Modular Light Control System

ECE 445 Final Report
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Abstract

This report documents the design and testing process of a modular light control system. The system aims to create a more affordable and modular solution for implementing automatic human sensing lights. Our design consists mainly of two components - a switch module and a wireless sensor module. The sensor module houses a passive infrared (PIR) sensor and a microphone and is battery powered allowing for wireless operation over WiFi. It communicates with the switch module, which ideally replaces conventional wall switches and is also able to trigger lights with an override. Even though the microphone component failed, the system as a whole was able to complete all major tasks such as detecting human presence and controlling lights but without the polished appearance and quality of a commercial product.

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1. Introduction

1.1 Objective

Modern home automation has been popular lately thanks to the internet, which wirelessly pulls the strings, so we do not have to. People love convenience and simplicity, which the internet provides. However, with convenience comes a cost.

Smart light systems can take time, expertise, and much money to install. Our goal is to design an affordable, modular, WiFi-capable sensor system solution in order to automatically control zonal lighting and help lessen power consumption. The system will be easy to install with minimum effort applied and little to no professional help required. The sensor should detect movement and human presence by sensor fusion between a passive infrared (PIR) and amplified microphone sensors and be able to change the switch's respective lights. Sensor fusion is beneficial in reducing false negatives in a case where the room is occupied and the PIR sensor does not detect movement; the microphone may detect sounds made by the occupants. Having multiple sensors can also eliminate false sensor positives, in cases such as where the heating, ventilation, and air conditioning system might trigger the PIR, in order to improve accuracy. One potential reach goal would be having a user interface to easily control sensor and switch groupings and policies and to add new sensors.

1.2 Background

If you've ever been in a room with motion sensing lights, you may be familiar with how frustrating it can be when the lights turn off whilst you're still occupying the room. You have to periodically stand up, move around, possibly even wave your arms, and go back to where you were. What if the room is very large and you want to control a set of lights in a certain portion of the room where the switch is far away? Who would want to move across a large room every twenty to thirty minutes?

Other systems require a hefty initial investment since they require multiple pricey smart switches all around the house, the majority linked together with a required standalone smart hub for control. Each switch can cost upwards of $50 [1], and hub, potentially up to $100 [2]. Outfitting an entire house may run over one thousand dollars! [3] In some switches, they are limited by having the sensor mounted on the switch itself, which can be potentially far from the lights.

Our system will address these issues by being cost effective and not requiring any major rewiring other than replacement of switches. The modularity of the sensors and the ease of mounting will allow for the sensors to be at any location. Our system will also be able to group multiple sensor units to one or more switches. Once setup, the system will work in the background with no required human intervention, unless the user overrides the sensors by a manual toggle on the switch.

1.3 High-Level Requirements

- Modularity to add and adjust the switches and sensors without requiring any professional help or tools
- Zonal Lighting through easy grouping of sensors and switches, allowing you to control multiple switches with a single sensor or vice versa. Grouping can be done via API’s
- Run the microcontrollers in the sensors using an interrupt driven approach in order to reduce power consumption

1.4 System Overview

The system can be divided into two main components as shown in Figure 1. All components of the system communicate over a local network using dedicated WiFi chips in each system. The major task of human detection is handled by the sensor modules. They use PIR and audio to accomplish this task; the PIR allows the module to detect whether there has been any movement in its vicinity, and the microphone enables the sensor to detect if there are any audio spikes which allow it to infer human presence. Whenever a sensor detects a human, it sends a message to its switch using an HTTP request over WiFi. The other component is the switch, which can be broken down into two types - the master switch and the slave switch. The master switch orchestrates the actions for the whole system. It is the sole point of interaction for the user to add more components to the system or change the settings. The master switch receives triggers from the sensors and sends ON and OFF commands to the appropriate switches based on the settings of the system. The slave switch is responsible for controlling the lights and receiving communication from the master switches. Both switches are powered by step-down transformers on mains power, have an override button, and activate the lights using an electromechanical relay.

