.3 AC Power Input

The AC power input for our system will be a standard 110VAC, 60Hz single phase wall outlet supply. Input voltage power and current ranges will be dependent on the environment and as a result are not in our control. Note that standard wall voltage regulations require an RMS voltage range of 104-128 VAC [10]. The relay and AC/DC converter will interface directly with the AC power input, with the relay distributing power to the tool when enabled. The input to the relay and voltage regulator circuits are safeguarded with a 25A slow-blow fuse to prevent overload conditions. The fuse will mechanically isolate the concerned system from the power supply to prevent overcurrent conditions from either the supply or system.

2.1.4 AC/DC Converter

The AC/DC converter will be responsible for regulating the microcontroller and sensor power supplies. The converter will be preceded by a fuse connected to the AC power input as previously described in Section 2.1.3. The output value will be a regulated DC supply with ranges as described in Section 2.5. In order to increase reliability and safety of our system, we will implement the AC/DC converter circuit using a commercial off-the-shelf (COTS) single-phase, 120VAC to 5VDC converter. As a cost-saving measure, this can be easily achieved using a high-current USB charger. This power will then be able to be safely transported through shielded USB cables to the microcontroller system, which will be responsible for distributing the power to the rest of the components. If time allows, we would like to be able to replace the USB charger with an inbuilt flyback converter in order to reduce the number of power ports used by the system.

2.2 Control Module

The Control Module will perform all of the logic necessary for our system. It will have a microcontroller and a set of status lights that provide feedback to the user about the current state of the safety zone.

2.2.1 Microcontroller

This ATMega328-20P microcontroller is responsible for the main processing of all data collected by the various sensors. It takes inputs from the PIR sensor, the ultrasonic range sensors, and the current sensor. Once this data has been processed, the microcontroller will output a signal to the relay to indicate if the tool should receive power or not. Additionally, it will signal a red LED to indicate that the tool will not receive power, a yellow LED as a warning when the tool is in use but a violation of our safety rule is being enforced, or a green LED indicating that the tool will be supplied power. This microcontroller was chosen for its affordability as well as its 23 I/O pins [11] that are necessary to take in all the sensor data we are collecting. It will be programmed through a USB interface on an Arduino Development board, streamlining programming and debugging of software elements for this project.

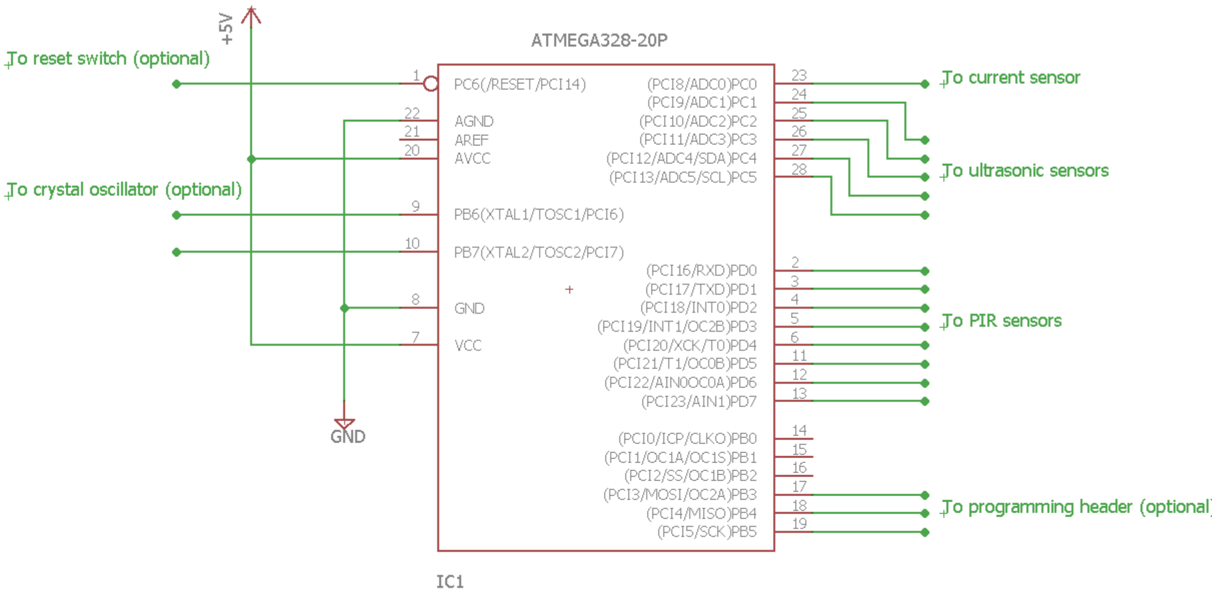

Figure 6: Microcontroller schematic with device interconnects and optional configurations listed

2.2.2 Status Lights

There will be three different LEDs that are used to inform the user of the status of the zone. The red LED indicates that there is more than one person in the zone and therefore the tool will not be powered. The green LED will inform the user that they are the only person in the zone and that the tool will receive power. The yellow LED serves as a warning light and will turn on if the tool is currently in use but another person walks into the zone. The microcontroller will drive the LED logic and power. The status LEDs will be placed on a board that will be able to be displayed above the power tool so that the user can easily see them.

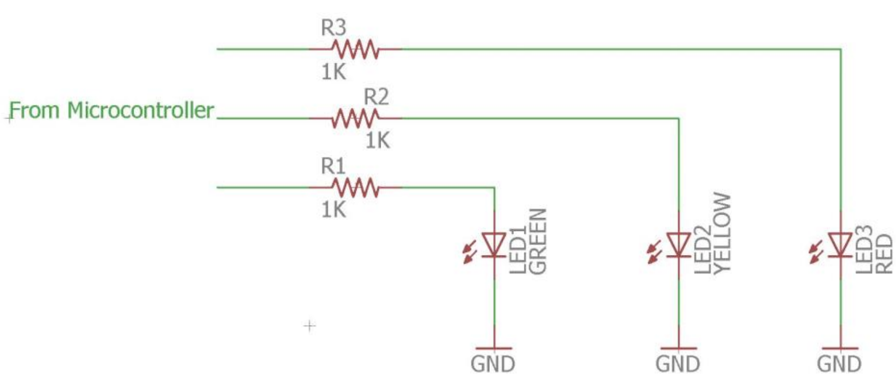

Figure 7: Schematic of status LEDs

2.3 Sensor Module

Our sensor unit is the physical layout of sensors we are using to receive information about the safety zone. We will use an array of PIR sensors and several ultrasonic range sensors to accomplish this. The specific geometries will be discussed in detail in this section.

2.3.1 Array of PIR Sensors

The PIR sensor array will consist of seven Zilog PS033601-1214 Zmotion Pyroelectric sensors. This type of sensor was chosen for its low cost and limited field of view (FOV). These sensors will be geometrically arranged such that the data collected via digital read from each sensor combined with the data from the ultrasonic range sensors will be able to provide the necessary information to determine if there are too many people in the zone. By having a diverse geometry of sensors, we should be able to detect a person or multiple people entering the zone, even if one person is in close proximity to the other. In order to get the existing FOV small enough to achieve the geometric layout desired, the sensor FOV will be modified by covering part of the lense with metallic tape. The field of view will be narrowed from 138 degrees [12] to approximately 20 degrees in the x-direction to help our distinguishability for people standing next to each other. However, we will keep the FOV in the y-direction the same because this will allow us to get a full top-to-bottom view of the area in front of the sensor, which will account for the different heights of people. Since the PIR sensors output mV-range pulses, each sensor will have a dedicated Rohm Semiconductor BD9251FV amplifier chip to filter and amplify the pulses to a shape readable by the digital pins of the microcontroller [13]. This chip adds the benefits of freedom to select filter parameters before amplification, simplification of external circuit complexity, and minimization of component area. The data collected from these sensors will be fed back to the microcontroller for processing. The microcontroller will then use this data in conjunction with the ultrasonic sensor data to analyze and enforce zone safety.

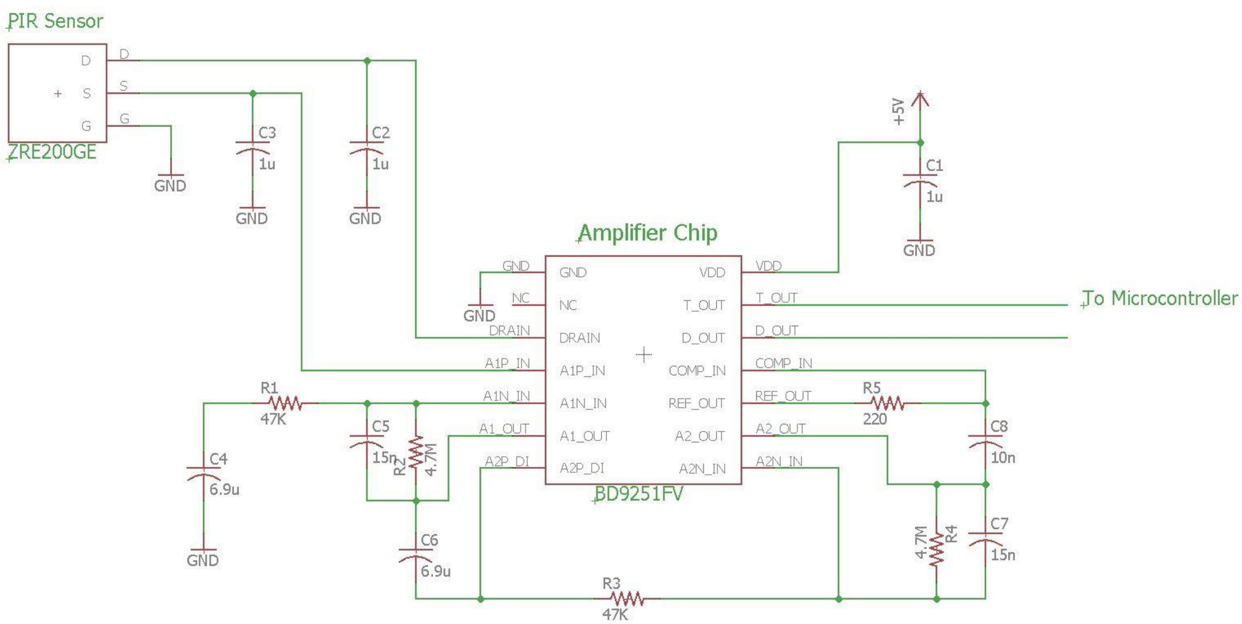

Figure 8: Schematic of PIR sensor and corresponding amplifier/filter chip.

