Ambient Light Detection and Auto Dimming Smart Switch

ECE445 Design Document

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1 Introduction

1.1 Problem

Most light switches are binary switches and do not have brightness control. There are dimmer switches that allow the user to control brightness, but they do not automatically adjust if the ambient light changes. Users may need to adjust the light if they are in the same room for a long period of time and do not want large changes in light level. There are existing smart no-neutral switches, and lights that detect ambient light (like the BenQ e-Reading Desk Lamp), but there are no existing solutions that combine the two. We are seeking to make users' lives more convenient by introducing this brightness adjusting smart switch.

1.2 Solution

We plan to create a smart switch that can be connected to any existing light switch (including switches lacking neutral connections) and intelligently control lights. Sensors on the switch will be able to detect the ambient light and any obstructions. These sensor measurements will then be combined with simple user input through switches by our control system. This control system will then adjust the power level of the lights according to the previously mentioned user inputs. The lights will vary in brightness and maintain a constant, user set level.

1.3 Visual Aid

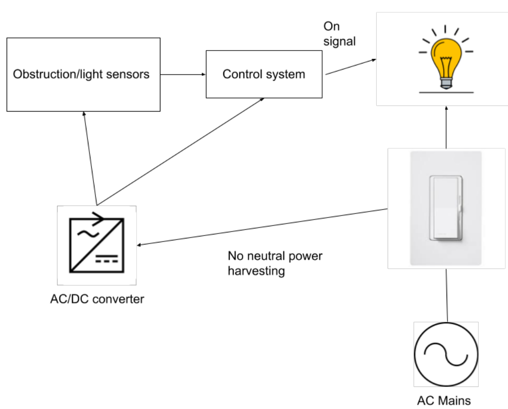

Figure 1: Visual Overview

As shown in figure 1, the switch will interface between the light bulb and the AC mains with the circuitry that we design.

1.4 High-level Requirements

Our project intends to achieve the goals listed below.

1. Be able to connected to existing light fixtures and switches, even those without a neutral wire.

2. Maintain a constant light level for the room at the user set brightness.

3. Prevent unintended fluctuations in light level due to obstructions in front of the switch.

4. Have an override switch that allows for absolute control of the lights.

2 Design

2.1 Block Diagram

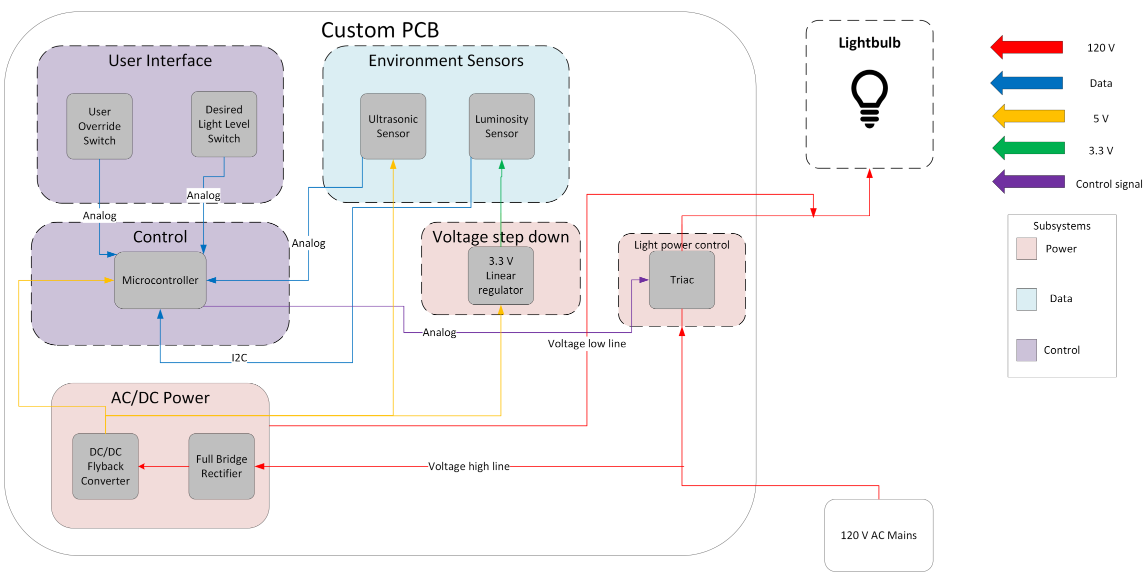

Figure 2: Block diagram

The block diagram in figure 2 outlines our three subsystems, and the power/data signals between the different subsystems. The power subsystem will take a voltage from the 120 V AC mains and convert it to a 5V output. This 5V output voltage is then used to power the control and data subsystems. The control system takes input from the user interface and sensors, and output a signal to triac conduct on and off. This triac controls whether or not the light bulb receives power.