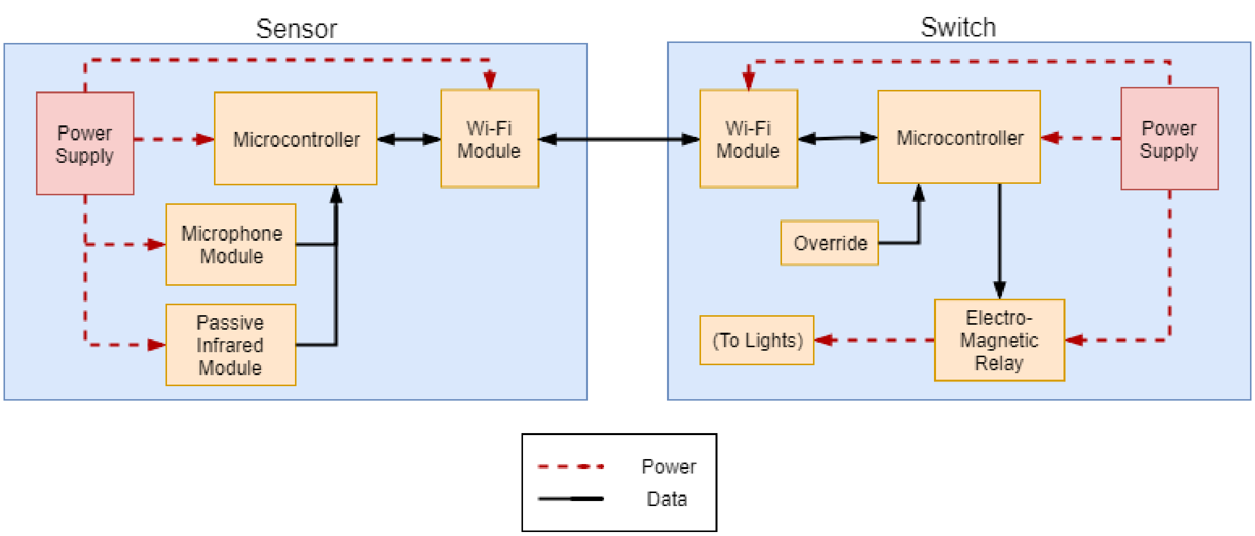


Figure 1. Top-level Block Diagram of Sensor/Switch Pair

2. Design

2.1 Sensor Subsystem

2.1.1 Overview

The sensor subsystem consists of the PIR sensor module and the microphone sensor module. The system is powered by a 9 V battery and communicates with other parts of the system through the ESP 8266 WiFi chip. The control unit for the system is an ATMega328P chip which handles the interrupts raised by the interrupt generator. The PIR sensor module contains the IRA-S210ST01 PIR sensor and the BD9251FV PIR amplifier chip. This module produces a high Vcc pulse whenever an object moves laterally in its field of view. The microphone module has an electret microphone which has a range of 20 Hz - 20KHz [4]. Along with the microphone, we have a second order bessel filter followed by a single stage amplifier. Both of these sensors feed into the interrupt generator, which on receiving a pulse higher than 0.75 V [5] from either the PIR module or the microphone module sends a low interrupt signal to the ATMega328P. After processing this interrupt, the ATMega328P sends a signal to the ESP 8266 chip, which then transmits a message to the master switch, indicating human presence within the field of view. This subsystem's functionality is depicted in Figure 2.