2.3.2 Ultrasonic Range Sensors

The ultrasonic sensor array will consist of five GP2Y0A60SZLF Distance Measuring Units that collectively serve as the range-finding portion of the sensor unit. This particular sensor was chosen based on its low cost, compact size, and analog output. It also has a maximum measurement range of 150 cm [14], which is more than sufficient for measuring objects within the safety zone. Each ultrasonic sensor will be interspersed geometrically along the PIR sensor array, returning only the distance of the nearest object. Theoretically, based on the long gating period of the sensor (23.9ms), it would be possible to detect multiple people at different distances based on the time delay of the reflected pulses off of each person. However, this introduces a large degree of measurement uncertainty, so we will only consider the effect of the first return pulse. Each ultrasonic sensor will occupy an analog port of the microprocessor, allowing for accurate distance calibration and rising edge triggering for the return pulses. In addition, the ultrasonic sensors have a digital control pin, permitting sensor synchronization and control via a digital output signal from the microcontroller. During each gating period, the analog data collected by each sensor will be sent to microcontroller for subsequent processing. This information, synthesized with the PIR sensor array output, will ensure successful identifications of hazards violating safety conditions.

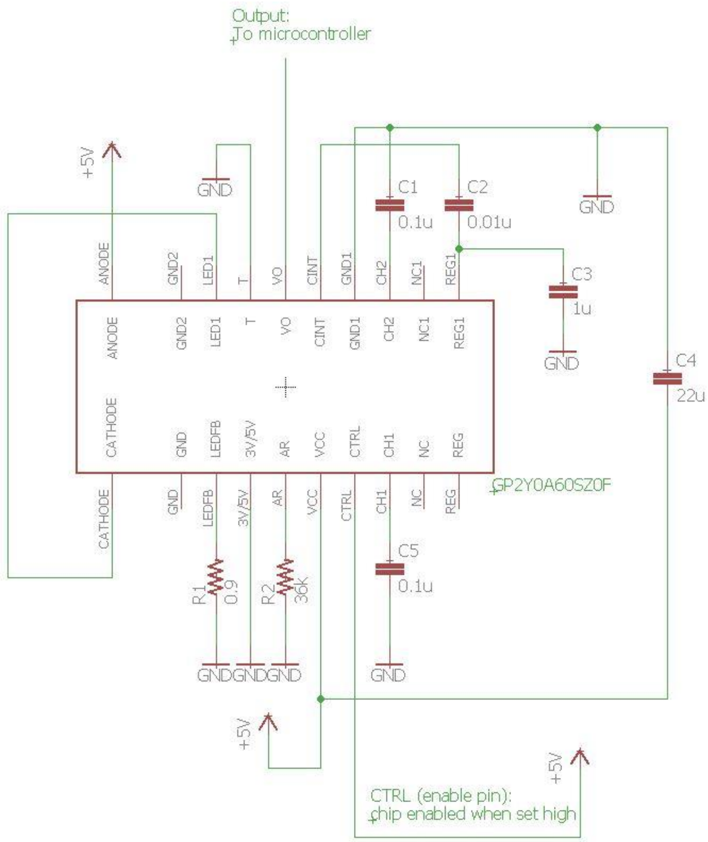

Figure 9: Ultrasonic Sensor schematic

2.4 Supporting Material

2.4.1 Measurements

In order to characterize our PIR sensor we connected the sensor as recommended in the datasheet and viewed the output on an oscilloscope. The results of these measurements are shown in Figures 10-13. In the first plot shown in Figure 10, we measured the steady state value of the sensor with no one in the field of view. This will serve as a reference for later plots so we can see how the voltage across the PIR sensor changes when someone enters the field of view. The orange line indicates the approximate average value for each time interval. The overall average voltage level is 9.04 mV.

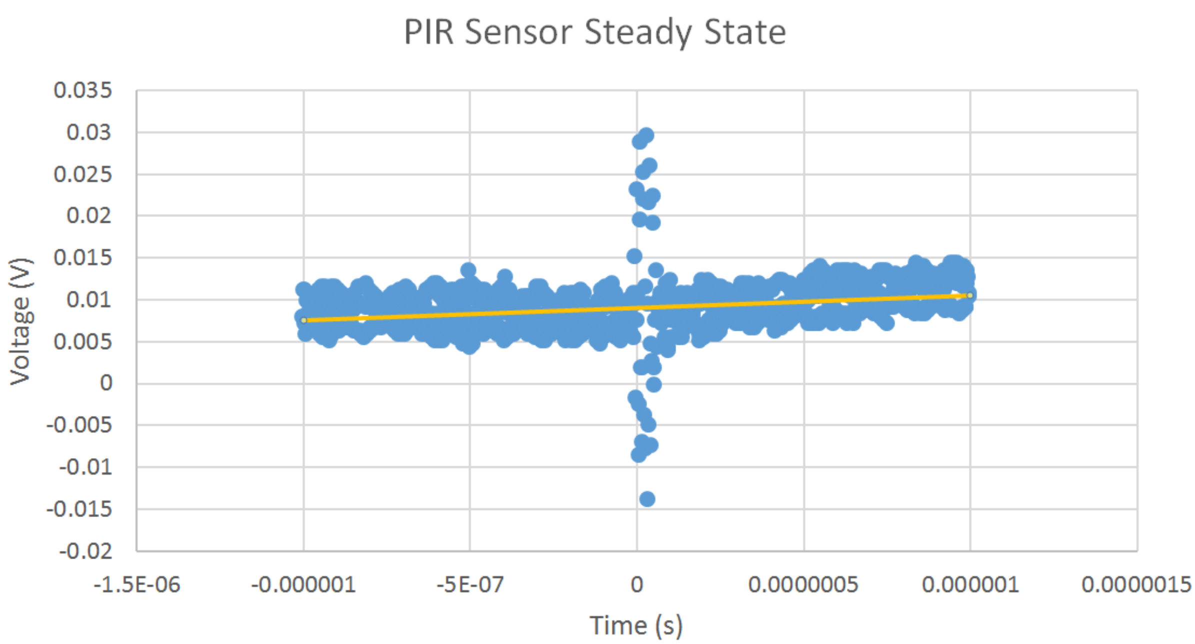

Figure 10: Steady-state PIR sensor signal

The second measurement we took, shown in Figure 11, was when someone entered the field of view walking left to right from the sensor's perspective. Since in reality there are two sensors stored in the PIR sensor, we can actually obtain directional information when a person crosses the sensor field of view. This functionality will be very important to be able to decipher the number of entrances and exits from our zone of safety. When walking left to right, the average voltage value increased from the steady state average value of 9.04mV to an average value of 17.37mV.

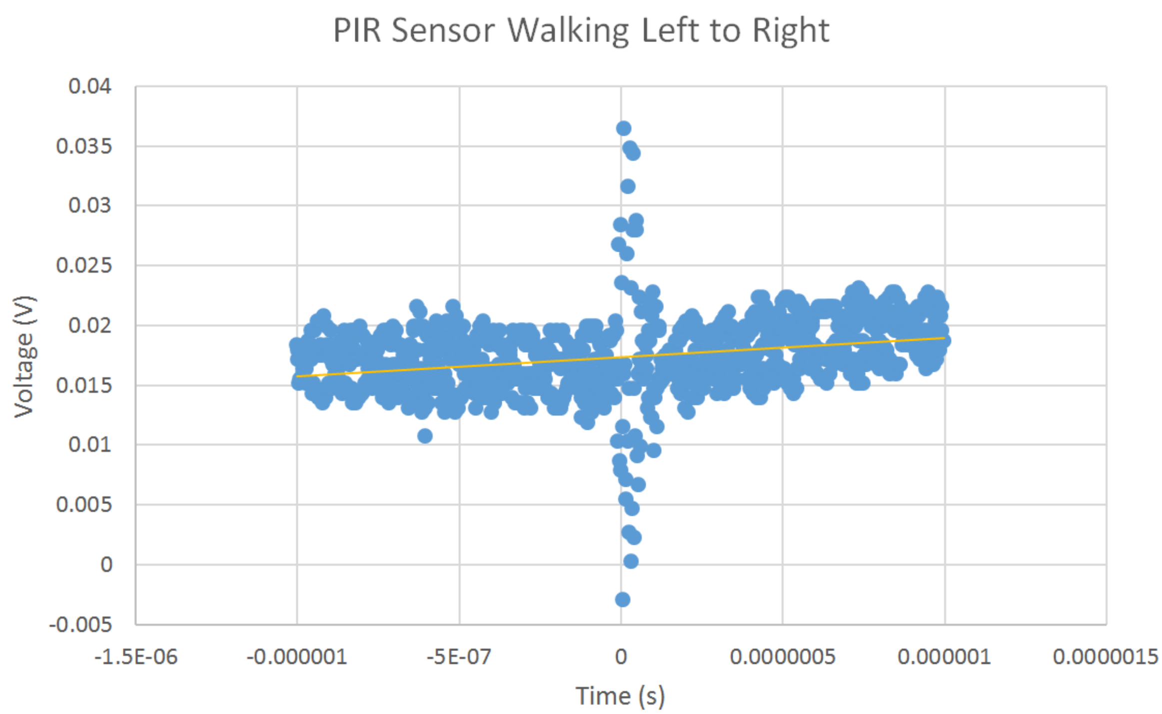

Figure 11: Detected IR signature when walking through the sensor field of view from left to right.

The third measurement that was taken was to determine sensor behavior when a person walked right to left through the sensor field of view. As you can see in Figure 12 below, the average value decreased from the steady state average value of 9.04mV to a new average value of -9mV.

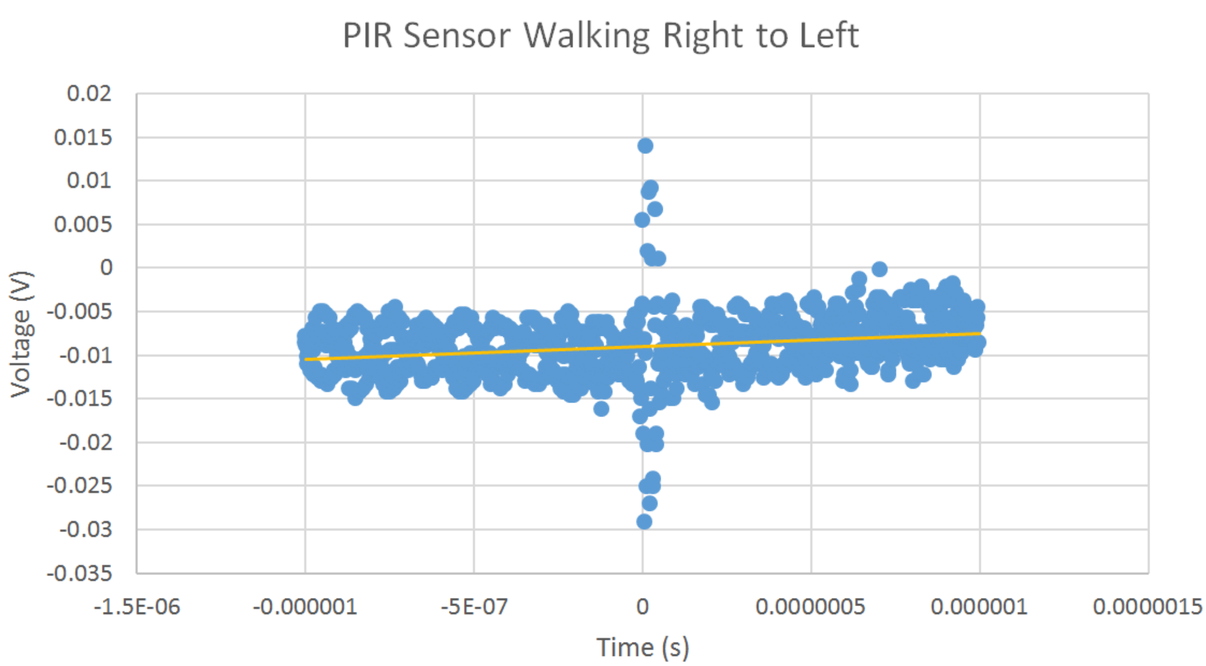

Figure 12: Detected IR signature when walking through sensor field of view from right to left.