2.2 Power Subsystem

Since we are designing a smart switch with no neutral connection, the smart switch has to obtain power and stay in standby mode. It will have a power harvesting circuit that allows a small amount of power to the light bulb even when the switch is not turned on to complete the circuit. When the switch is turned on, enough power will be sent to the light bulb to light it up. The power supply should be able to extract power from the open circuit over a wide voltage range.

In order to power the switch, we are sourcing power from the 120V 60Hz AC source existing in the wall circuit on the neutral side and providing isolated switching conversion in DC. The circuit design will consist of a triac optocoupler to control the power passing to the bulb, chopping up the waveform into the desired trigger angle with the optocoupler [5] [9]. From there, a zener diode will be paired with the input filtering needed to feed into a flyback converter to provide isolated DC/DC conversion to power the rest of the control circuits [10]. The decision of opting for a switching regulator over a linear regulator was made based on efficiency characteristics, and the isolation included in a flyback reduces the potential for a short [1] [6] [3]. This increases safety for the user.

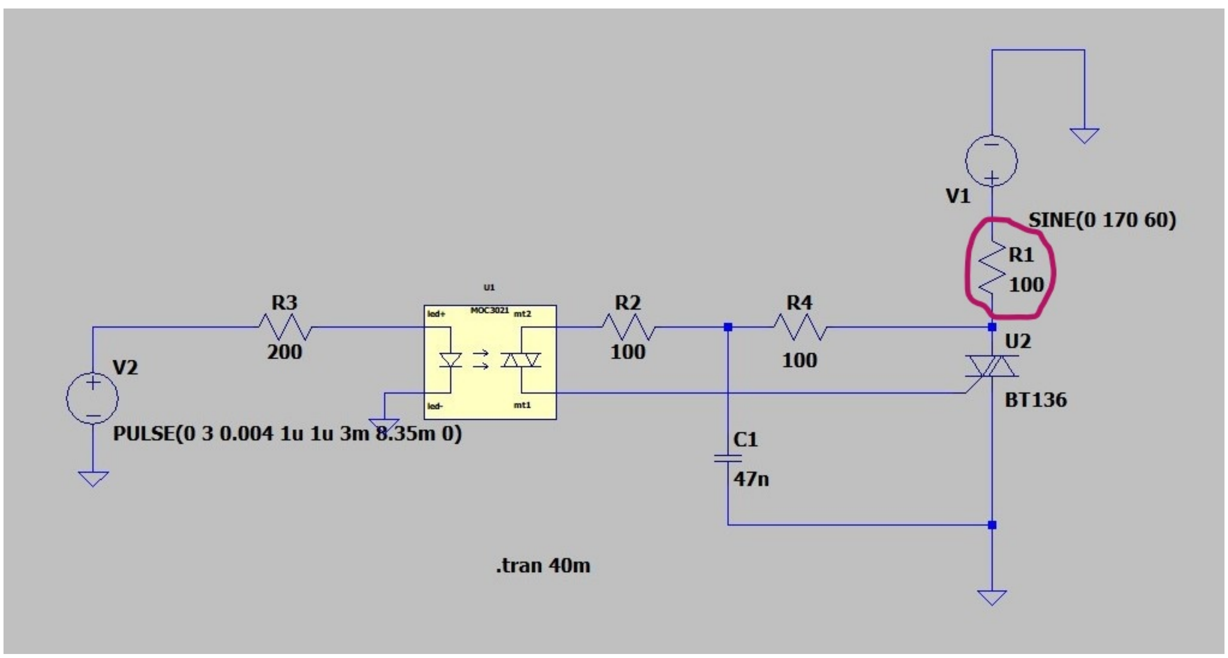

Figure 3: Triac Dimming Circuit

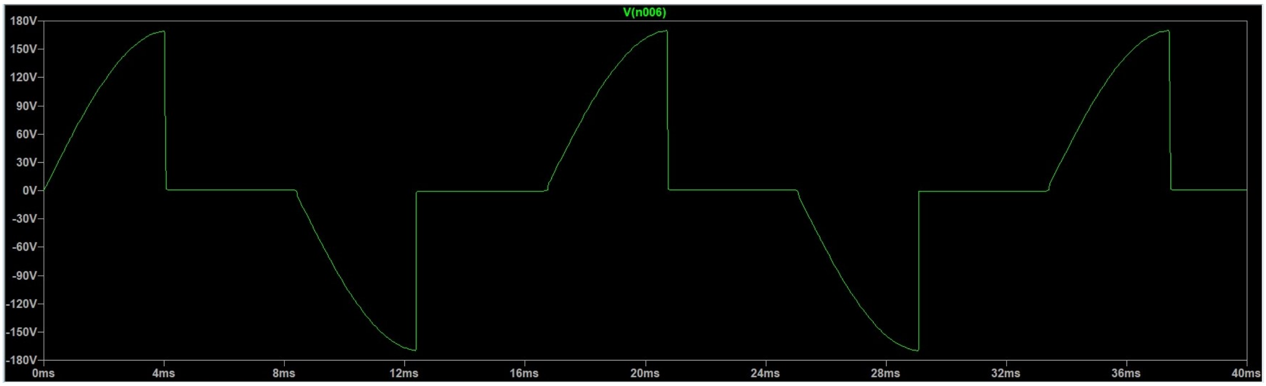

Figure 4: Triac Dimming Waveform

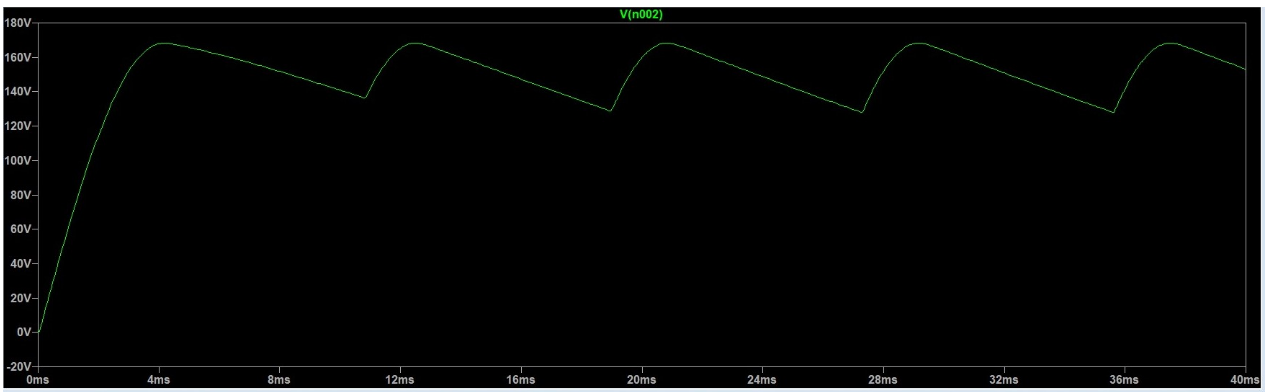

Figure 5: Rectifier Output

2.2.1 Full Bridge Rectifier