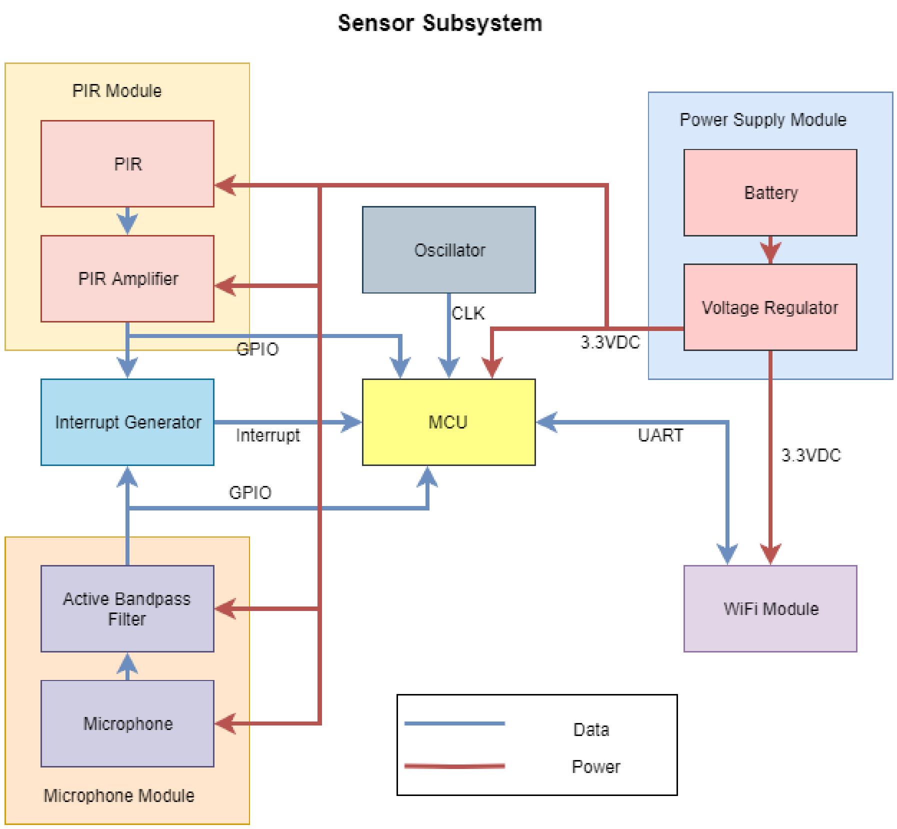
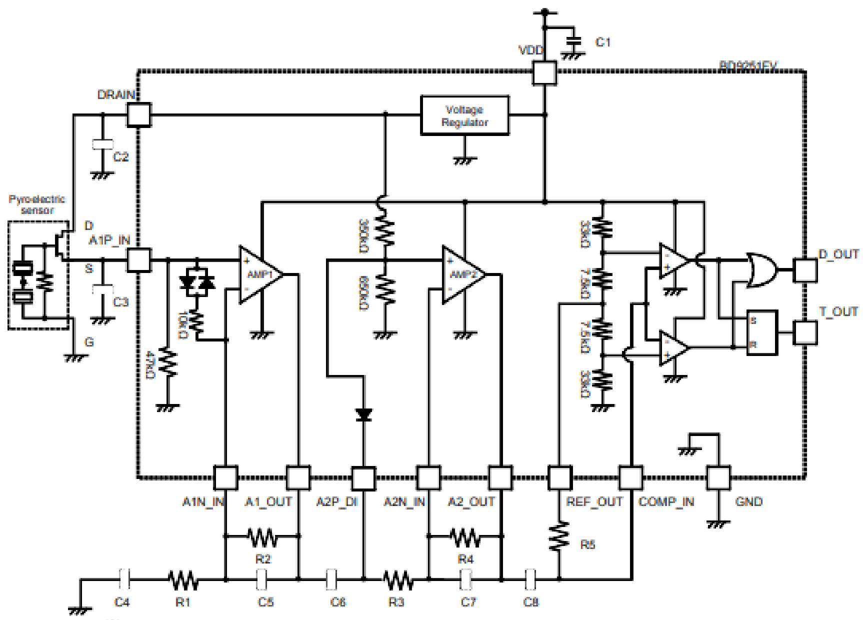


Figure 2: Sensor Subsystem

2.1.2 Passive Infrared (PIR) Module

For the PIR sensor, we use the BD9251FV chip to filter and amplify the signal. The PIR sensor chip works by creating a differential across its drain and source as an object moves pasts several infrared detector sections in the sensor. The amplifier and filter chip acts to select instances in which this signal change can be mapped to human movement and amplify these signals. The chip outputs two pulses for movement through D_OUT and a signal inversion for direction change through T_OUT. Given the suggested circuit in the BD9251FV datasheet, the two-stage amplification has a gain of about 1,000 and a center frequency of 1 Hz [6]. These specifications work in practice for our purposes in sensing human presence. The suggested circuit configuration is shown in Figure 3 [7].



※ Please decide the constant after it confirms it enough examing the characteristic and the condition of the pyroelectric sensor.

Example of circuit constant :

C1=C2=C3	: 1uF	R1=R3	: 47kΩ
C4=C6	: 6.9uF	R2=R4	: 4.7MΩ
C5=C7	: 15nF	R5	: 220kΩ
C8	: 10uF		

Figure 3: PIR Amplifier/Filter Circuit and Suggested Values

2.1.3 Interrupt Driver

For power consumption as well as security purposes. The driver must accept digital pulses as well as sinusoidal inputs above a certain magnitude threshold. In order to pull a digital interrupt pin to the proper voltage and maintain the interrupt voltage for a period of time, we design a circuit using a Bipolar Junction Transistor (BJT) and a resistor-capacitor (RC) low-pass filter to maintain the interrupt signal for longer than a clock cycle in order to trip an interrupt in the ATMega328P.