After taking the different state measurements, we decided to observe if we could make our signal cleaner and eliminate the peak in the middle of the plot. To do this we passed our sensor output through a basic low pass filter before reading the data. As you can see in Figure 13 below, the peak that is present in the other measurements is now gone, which was the goal of using the filter.

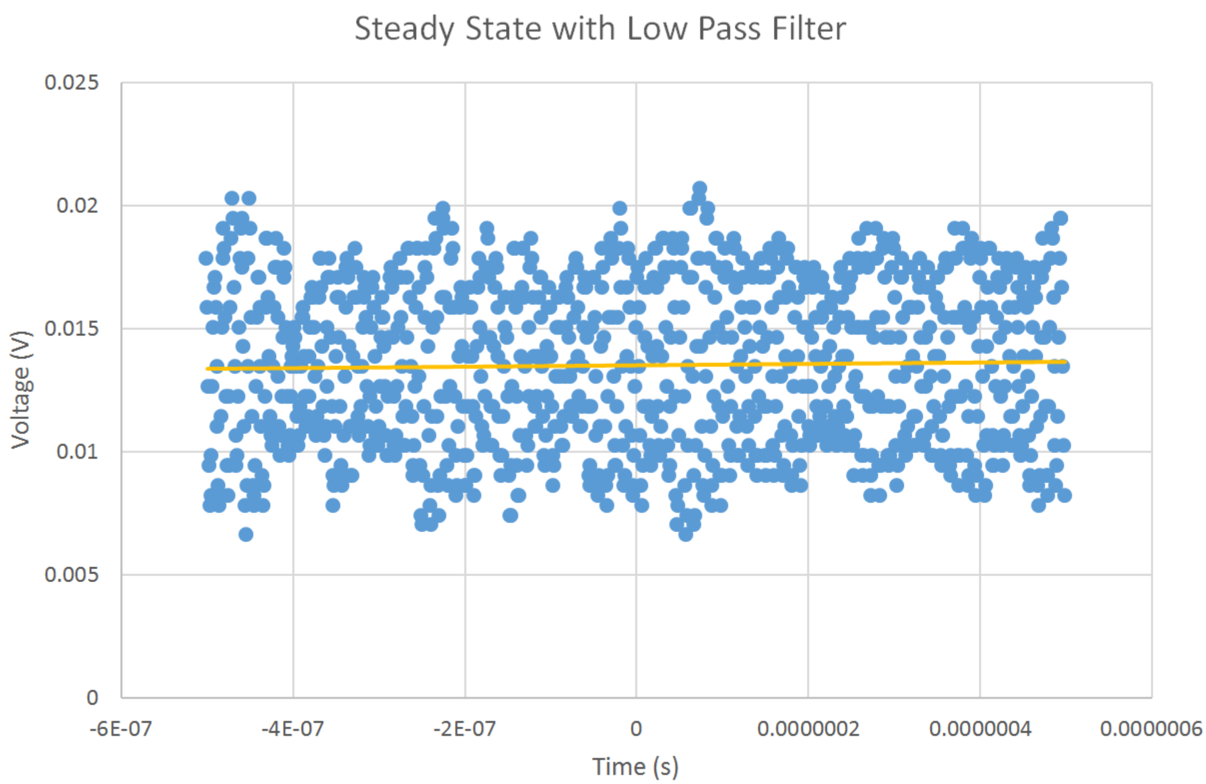

Figure 13: Detected IR signature for PIR sensor in steady state with a low pass filter applied on output.

By obtaining these measurements, we have been able to learn more about our sensor's behavior. This information will be very helpful to determine the best sensor array layout and enabled us to determine what kind of amplification the sensor needs.

2.4.2 Calculations and Simulations

Total Current Calculation

In order to ensure that our system will not enter an overcurrent condition, a current budget must be created to place minimum requirements on the AC/DC converter. A good estimate for the maximum requirement of the AC/DC converter can be calculated by taking the summation of the maximum current draw of all 5VDC-powered components. In addition, some additional current draw will be present in solder junctions, traces, and device non-idealities. In order to account for this uncertainty, a healthy margin is added to the calculated maximum current draw total. The calculation results are included in Table 1 below.

Component	Part Number	Max. Current Draw	Quantity	Subtotal
Ultrasonic sensor	GP2Y0A60SZLF	400mA	5	2000mA
Microcontroller	ATMega328-20P	0.2mA	1	0.2mA
Relay	ALF1T05	180mA	1	180mA
Current Sensor	ECS1030-L72	15mA	1	15mA
PIR sensor	PSO33601-1214	1mA	7	7mA
PIR filter-amplifier	BD9251FV	85mA	7	595mA
LED	N/A	15mA	3	45mA
Extra Current Allowance	N/A	N/A	N/A	1157.8mA
Maximum output current requirement for AC/DC converter				4000mA

Table 1: AC/DC converter current budget calculation

Filter Cutoff Frequency and Amplifier Gain Calculation

Since we are detecting human movement, we use high-pass and low-pass filters to filter the output of the PIR sensor. Since we still have yet to receive the PIR amplifier chip we selected to amplify the output of the PIR sensor, we have tentatively selected the filter cutoffs and amplifier gains recommended by the chip. These filters include a high-pass filter with a cutoff frequency ($f_{c,L}$) of 0.5 Hz and a low-pass filter with a cutoff frequency ($f_{c,H}$) of 2.25 Hz. Since this is a two stage amplifier, the first high-pass filter is R1 and C4 (in Figure 8), and the second one is C6 and R3. The first stage low-pass filter is between the negative input of the op amp and the output of the op amp (pins A1N_IN and A1_OUT) which is the R2 and C5 combination. The second stage low-pass filter is the R4 and C7 combination. The gain of each stage is also determined by the selection of these resistors. The gain of the first stage (A_1) is dependent on R1 and R2 and the gain of the second stage (A_2) is dependent on R4 and R3.

$$f_{c,L} = \frac{1}{2\pi R_1 C_4} = 0.491 \qquad (1)$$

$$f_{c,H} = \frac{1}{2\pi R_2 C_5} = 2.258 \qquad (2)$$

$$A_1 = 1 + \frac{R_2}{R_1} = 101 \qquad (3)$$

$$A_2 = 1 + \frac{R_4}{R_3} = 101 \qquad (4)$$

Equation 1 is the calculation of the cutoff frequency of the high-pass filter, and it is labeled as the low cutoff frequency because it needs to be at a lower frequency than the cutoff frequency of the low-pass filter. The cutoff frequency of the low-pass filter is calculated in Equation 2, which for the inverse reasoning as before, is labeled as the high cutoff frequency. Since the first stage amplifier is set up as a non-inverting amplifier, the gain equation is given and calculated based on the resistances in equation 3. The second stage amplifier is also set up as a non-inverting amplifier with the same resistance and capacitance values as in the first stage. Therefore, the gain calculation is the same for this stage. However, the gain calculation 3 and 4 are not complete because they do not take into account the filtering of the amplifier.

$$A_{Low} = \frac{A}{\sqrt{1 + (\frac{f}{f_{c,H}})^2}} \tag{5}$$

$$A_{high} = \frac{A(\frac{f}{f_{c,L}})}{\sqrt{1 + (\frac{f}{f_{c,L}})^2}} \tag{6}$$

For high frequencies, the high-pass filter will approach the DC gain calculations (equations 3 and 4) while the low-pass filter will attenuate the signal. These characteristics can be seen in equations 5 and 6 because when f goes to infinity, the low-pass gain approaches 0 while the high-pass gain approaches A. You will also see that for low frequencies, the high-pass filter will attenuate the signal while the low-pass filter will approach the DC gain calculations. This can be seen in equations 5 and 6 because when f goes to 0, the low-pass gain approaches A while the high-pass gain also goes to 0. Since we have both filters in our circuit, we need the high-pass cutoff frequency to be lower than the low-pass cutoff frequency so that there is a section between the cutoff frequencies that will not be attenuated. We are essentially making a band-pass filter. Since both of the amplifier stages will be comprised of the DC gain with a high-pass and low-pass filter, the overall gain of each stage will be modeled by Equations 7 and 8 below.

$$A_{D,1} = \frac{A_1(\frac{f}{f_{c,L}})}{\sqrt{1 + (\frac{f}{f_{c,H}})^2}\sqrt{1 + (\frac{f}{f_{c,L}})^2}} \tag{7}$$

$$A_{D,2} = \frac{A_2(\frac{f}{f_{c,L}})}{\sqrt{1 + (\frac{f}{f_{c,H}})^2}\sqrt{1 + (\frac{f}{f_{c,L}})^2}} \tag{8}$$

In each of these equations as the frequency approaches 0 or infinity, the gain will be attenuated. Only when the frequency is between or near the two cutoff frequencies will the DC gains show up. Also, since our overall amplifier circuit is a two-stage amplifier, the overall gain of our entire amplifier is the product of each stage as shown in equation 9 below.

$$A = \frac{A_1 A_2 (\frac{f}{f_{c,L}})^2}{(1 + (\frac{f}{f_{c,H}})^2)(1 + (\frac{f}{f_{c,H}})^2)} \quad (9)$$

The square root terms are the same because we use the same cutoff frequencies in each stage, which allows us to use this rather simplified gain equation. If our maximum DC gain (A_1A_2) is able to be realized we should see a maximum gain of 10,000 since each stage has a DC gain of 100. Now that all of these values have been chosen, we need to simulate this circuit to make sure that we get the amplification we want. Our circuit used in our simulation is shown in Figure 14.