The full bridge rectifier will take the AC mains waveform and output a DC waveform to the DC/DC flyback converter. An input capacitor will be used to reduce the ripple and smooth the waveform provided to the flyback converter. As illustrated in figure 6, the full bridge rectifier consists of 4 diodes in a bridge configuration to produce a steady DC value with less ripple. The voltage ripple can be smoothed out by the smoothing capacitor placed parallel on the output side of the rectifier, improving the average DC output while reducing the AC variation of the output. A full bridge rectifier is more advantageous to use in our application over a using a center tapped full wave rectifier as it requires more size and cost. The expected output waveform is attached as shown in figure 5.

2.2.2 DC/DC Flyback Converter

The flyback converter will receive input power from the full bridge rectifier and output a 5V signal. This 5V signal will be the basis for all the DC electronics included on the PCB. Due to the nature of the no neutral power harvesting circuit, the converter must be able to function over a wide voltage range and maintain the 5V output. This 5V output will power the microcontroller and ultrasonic sensor. A flyback converter essentially offers a buck-boost topology isolated by a transformer as the storage inductor, with the output voltage adjustable. For our design purposes, we will be operating in CCM (continuous conduction mode) where part of the energy stored in the flyback transformer remains in the transformer when the switch is on. CCM offers smaller ripple as well as lower RMS current, lower MOSFET conduction and turn-off losses, and better full-load efficiency, best suited for medium to high power operations. We are still in the process of confirming the exact component sizes, but figure 6 is our targeted approach. T1 is our transformer, U1 is our switching controller, and U2 is our linear regulator. To accomplish our desired functionality, we define the system specifications using the following equations.