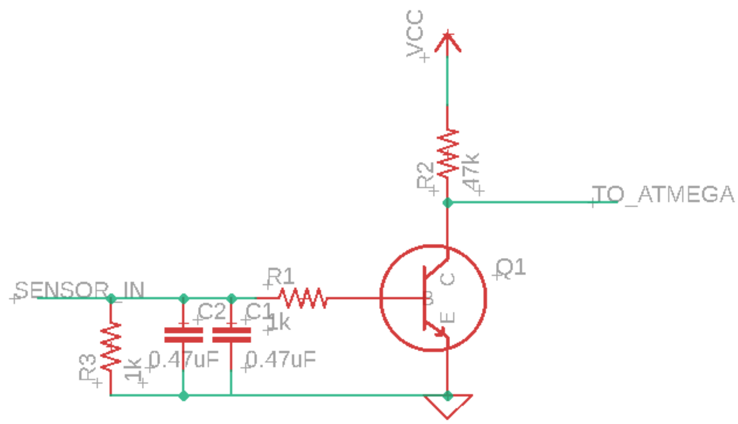


Figure 4: Interrupt driver schematic

In Figure 4, R2 acts as a pull-up resistor when the interrupt is not active. R3, C2, and C1 act to maintain the interrupt signal for longer than a clock cycle. R1 acts to limit the current into the BJT.

In order for the interrupt to occur, the interrupt pin must be pulled low for at least one clock cycle. Given our 16 MHz clock cycle, we have a clock period of

$$T = \frac{1}{f_{clk}} = \frac{1}{16\,MHz} = 0.625\,ns.$$

With an RC time constant of

$$\tau = R * C = 0.94\,ms,$$

the input stays above the proper threshold of the collector-emitter saturation voltage of 0.75V of the 2N4401 BJT [8].

2.1.4 Microphone Module

A microphone was incorporated as an additional method for human detection and a false eliminator as described in 1.1 Objective. We use the CMA-4544PF-W electret condenser microphone for our purposes. We initially intended to use the ICS-40180 microphone, but PCBWay tolerances could not accommodate its small footprint. This microphone detects signals

between 20 Hz and 20 kHz and outputs a signal voltage in the millivolts range. This signal must be filtered and amplified properly for the interrupt generator.
To filter the signal, we use an active low pass bessel filter configuration, which has the configuration as shown in Figure 5 and the transfer function [8]

$$H(s) = \frac{G_1 G_3}{s^2(C_2 C_4) + sC_4(G_1 + G3_3) + G_1 G_3}.$$

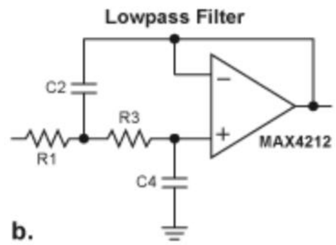


Figure 5: Active Low Pass Filter Prototype

Designing the second order transfer function with a cutoff of 4 kHz through MATLAB's *besself* function yields the following values.

$$R_1 = R_3 = 1k\Omega$$
$$C_2 = 45.94\,nF$$
$$C_4 = 34.46\,nF$$

Designing the circuit with these values yields a 3 dB bandwidth of ~4 kHz. We design the filter at this frequency as human intelligibility is achieved in the 2 kHz to 4 kHz vocal range [9]**.** This filtering allows us to ignore higher frequency sources of false positives while leaving the possibility open for voice detection algorithms in future development. We use a bessel configuration as opposed to a butterworth or chebyshev filter in order to achieve constant group delay and minimum distortion in the passband. This decision considers potential voice detection schemes as mentioned previously.
We must then design an amplifier to bring the signal to a detectable level for the interrupt generator. We can design a simple op amp signal amplifier using the configuration in Figure 6 [10].

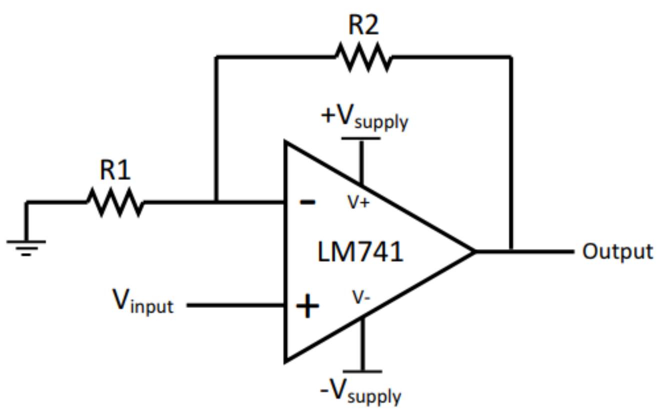


Figure 6: Op Amp Amplifier Prototype

The amplifier in Figure 6 has a gain of

$$A = 1 + \frac{R_2}{R_1}.$$

As the CMA-4544PF-W datasheet offers no data on the signal strength of the microphone, we attempted different amplifier gains ranging from 3 to 100 to bring the signal to a peak-to-peak voltage of Vcc with a maximized signal. Observing the microphone output of ~100 mV and amplified signal through an oscilloscope at different gains and different source voltages in the range of 3 V to 9 V, we find only negligible signals, even when switching out components. Given little documentation for the microphone and little time to pick a third microphone, we could not create a functional microphone block.