PIR Sensor Filter and Amplifier Simulation

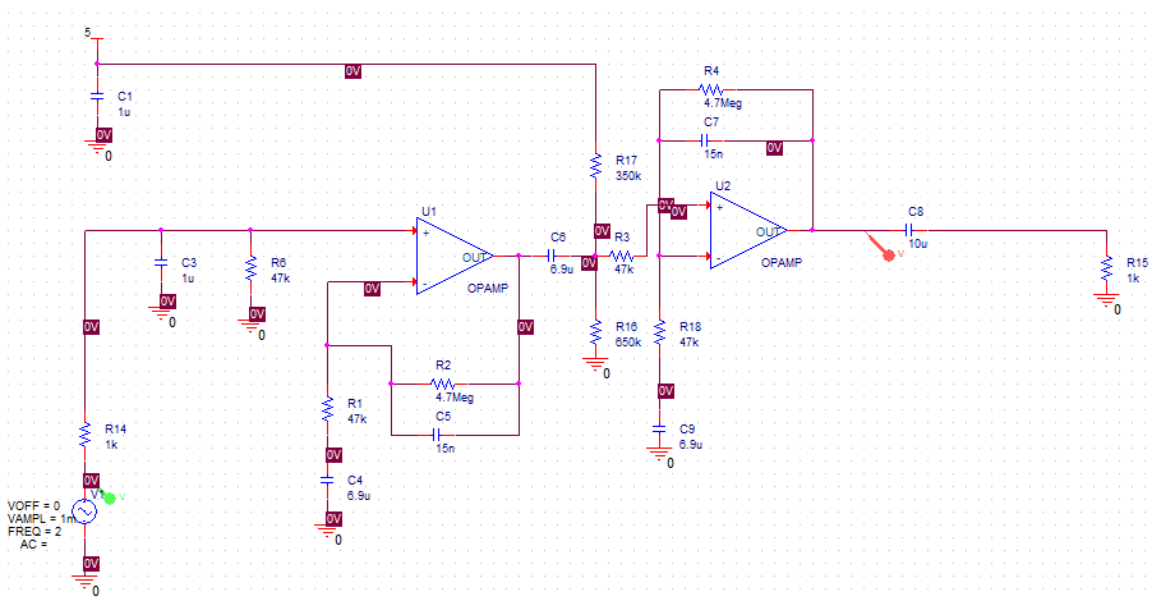

Figure 14: Simulation of PIR amplification circuit

This circuit was made to represent the PIR amplifier chip we selected based off of the internals provided in the datasheet. We are simulating this because we want to make sure that the chip does what we need it to do to get valuable information from our PIR sensors. The only aspect of the chip that we do not simulate in this circuit is the part at the end where output of the second amplifier will actually go to a comparator that will determine when a person has entered or exited the sensor's FOV. Because the theoretical gain of our sensor is so large, we only send a 1mV signal as an input to our simulation. We set the frequency of our input to 2Hz because we chose our "bandpass" region to be between 0.6Hz and 2.25Hz.

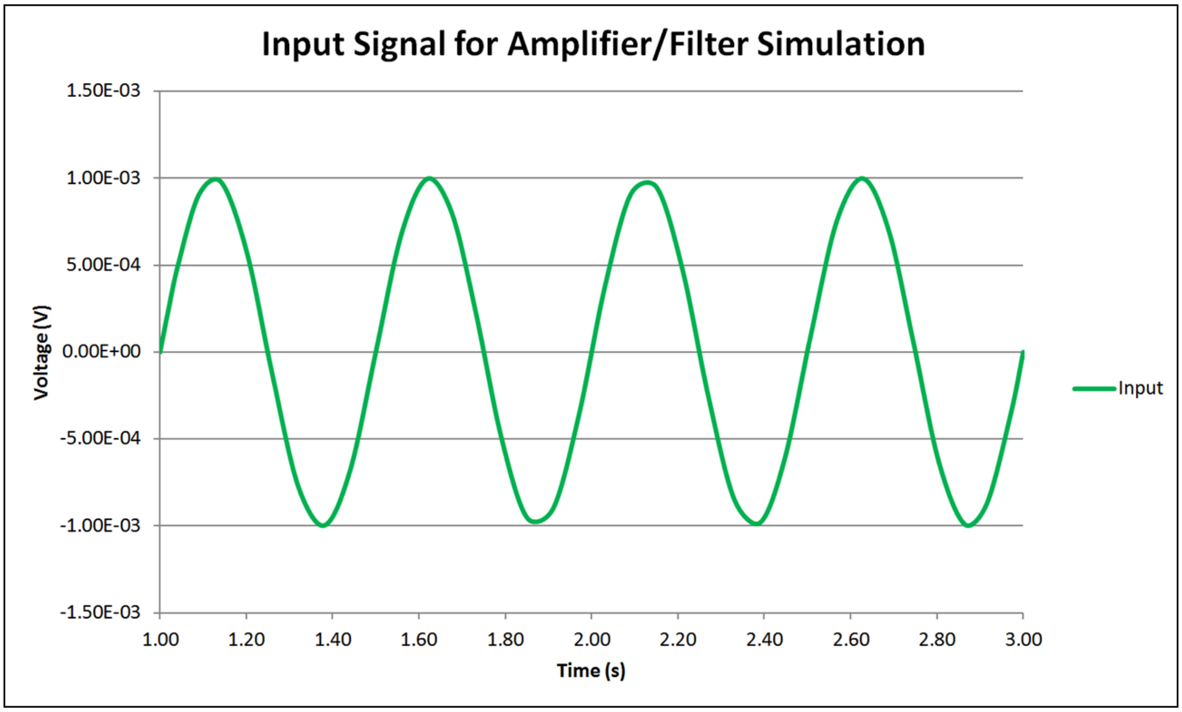

Figure 15: Input voltage waveform to simulation

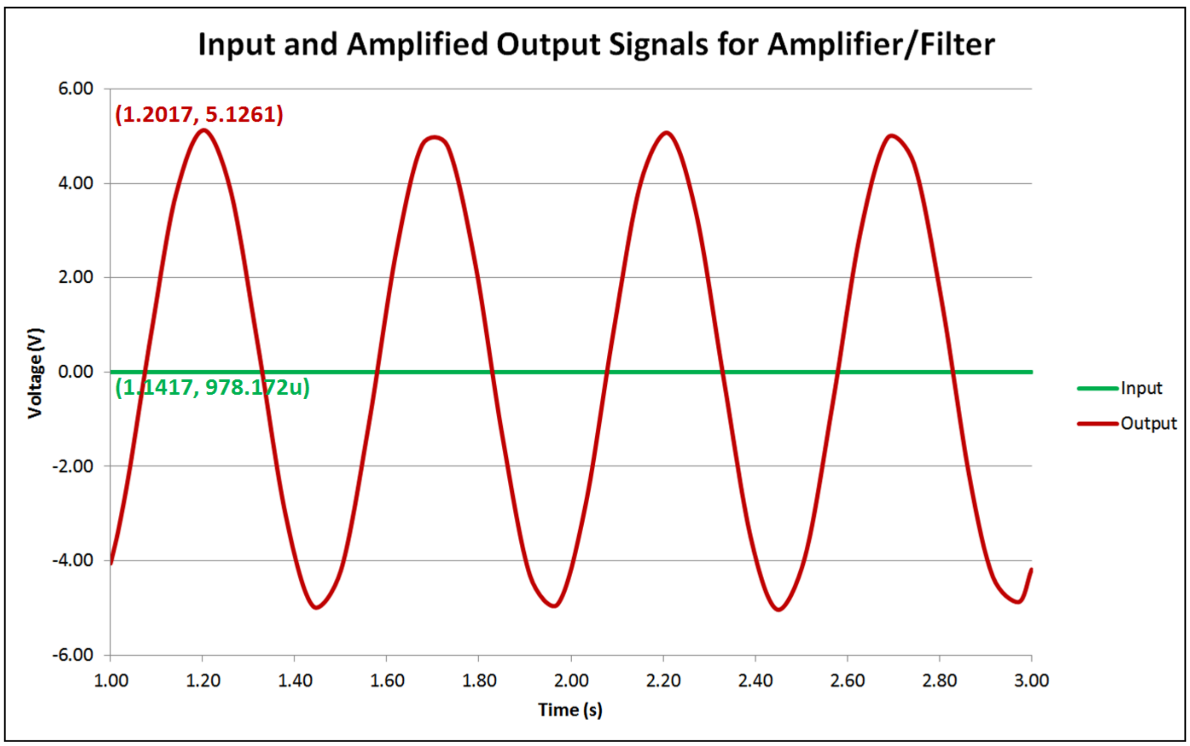

Figure 16: Input (green) and output (red) voltage waveforms of simulation

In Figure 15, we show a zoomed in plot of the input voltage waveform sent into our simulation circuit. In Figure 16, we show both the output and input of our simulated circuit. From the plot, we can see the output voltage has a maximum of 5.13V for the input of 1mV. This output voltage falls within our target range necessary for the amplifier chip we selected to work as desired.

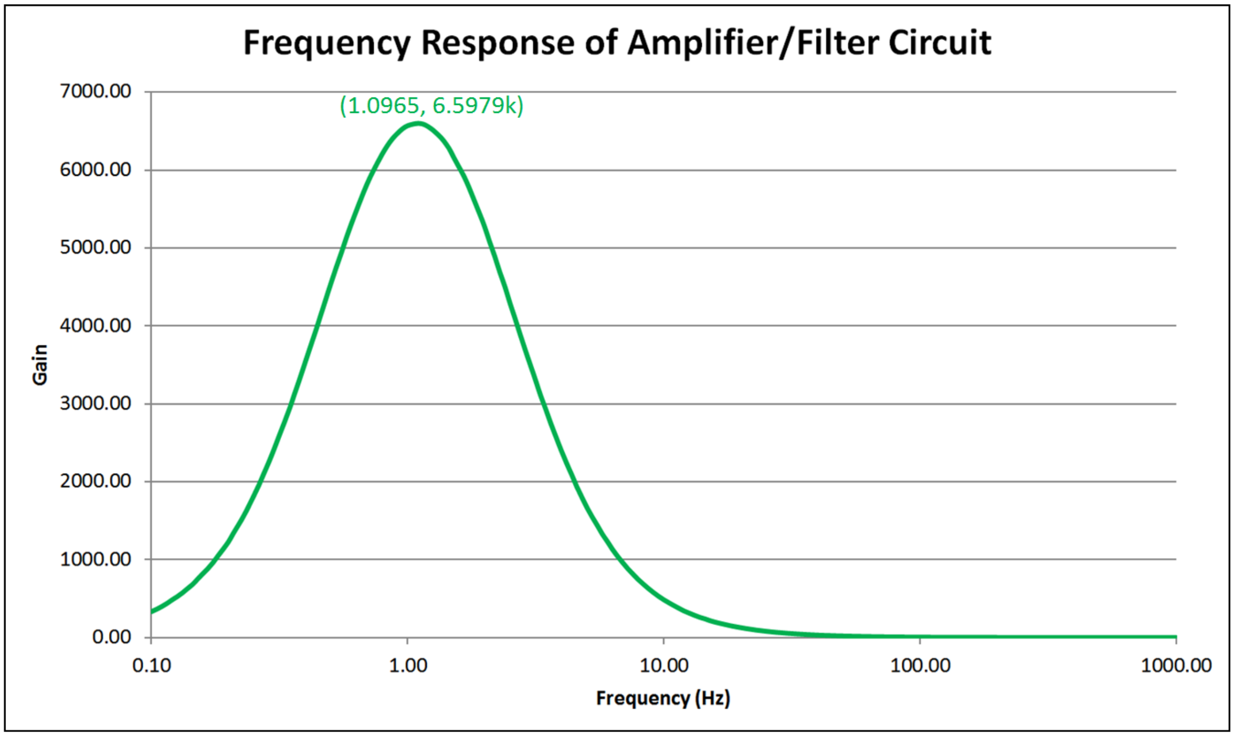

Figure 17: Frequency response of two-stage amplifier simulation

From Figure 17 we can see the frequency response of our amplifier circuit. We notice that, as shown in our equations, signals with frequencies tending towards 0 and infinity will be attenuated while only the frequencies near and between the cutoff frequencies will survive. However, we also notice that the maximum gain of our circuit is only 6,598 rather than the ideal 10,000. The reason for this is because our cutoff frequencies are so close to each other that each filter will attenuate the other before it reaches it can reach its maximum gain. We also notice that if we look at around 2Hz, we see that our gain will be somewhere between 5,000 and 6,000, and in our simulation using a 2Hz signal we saw a gain of 5,130 because our max output voltage was 5.13V with a 1mV input.