2.3 Switch Subsystem

2.3.1 Overview

Intended to replace conventional light switches, the switch module can trigger the lights by either receiving a wireless signal or a manual toggle override. Irrespective of being master or slave, the switch is powered via a stepped-down line voltage of 104-127 VAC [11] using a PSK-S5B-5-L AC-DC transformer. As seen in Figure 7, this module also contains a 16 MHz clocked ATMega328P as its microcontroller, a SRD-05VDC-SL-C electromechanical relay (EMR) to control the lights, an override toggle button and indicator LED, and an ESP 8266 to let allow communication with other sensors and switches.

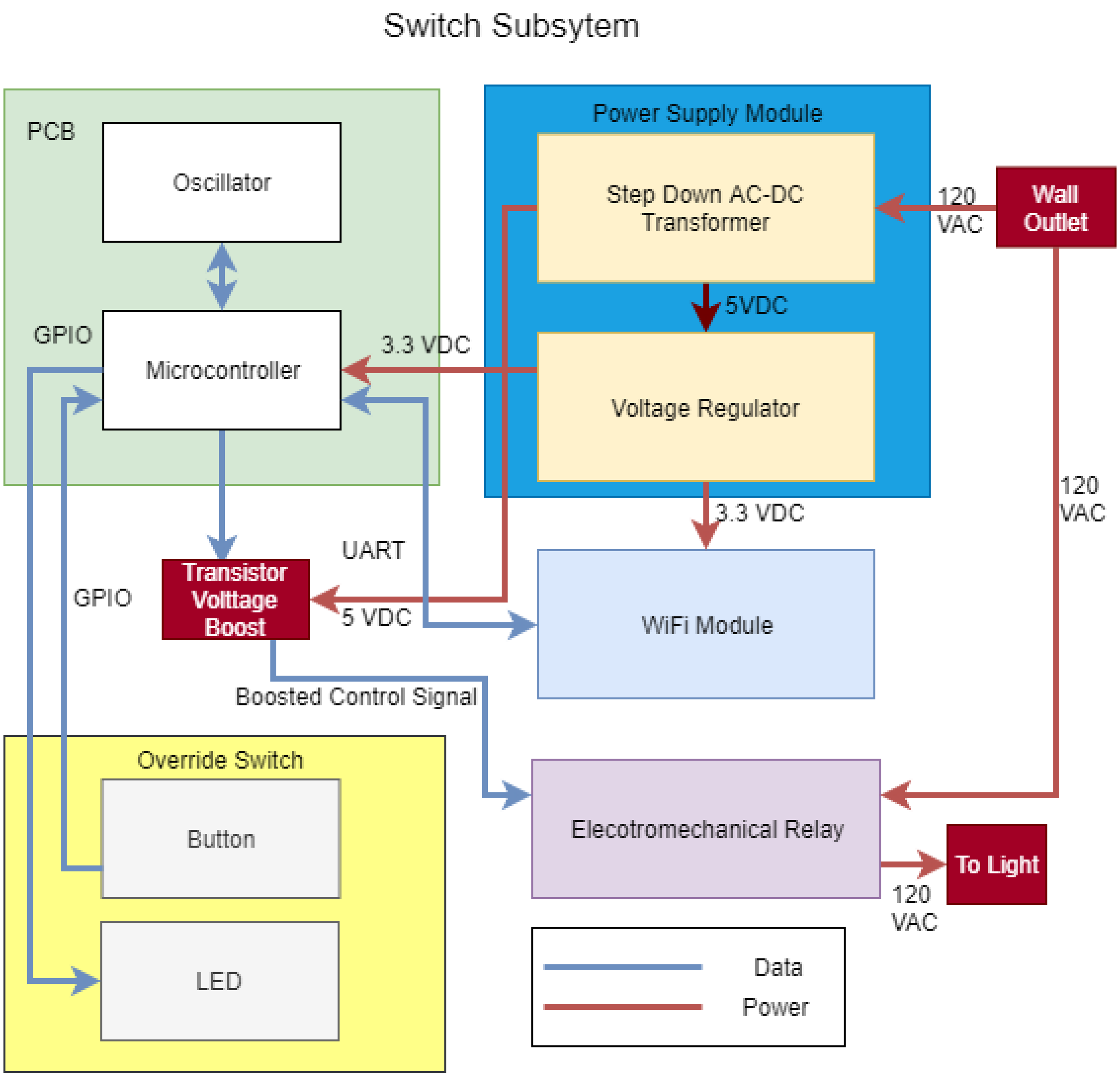


Figure 7: Switch Subsystem Block Diagram

2.3.2 Step-Down AC-DC Transformer

The most seamless method to power the switch module is to tap into the mains power. However, this is incredibly dangerous due to the 104-127 VAC [11]. A commercial off-the-shelf PSK-S5B-5-L step-down transformer is used for the sake of safety as a built bridge rectifier may not satisfy safety requirements due to tolerances. It can receive input voltages ranging from 84 to 264 VAC [12] and is power-limited to 5 W due to its included varistor and fuses. When tested using standard 119.8 VAC, filtering capacitors of 1 and 150 uF and a transient voltage suppressing SMBJ7.0A diode to protect against voltage spikes as in Figure 8, it adhered to our requirement and outputted a steady 5.02 ± .5% VDC up to 990 mA.

2.3.3 Voltage Regulator

Because the ESP 8266 requires 3.3 - 3.6 V, a LD1117S33 voltage regulator is used to further throttle the 5 V from the step-down transformer. It also acts as a secondary fail-safe in the event that the transformer sends too high an output. This is actually within the ATMega328P's input voltage range of 1.8 -5.5 V [13] and using 3.3 V will help with power consumption. With input and output filtering capacitors of 100 nF and 10 uF in Figure 8 and a swept input of 4 - 14.5 V, the regulator satisfied the requirement with a steady output of 3.3 ± .2% VDC.