2.4.3 Software

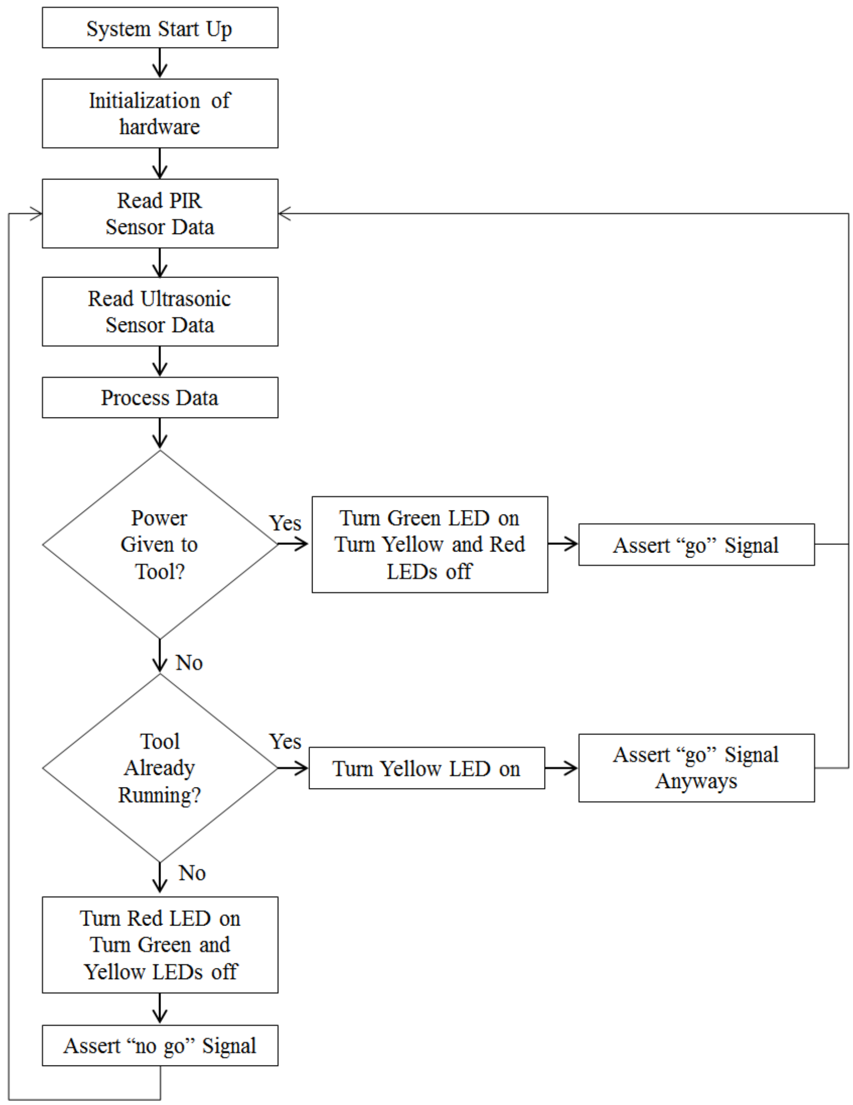

Figure 18: Flowchart of main program loop.

On startup, the system will be powered on and will wait for initialization of sensors to finish. Once this initialization has occurred so that the sensors will have time to reach a steady state value, we enter the program loop. First, we must collect data from both of our sensor arrays. The basic method of how to do this is shown below in Figures 19-20.

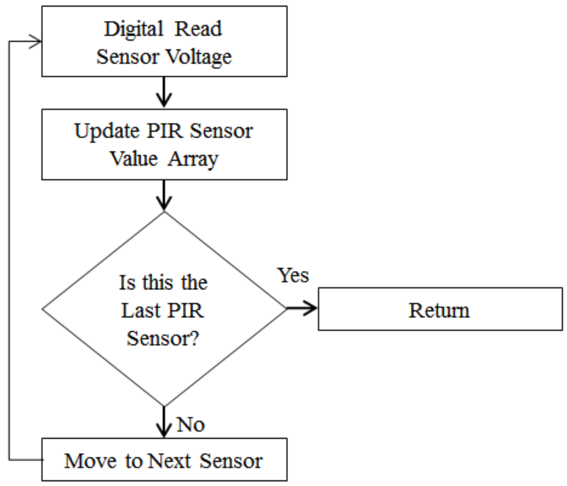

Figure 19: Flowchart detailing the basic method to read the PIR sensor data.

To collect data from the PIR sensors, we use a digital read to sample the input of each at their corresponding input pin and then store these values for later processing.

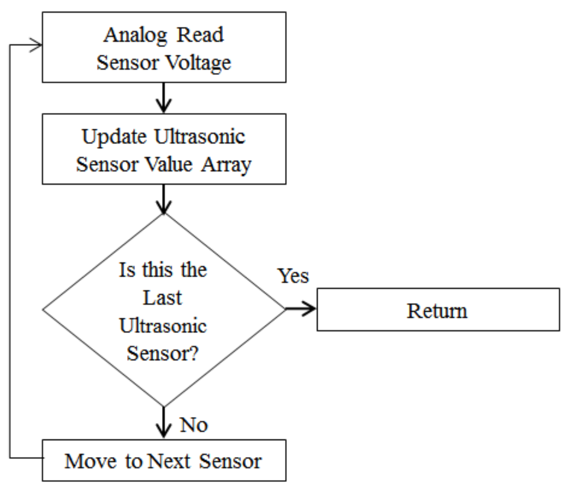

Figure 20: Flowchart detailing the basic method used to read Ultrasonic sensor data.

Similarly, to collect data from the Ultrasonic Range sensors, we will cycle through all of them, but unlike the PIR sensors, we will read an analog value and store these values to be used when processing data. After both sets of data have been collected, we then move onto processing the data. A high level method of how to process this data from an individual PIR sensor and ultrasonic sensor is shown in Figure 21.

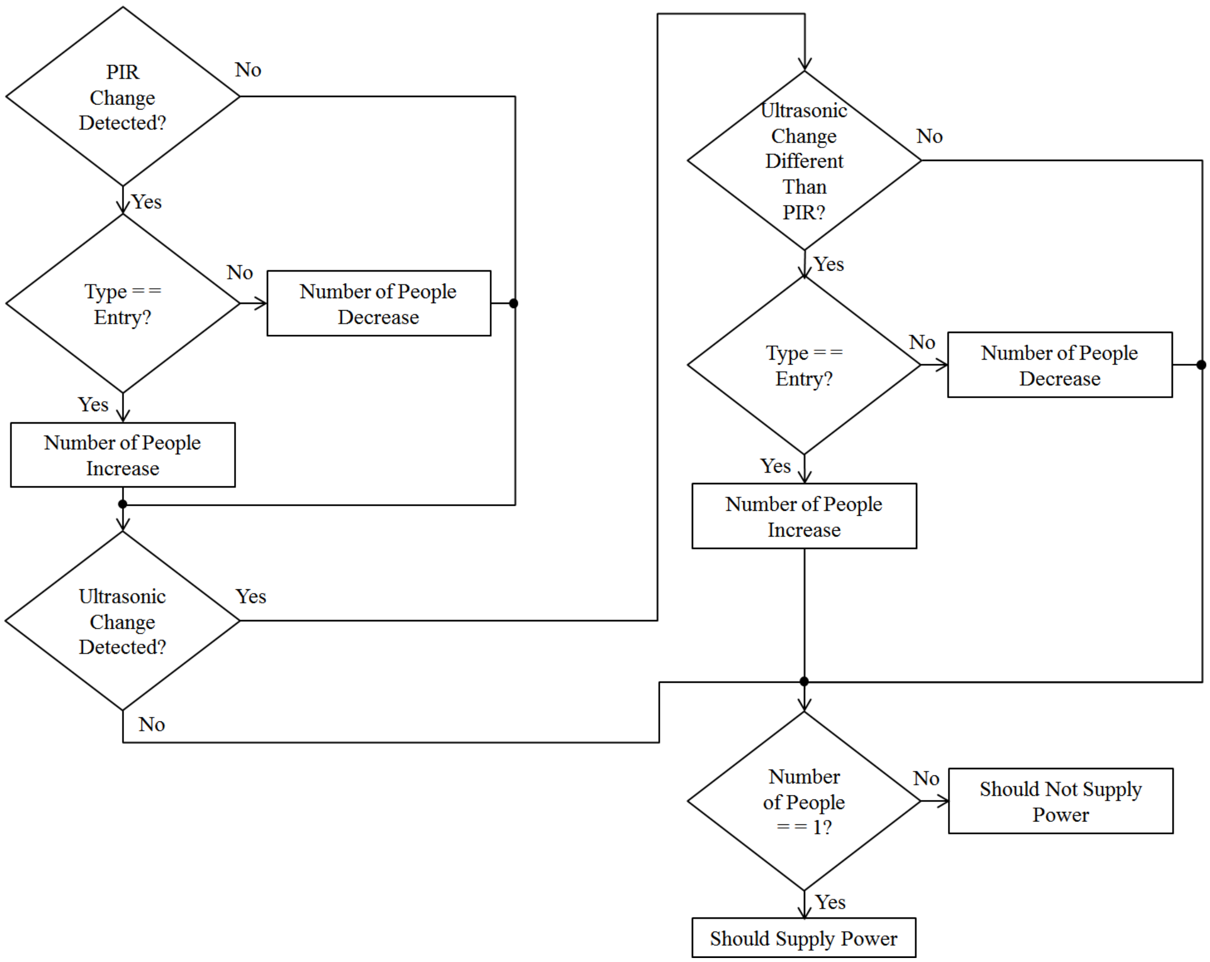

Figure 21: Flowchart showing method to process PIR and Ultrasonic Sensor Data.

If no change is detected then we maintain the old output that indicates whether or not the tool can be powered. If change is detected for the particular PIR sensor, we then look at the type of the detection. If the type of detection is an entry into the sensor field of view then the current number of people is increased. If the type of detection is an exit then the current number of people is decreased. Depending on the location of each particular sensor, the detection of an entry or exit might be treated differently. Then, similar to how the PIR sensors have been checked, we check the ultrasonic sensors. If there has been a change to the ultrasonic sensor value then we maintain the old output that indicates if the tool should be powered. If there has been a change to the ultrasonic sensor and the type of change is an entry (determined by a distance that is within the zone now) the number of the people in the zone is increased, and if the type is an exit then the number of people is decreased.

After this, we check the number of people in the zone. If there is only one person the tool should receive power, but if there is more than one person then the tool should not receive power. If the tool should receive power, only the green LED should turn on and power should be supplied to the tool. If the tool should not be powered, we must check if it is already receiving power. If it is already receiving power, we do not want to cut power so we will maintain power but will light up a yellow warning light. If the tool should not get power and the tool is not already on, then we can illuminate only the red LED and not supply power to the tool by not asserting the signal to the relay.

2.5 Requirements and Verification

Component	Requirement(s)	Verification
AC Relay (2 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.
Current Sensor (4 points)	1. *The current sensor shall output a current such that the AC voltage drop across the resistive load shall be above 30mV if there is at least 10A of current flowing.* *(2 points)*	1. Verification for Requirement 1 a. Using a voltmeter, place voltage probes in parallel with the resistive load of the current sensor. b. Construct a simple resistive circuit with a 110VAC wall outlet input. c. Adjust resistance of power resistor such that input current is 10A (referenced using AC load tester). d. Attach current sensor to 10A branch. e. Measure output current of current sensor using the voltmeter, ensuring a minimum of 30mV is present across the resistive load.
	2. *The current sensor shall sense a minimum of 5A.* *(1 point)*	2. Verification for Requirement 2 a. Construct a simple resistive circuit b. Adjust input voltage such that input current is 5A. c. Attach current sensor to 5A branch d. Measure current using the current sensor and verify that current reading within 1A of actual current.
	3. *The current sensor shall identify current levels up to at 15A.* *(1 point)*	3. Verification for Requirement 3 a. Construct a simple resistive circuit b. Adjust input voltage such that input current is 15A.

		c. Measure current using the current sensor and verify sensor accuracy is within 1A of actual current.
AC Power Input (1 point)	1. *A current of more than 25A will blow a 250VAC, 25A slow-blow fuse, disabling power input to the system within one second* *(1 point)*	1. Verification for Requirement 1 a. Construct a simple resistive circuit using a power resistor relay b. Apply a source voltage such that the input current is 15A c. Run source for ten seconds, ensuring system is not disabled. d. Repeat a-b for 25A and 26A. Ensure system is disabled within one second for each case.
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$\pm$0.2VDC
Microcontroller (20 points)	1. *Microcontroller must use no more than 50 mA 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.* *(7 points)* 4. *The software on the microcontroller shall be*	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 one second. e. Run 100 measurement simulations and average the latency of each. 3. Verification for Requirement 3 a. Connect PIR sensor to a digital input pin. b. Continuously perform a Digital Read of corresponding pin. c. Verify that result should be logic 1 or 0 using multimeter. d. Connect Ultrasonic Sensor to analog input pin. e. Continuously perform Analog read of corresponding pin. f. Verify Analog Input matches Analog Read within +/- 0.2 VDC using multimeter. 4. Verification of Requirement 4 a. Randomly choose a number of people and

	able to process sensor data to determine if there are zero, one, or more than one person in the zone 95% of the time. *(7 points)*	entry direction. b. Choose arbitrary duration of time in zone. c. Perform test and determine if output is correct based on input parameters. d. Repeat a-c 99 more times.
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 (15 points)	*1. Each sensor must be able to output an amplified pulse with magnitude greater than 4.0V when a person enters or exits its field of view.* *(6 points)* *2. Each sensor must have a modified field of view of 20° +/-10°* *(3 points)* *3. The array as a whole shall be able to determine whether there is zero, one, or more than one person within the 1.2m x 1.8m safety zone.*	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 2b 25 times for each side of the beam. d. Use best-fit line of data to determine triangle corresponding to sensor FOV 3. Verification of Requirement 3 a. Mark out the safety zone on the floor in front of the sensor array. b. Have 1, 2, or 3 people walk through or stand in different areas of the safety zone and monitor the response of the system via the

	(6 points)	status lights. c. Record when the machine allows the machine to be powered and check its accuracy.
Ultrasonic Range Sensors (5 points)	1. *Each ultrasonic range sensor shall return an analog signal within the range 0-5.5V corresponding to the distance of the nearest object within its field of view.* *(1 point)* 2. *The microcontroller shall be able to use each ultrasonic range sensor to determine the distance of an object with an accuracy of +/-10 cm within a range of approximately 1.5 m.* *(4 points)*	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. Verification of Requirement 2 a. Connect a single ultrasonic sensor channel to the microcontroller b. Have a person stand 10cm away from the sensor in the broadside direction c. Record voltage reading acquired by microcontroller d. Repeat 2b-c four times e. Repeat 2b-d in increasing increments of 10cm through 1.5m. f. Make a final measurement at 25cm, ensuring calibrated sensor meets specification. g. Repeat 2a-f for all ultrasonic sensors.

Table 2: Requirements and Verification Table

2.6 Tolerance Analysis

One important part of our project will be the amplification of the PIR sensors' outputs. This circuit will be implemented using the BD9251FV chip which has a built-in two-stage amplifier along with a voltage comparator that is used to detect human movement. This chip, however, leaves the selection of the resistors and capacitors for the gain and filters to the users. So in designing the appropriate filters and gain for this circuit, we need to also be aware of the tolerances on each of the capacitors and resistors. If we consider a +/- 5% on these values, we can adjust our previous simulation to account for the "worst case" scenario in each direction. One is for when all of the tolerances are applied that decrease the bandpass region and gain of our filter as much as possible, and the other is for when the tolerances are applied that increase the bandpass region and gain of our filter. We need to consider both cases because both cases can be detrimental. In the first case, we may not have enough gain at the required frequency to be able to determine if there is a person present. However, having too much gain may cause the comparator in the second half of the chip to think a person has been detected when in reality, there was some noise that was amplified too much, mimicking the signal when a human is present. The first case is explored below starting with Figure 22.

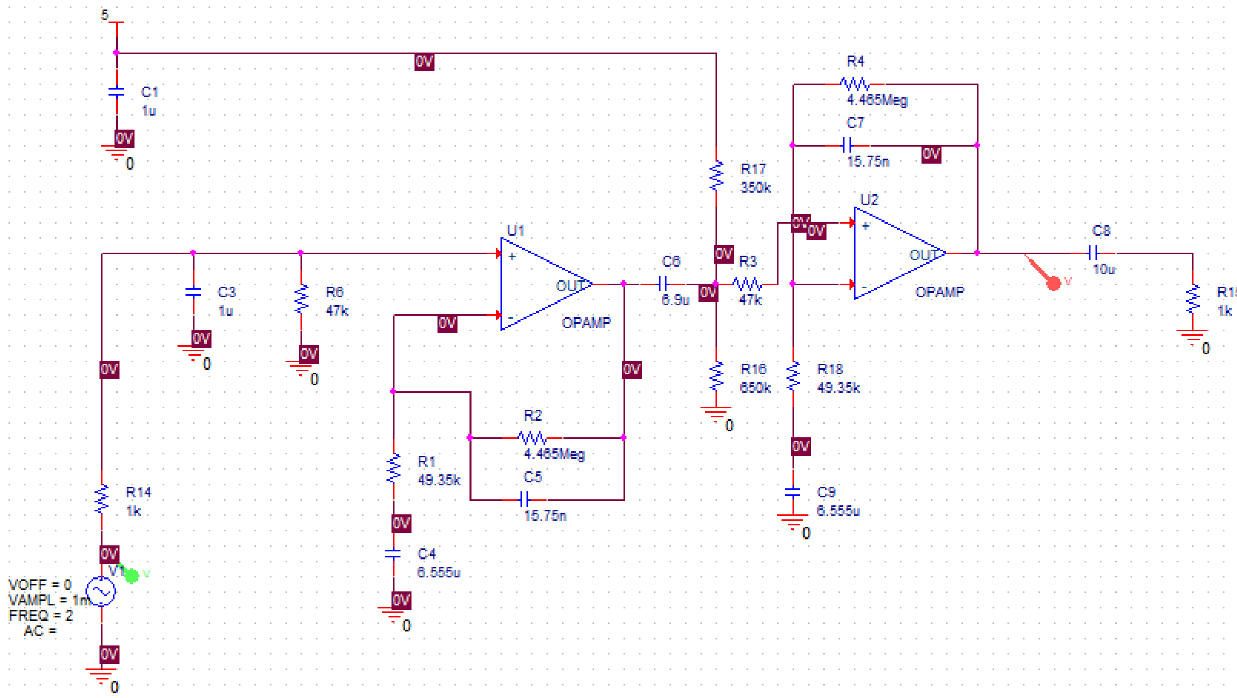

Figure 22: Schematic with tolerances reducing gain and bandwidth

For this simulation, we are only looking at which resistors will affect the gain and bandwidth of the amplifiers. Since stages one and two are identical, we will only look at the first stage, however, the changes have been made on both stages. In the first stage, R1 and C4 are used to determine the high-pass cutoff frequency using equation 1. As we have already discussed, we want the cutoff frequency of the high-pass filter to be lower than the cutoff frequency of the low-pass filter in order to leave a bandpass region between them. If the tolerances caused this cutoff frequency to increase, it would essentially decrease our bandpass region. Based on equation 1, if R1 and C1 both decrease, the overall cutoff frequency will increase. Conversely, and using equation 2, if both R2 and C5 are increased, the low-pass cutoff frequency will decrease, also reducing the bandpass region. However, according to Equation 3, if we want the gain to decrease, we want R1 to increase and R2 to decrease. Since a reduction in DC gain in the bandpass region using R1 and R2 will outweigh the effect of the narrowing of the bandpass region, will instead increase R1 and decrease R2. Therefore, to achieve the largest reduction in gain in the bandpass region, we will increase R1 and C5 while decreasing R2 and C4 by 5% of their respective values. The results of these changes are shown below in Figures 23-24.