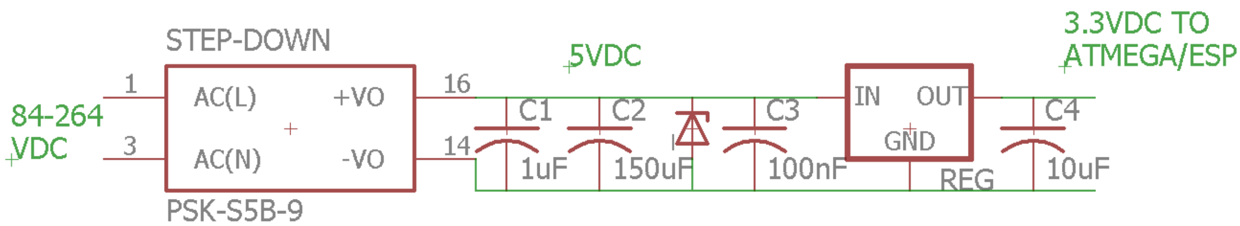


Figure 8: Power Module Circuit

2.3.4 Electromechanical Relay

A 10 A, 125 VAC SRD-05VDC-SL-C electromechanical relay module allows the microcontroller to control the power sent to bulbs. It contains both normally open and closed (NO/NC) configurations and switches them depending on a 5 V control signal. The bulbs are connected to the NO path which close and complete the circuit given a high signal. Because the ATMega328P runs off 3.3V and outputs a high signal of 3.3 V, a transistor initially used to boost the control signal back up to 5 V; however, in practice this was not needed since the relay module operated normally even with the 3.3 V signal.

2.3.5 Button

A normally open (NO) button is used to send a high signal to the interrupt. The interrupt input pin is also pulled down with a 4.7 kΩ resistor to mitigate a floating status and provide a strong low signal to the input.

2.3.6 LED

An LED is incorporated into the switch module to mimic the state of the lights. When the ATMega328P sends a signal to the EMR, it also sends a signal to the LED corresponding to the light's status.

2.4 Microcontroller Unit

The microcontroller chosen for our applications was the ATMega328P. This was done due to the versatility of the chip and its vast documentation. During testing the maximum latency observed in our system was 200 ms, which satisfied the requirement

2.4.1 Switch Microcontroller

The microcontroller on both the slave and the master switch perform the exact same actions. They monitor the state of inputs from the button and the ESP 8266 chip and send an appropriate control signal to the EMR to control the lights. Whenever the microcontroller receives a high signal from either of the two inputs, it toggles the output to the EMR chip thereby changing the state of the lights.