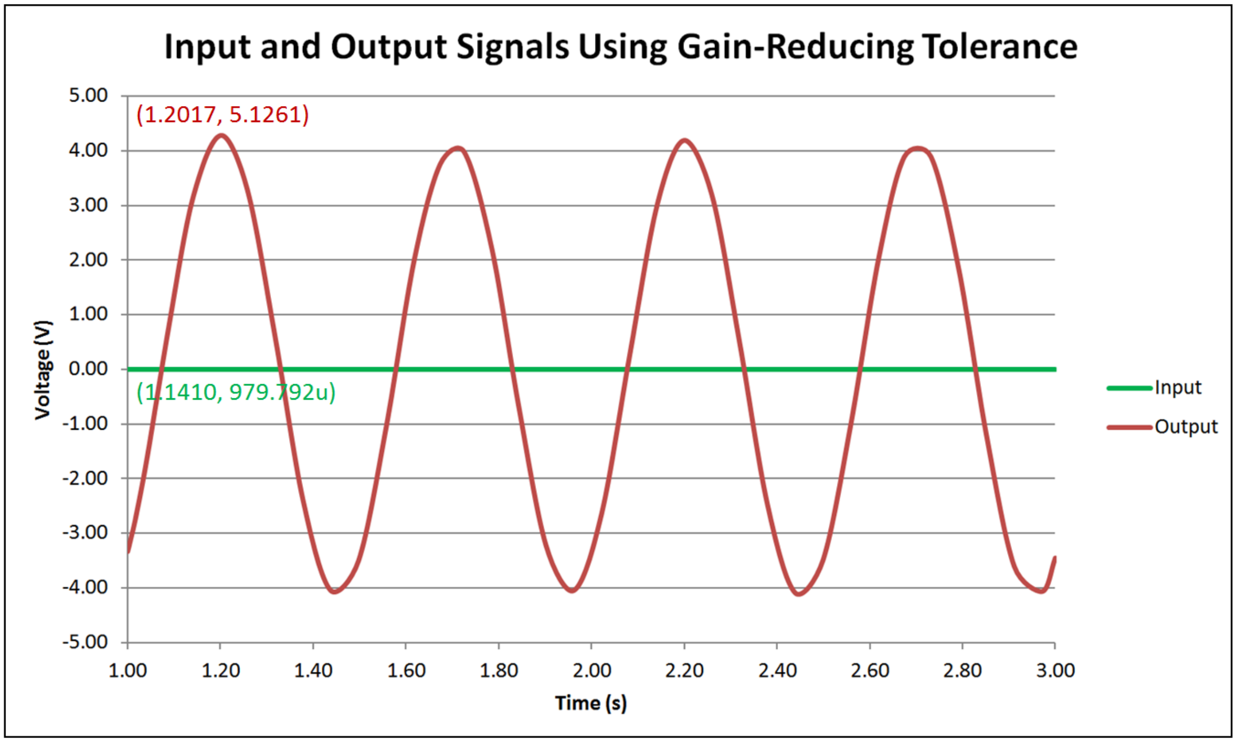

Figure 23: Input (green) and output (red) of amplifier with tolerances reducing gain and bandwidth

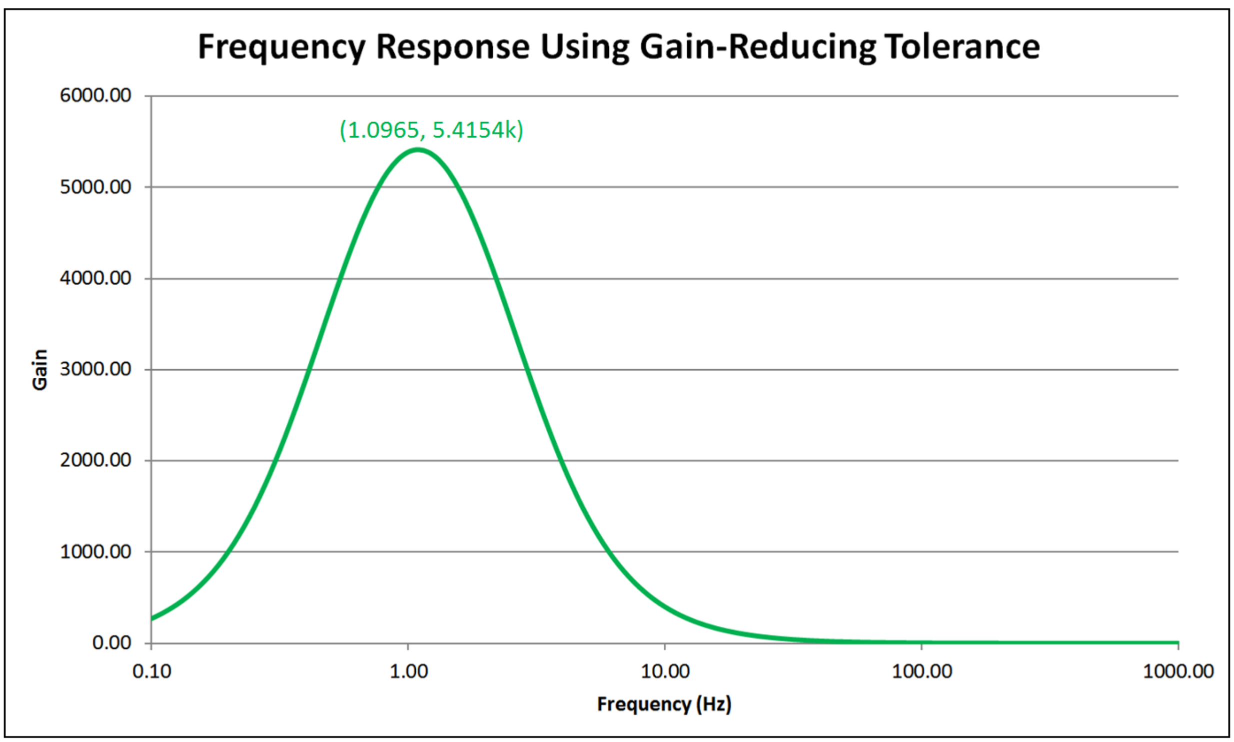

Figure 24: Frequency response of amplifier with tolerances reducing gain and bandwidth

From this simulation, we can see from Figure 23 that with a 1mV input, just like before, the output peak voltage is now only 4.29V rather than the 5.13V we had without accounting for these tolerances. Also, the frequency response in Figure 24 shows that our maximum gain is 5,415 rather than the previous 6,598. While these tolerances do in fact reduce the gain of our system, the trigger points for the signal to be registered by the comparator are at +/- 3.4V so a peak voltage of 4.29 would still be detected correctly. This shows that even with taking into account the worst possible tolerances to reduce the gain and bandwidth of the amplifiers, our circuit will still function correctly.

We now need to consider the second case where the tolerances serve to increase the gain and bandpass region of the amplifier circuit.

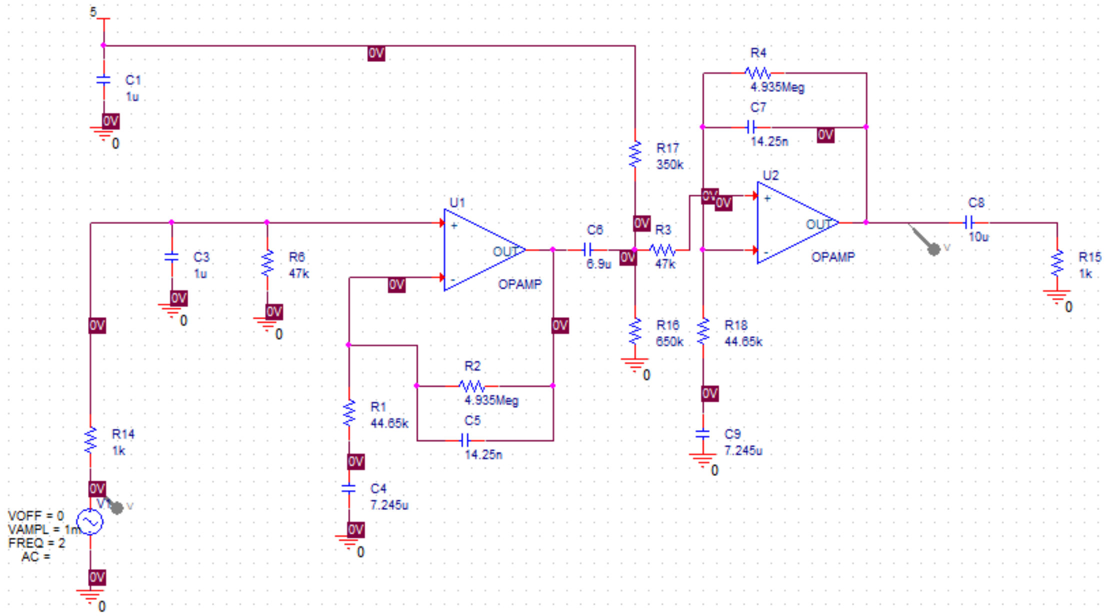

Figure 25: Schematic with tolerances increasing gain and bandwidth

Just like in the first case, we are only looking at the resistors and capacitors using in calculating the gain and frequency cutoffs. In this case we are looking at the scenario where the gain and bandpass region increase as much as possible due to the tolerances on these resistors and capacitors, and again, since both amplifying stages are the same, we will just look at the first stage. In order to cause the largest gain increase, according to equation 3 we want to increase R2 and decrease R1. However, in order to increase the bandpass region, we want the cutoff frequency of the high-pass filter to decrease. According to equation 1, we want to increase both R1 and C4 in order to do this. Conversely for the low-pass filter, we want to increase its cutoff frequency. According to equation 2, this is done by decreasing R2 and C5. The gain and filter equations again contradict each other, but because the change in gain will dominate the change in the bandpass region, we will ultimately increase R2 and decrease R1 to see the increase in gain. Therefore, for this simulation, we have increased R2 and C4 and decreased R1 and C5 by their tolerances of 5%. We notice that these are the exact opposite changes as made in the first tolerance simulation.

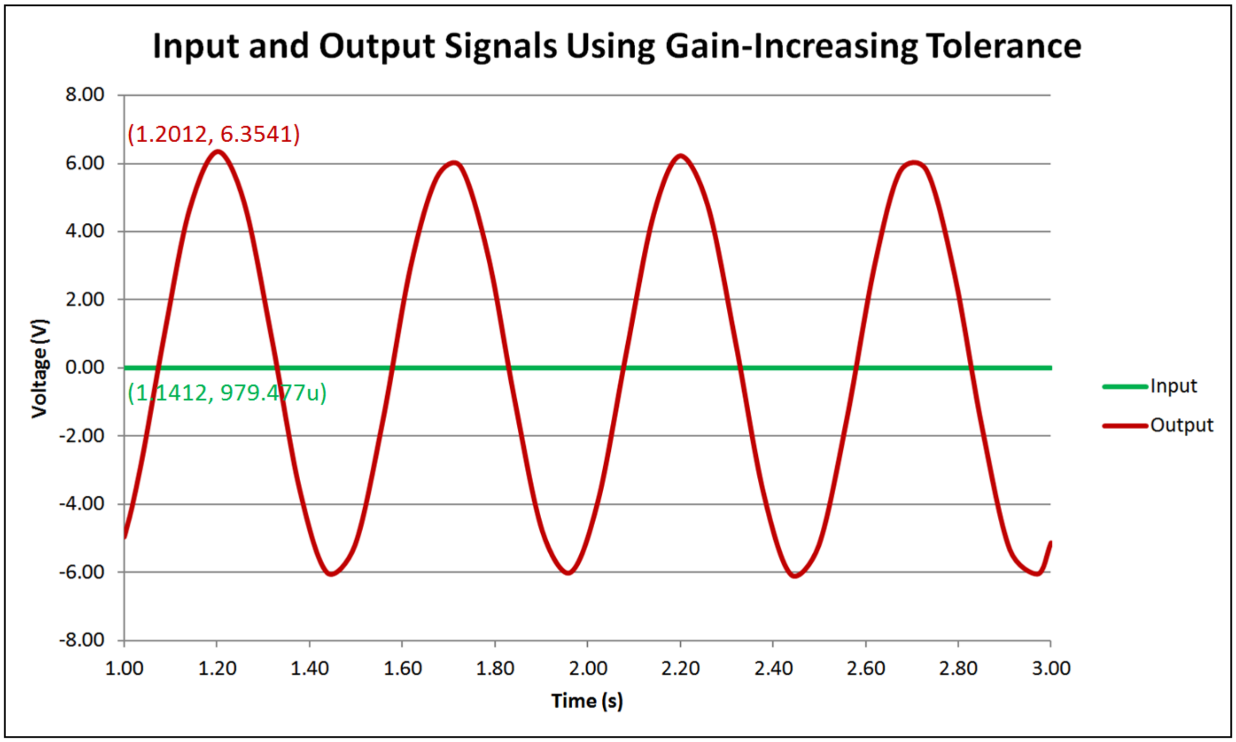

Figure 26: Input (green) and output (red) of amplifier with tolerances increasing gain and bandwidth

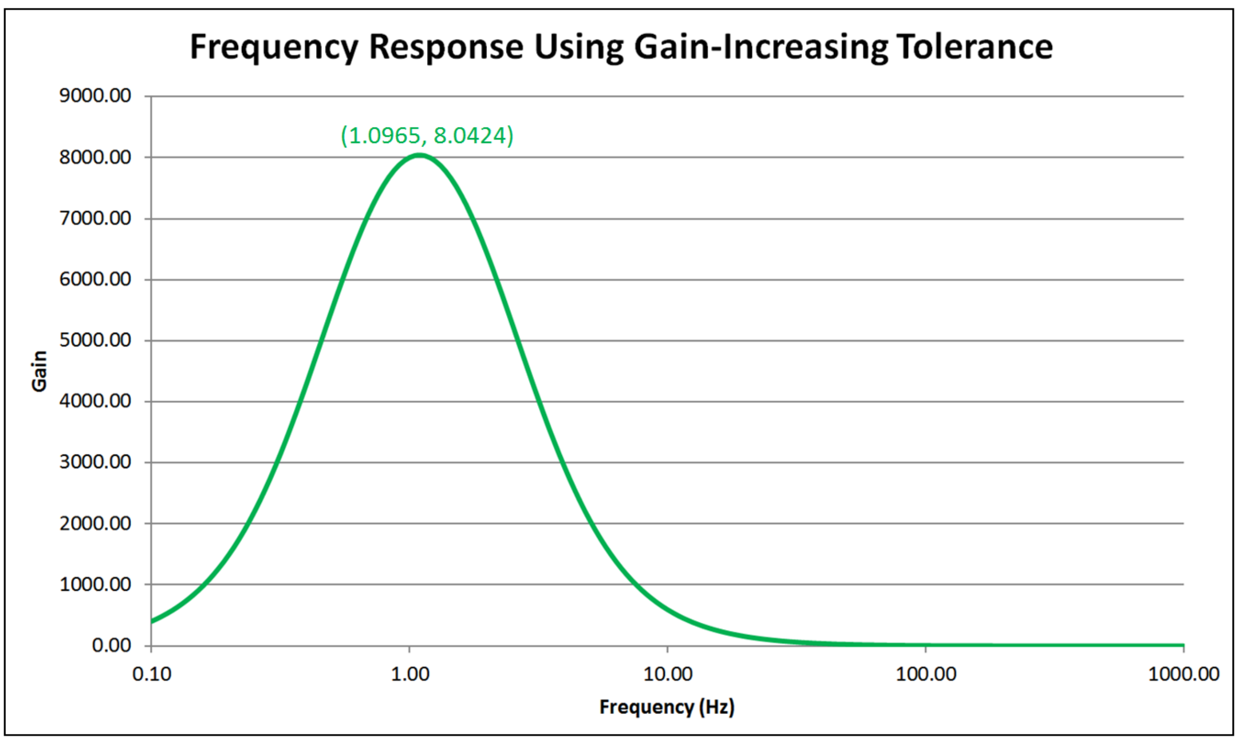

Figure 27: Frequency response of amplifier with tolerances increasing gain and bandwidth

From this simulation, we can see from Figure 26 that with a 1mV input, just like the original circuit, the output peak voltage is now 6.35V rather than the 5.13V we had without accounting for these tolerances. Also, the frequency response in Figure 27 shows that our maximum gain is 8,042 rather than the previous 6,598. While these tolerances increase the gain and the bandwidth, this voltage output just goes to the comparators. In order for this voltage to become a problem, it would need to cause a difference of greater than 6V above the trigger point because the maximum differential into the comparator is 6V. Since the trigger level is 3.4V, we are still below the maximum allowed voltage for our circuit to perform correctly.

From this tolerance analysis, we have seen that our maximum gain of our two-stage amplifier can range between 5,415 and 8,042 with an ideal value of 6,598. We also saw that the voltage output maximum can be anywhere between 4.29V and 6.35V. While this is a fairly large potential swing, all of the values are still acceptable for our circuit to function properly.

3. Cost and Schedule

3.1 Cost

3.1.1 Parts

Part Name	Part Number	Unit Cost	Quantity	Total
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
Microcontroller	ATMega328-20P	$5.50	1	$5.50
PIR Sensors	Zilog PS033601-1214 Zmotion Pyroelectric Sensors OR Murata IRA-S210ST01 sensors	$2.31 - single order $1.49 - 25+ order $3.15 - single order $1.81 - 10+ order	10	$23.10 $18.10
Ultrasonic Range Sensors	GP2Y0A60SZLF	$7.18	5	$35.90
Various Capacitors, Resistors, LEDs, and circuit elements	N/A	$5.00		$5.00
25A Slow Blow Ceramic Fuse	0326025.MXP	$1.72	3	$5.16
Wall Socket	Leviton 15 Amp Tamper Resistant single outlet	$2.99	1	$3.49
Wall plug	Leviton 15 Amp 3-Wire Plug	$2.97	1	$2.97
Power Cord	Nema 5-15 SJT Power Cord	$6.48	1	$6.48
Rohm Semiconductor Amplifier for PIR	BD9251FV	$1.69	7	$11.83

3M Foil Tape	3381 Silver	$9.21/50yd	1yd	$0.19
Total				**$144.56**

Table 3: Initial Bill of Materials (BOM)

3.1.2 Labor

Name	**Hours Invested**	**Hourly Rate**	**Total Cost** = Rate*Hours*2.5
Nick	180	$30	$13,500
Kristina	180	$30	$13,500
Channing	180	$30	$13,500
Total	540	N/A	$40,500

Table 4: Estimated labor costs

3.1.3 Grand Total

Parts	**Labor**	**Total Cost**
$144.56	$40,500	$40,644.56

Table 5: Grand total of costs

3.2 Schedule

Week	**Tasks**	**Who is Responsible?**
1/30/17	Write and respond to comments on RFA Plan and write proposal Order sensors for prototyping and characterization	Nick Kristina Channing
2/6/17	Begin writing design document PIR sensor characterization	Kristina Nick and Channing
2/13/17	Begin writing software algorithms Finish design document Microcontroller circuit design	Kristina Kristina Channing

	Design filter-amplifier for PIR array	Nick and Channing
2/20/17	Sensor field of view modification and testing Determine sensor array layout and begin design of software algorithms Ultrasonic sensor characterization and calculate distance from objects Finalize Design Document	Nick Kristina Channing Nick, Kristina
2/27/17	Assemble PIR array on mounting device Test power control software with hardware Design/test ultrasonic sensor array geometry	Nick Kristina Channing
3/6/17	Finish breadboard prototype Assemble/Test power control unit Begin PCB layout/design	Nick Kristina Channing
3/13/17	Test/Debug power control unit Combine ultrasonic and PIR arrays and test with software Finalize/order PCB	Nick Kristina Channing
3/20/17	Individual progress reports Document progress in final report	Nick, Kristina, and Channing Nick, Kristina, and Channing
3/27/17	Attach sensors to individual mounting systems Test/Debug software running with PCB Assemble PCB, Test/Debug PCB connections	Nick Kristina Channing
4/3/17	Test/Debug system for sensors Assemble overall physical system Take measurements for tolerance analysis	Nick Kristina Channing
4/10/17	Begin presentation preparation Test/Debug overall system Prepare demo	Nick Kristina Channing
4/17/17	Prepare presentation Sign up for demo and presentation Prepare demo	Nick Kristina Channing
4/24/17	Proofread final paper Prepare final paper Proofread final paper	Nick Kristina Channing
5/1/17	Proofread final paper Turn in final paper Lab Checkout	Nick Kristina Channing

Table 6: Project schedule and personnel allocation

4. Safety and Ethics

Since this project involves creating a product that will increase worker safety in machine shops, it is important to mention the Occupational Safety and Health Administration (OSHA), the regulatory body for workplace safety, and what requirements they have in place. 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" [15]. 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 since serious workplace injuries must be investigated by OSHA and could result in negative consequences for the particular shop [16].

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 will attempt to minimize the risk of tripping by placing our sensor array right up against the base of the power tool and trying to minimize the distance that the array protrudes into the work zone.

An additional safety concern occurs in the event that our system suddenly malfunctions while the tool is being operated. This would cut the power to the tool in the middle of use, causing potential damage to the tool. Also, if the system were to briefly cycle power to the device while operating, the worker may assume a malfunction has occurred once the tool shuts off. The worker would not expect the tool to be powered on again and would be in danger of bodily injury.

We also must be aware of the potential hazards of using wall outlets. Wall outlets have the potential to provide AC current levels far above the minimum 10mA lethality level. Power tools are typically higher power devices, so additional care must be given to properly addressing safety concerns with the power bus. All power components of our product will need to be well-insulated, with earth and chassis ground interlocked and the live and neutral lines isolated. The greatest safety concerns regarding the wall outlet are all associated to accidental shorting between any of the three lines present in the power system. Shorting can cause either damage to equipment or accidental electrification of the chassis ground, creating the potential for workers to be electrocuted upon contact with any conductive components of the tool or our product.

Another concern that we must address is the accidental or intentional misuse of our project. As with any project, there will be a way to trick the sensors or to disconnect the power tool from our device. However, it is important to note that this system is there for the user safety and in almost all professional work environments the employees recognize that. If anything, our system is there to remind them of rules more than protect against malicious behavior.

We must also be aware of the IEEE Code of Ethics [17]. 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 that we are following IEEE Code of Ethics #3, as part of our sensor characterization procedure, we will ensure that 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 will be explicitly stated and will not deviate from the listed range when physically implemented. Our claims will be 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.

When creating our system, we will also keep IEEE Code of Ethics #5 in mind by providing documentation and warning labels regarding proper use of wall voltage. Part of ensuring worker safety is addressing all potential dangerous causes such that each worker understands the associated risk and consequences of actions violating proper use of equipment. In addition, our simple user interface will provide immediate feedback to workers regarding power state of the tool and immediate proximity hazards, as previously described.

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