2.4.2 Sensor Microcontroller

The microcontroller on the sensor module is responsible for receiving interrupts from the interrupt generator. On receiving these interrupts, the microcontroller sends a high signal to the WiFi chip signifying the occurrence of a trigger event.

2.5 WiFi Chip

The WiFi chip chosen for our project was the ESP 8266. This was done because of the low power settings and the ease of firmware flashing through the Arduino IDE. The chip was tested as a webserver and was able to respond to a ping from a node in the local network with 0% of the packets dropped

2.5.1 Master WiFi Chip

The master WiFi chip performs the task of orchestrating the whole system. The chips hosts a local web server on a static IP and receives incoming HTTP requests on this IP. It also houses the policies for the system and is the link between the sensors and the switches. The chip acts as the point of contact for the user to send commands to, as seen in Table 1. The chip also sends trigger commands to the slave switches using an HTTPClient. Apart from its tasks as the master switch, the chip is responsible for sending interrupt signals to the ATMega328P. Based on the sensor message and the current state of the light, it sends a high signal to the ATMega328P to toggle the lights.

HTTP Command	**Use**
GET \MAPxy	To map switch x to be triggered by sensor y
GET \RESET	To reset all mappings
GET \ONx	To switch on switch x
GET \OFFx	To switch off switch x

Table 1: HTTP commands for master WiFi Chip

2.5.2 Slave WiFi Chip

The slave WiFi chip hosts a local web server which receives HTTP requests from the master WiFi chip. The chip also monitors the current state of the lights and send interrupts to the ATMega328P to toggle the state of the lights.The chip is also responsible for sending an initialization request to the master switch on startup to signify its presence.

2.5.3 Sensor WiFi Chip

The sensor WiFi chip, on receiving a high signal from the ATMega328P is responsible for sending an HTTP request to the master switch using an HTTPClient. The chip is also responsible for sending an initialization request to the master switch on startup to signify its presence.

3. Cost and Schedule

3.1 Cost

Table 2 lists out all the parts used in the project along with the unit cost and bulk cost.

Part	#Units	Cost	Bulk cost/unit (500 num)
LD1117S33CTR (digiKey)	2	$0.44	$0.23
ESP8266(digiKey)	1	$6.95	$2.00
PSK-S5B-5-L(digiKey)	1	$11.22	$9.10
Assorted RLC+(Misc)	1	$2.00	$0.50
SRD-05VDC-SL-C(Amazon)	1	$5.99	$1.50
ATMega328P	2	$1.46	$0.50
LR6XWA/B Battery (DigiKey)	4	4*0.35 = $1.40	4*0.18 = $0.72
LM27761DSGT (digiKey)	1	$1.88	$1.35
IRA-S210ST01(digiKey)	1	$3.12	$1.42576
ICS-40180(digiKey)	1	$1.52	$0.813
BD9251FV-E2(digiKey)	1	$1.6	$0.919
ESP8266(digiKey)	1	$6.95	$2.00
Assorted RLC+(Misc)	-	$4.00	$0.50
IML-0688(digiKey)	1	$3.30	$1.595
Total		$53.33	$23.87

Table 2: Parts Cost

Assuming labor cost of $40/hour;

Person	**Total Hours =** **Hours/Week * Weeks**	**Total Cost =** **40 * Hours * 2.5**
Ibrahim	12 * 16 = 192 Hours	$19,200
Rohan	12 * 16 = 192 Hours	$19,200
Konrad	12 * 16 = 192 Hours	$19,200
Total	**576 Hours**	**$57,600**

Table 3: Labor Cost

3.2 Schedule

Table 4 is the schedule we followed during the semester.
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Week	Ibrahim	Rohan	Konrad
2-17-19	Design Document	Design Document	Design Document
2-24-19	Parts, Design required PCB's, Prototype amplifier and filter microphone module.	Set up WiFi module with UART comms,decide on final model for detection	Parts, Design required PCB's
3-3-19	Tune Amplifier and filter module, test PIR. Verify PCB, Prototype Interrupt	Setup communication protocol between subsystems and verify speeds.	PIR Field of View, and Breadboard Mockup
3-10-19	PCB #1 Finalization & Order,	PCB #1 Finalization & Order	PCB #1 Finalization
3-17-19	Spring Break	Spring Break	Spring Break
3-24-19	Individual Progress Reports, PCB #2 Finalization & Order, test PIR amplifier chip	Individual Progress Reports, PCB #2 Finalization & Order	Individual Progress Reports, PCB #2 Finalization & Order, Test Power systems
3-31-19	Fine tune circuit and test major modules	Fine tune circuit and major modules	Fine tune circuit and major modules
4-7-19	Test and Debugging	Test and Debugging	Test and Debugging
4-14-19	Debugging & Mock Demo	Debugging & Mock Demo	Debugging & Mock Demo
4-21-19	Final Debugging, Demo	Final Debugging, Demo	Final Debugging, Demo
4-28-19	Presentation, Final Paper, Lab Checkout	Presentation, Final Paper, Lab Checkout	Presentation, Final Paper, Lab Checkout

Table 4: Schedule

4. Conclusion

4.1 Results

We have met all three of our high-level requirements for this project. The network communicates the necessary information between boards, the sensor boards are modular and can be placed independently of the hub location, and the sensor board microcontrollers are properly driven through an interrupt-based approach to minimize power consumption.

Our system works properly with the sensor ATMega328P reading the PIR sensor input and sending the proper message to the hub board. The hub board receives this message properly and can transmit this message to slave switches as well as activate the connected relay. The only individual block that does not work is the microphone module.

The microphone output, amplified or otherwise, outputs no proper signal. Given a PCB that tolerates the ICS-40180 footprint, we could test with the two microphones we selected and observe which one has the proper sensitivity for our purposes. For future development, we will take more microphone designs into account while carefully considering the subsequent ethical considerations of a microphone in our design.

4.2 Safety and Ethical Considerations

The Modular Light Control can potentially expose the user to extremely dangerous and fatal voltages. To mitigate this, we take precautions to make the device as safe as possible for the installer and the user.

The electromechanical relay in our device is connected to wall outlet power and is conducting this wall power in its active state. This posed a safety risk during our own testing procedures and would during installation by any consumer. Should we market this device, we will make the shock hazards abundantly apparent and will encourage support by others more familiar with the dangers for those who are entirely unfamiliar with rewiring electronics in order to maintain #1 of the IEEE code of ethics - “to disclose promptly factors that might endanger the public” [14]. We approached our design and testing following the OSHA standards for power safety [15] and intend to include descriptions of proper safety practices regarding mains power with our product. The ground and power rails on our device are clearly marked so that polarities are not switched. When rewiring the circuitry, the power to the device was off. In testing, we used the “one hand rule” with one hand in pocket when working with the relays and transformers [16], and urge the disabling of the circuit breaker and a ground-fault circuit-interrupter and insulating gloves to ensure no significant electric shock.

We utilized commercial manufactured parts like the step-down transformer and pre-fabricated voltage regulator ICs. These commercial parts contain peripheral components and are designed to be safe compared to prototyped designs.

Physically isolating high VAC from the rest of the components and keeping them off PCB traces can not only help with EMF, but also with durability. The reasoning behind this is that if we were to design our own AC to DC converter, step-down transformer and diode rectifier, the tolerances and design may be awry which could lead to the destruction of components and even physical harm. This is why we used commercial voltage components.

Fuses are added near the inputs and outputs of the voltage supplies. This is a preventative measure to break the circuit before too much power can run through other components, potentially frying them. There was also transient voltage suppression diode added, which acts as surge protection if, for example, a lightning strike were to occur.

Since our device connects the modules through WiFi, an ethical and safety concern arises with the possibility of unauthorized users who would be able to gain access to the network and control the lights manually and/or retrieve the sensor data to detect a person's presence in the building in order to use this information for malicious intent, directly infringing upon #9 of the IEEE code of ethics - "to avoid injuring others, their property, reputation, or employment by false or malicious action" [14]. In order to prevent this, we use a local network not open to the public internet.

The security risks regarding sensor data would be especially concerning given a functional microphone. We mitigate this issue in our current iteration by sending the audio cues through the interrupt generator that essentially transforms this signal into a pulse. Given future iterations that may use voice detection algorithms, we must mitigate this particular concern further.

4.3 Future Work

We believe that the following items, if implemented, would greatly increase the robustness and marketability of the Modular Light Control System.

- Implement and test the microphone sensor module
- Scramble audio in hardware to mitigate security vulnerability
- Add additional sensing mechanisms such as an ultrasonic sensor
- Design enclosures for both the switch and sensor modules
- Add robust user interface for easy control
- Change from HTTP to HTTPS for better security
- Allow for more customization such as timeouts
- Streamline and optimize software to increase efficiency and reduce power consumption
- Remove ATMega328P and use ESP 32 package of the ESP 8266 to reduce footprint and power consumption

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