The conversion ratio from the output of the rectifier into the converter should ideally be stepping down from approximately 150V to 5V. We can accomplish this through the following equation. Since we are working at a 60Hz fixed frequency, our duty ratio will then be adjusted accordingly.

$$\frac{V_{out}}{V_{in}} = \frac{D}{1-D}\frac{N_2}{N_1}$$

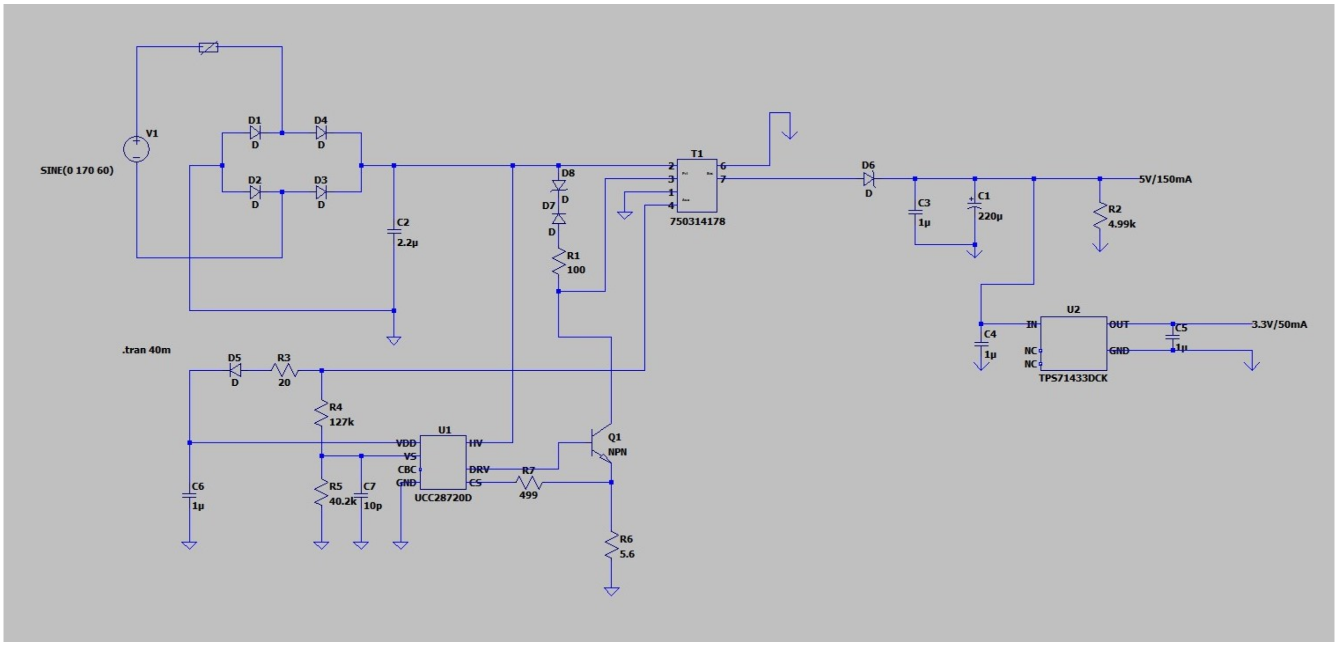

Figure 6: AC/DC to DC/DC

2.2.3 Light Power Control

Conduction to the light will be managed by a triac dimming circuit as picture in figure 3. The circuit illustrated has a simulated PWM source labelled as V2, which would be an output from our microcontroller. That signal will be the trigger into the MOC3021, a triac driven optoisolator, which is an ideal choice when controlling high voltage AC loads through digital control. The optocoupler cannot directly drive loads due to its limited current rating, so it is connected to another triac to act as a power switch to provide enough current to drive the loads. When we trigger the control to turn the LED on with our microcontroller, we adjust the time delay to cut the waveform to our desired preference. Since we are sourcing from the 120V/60Hz AC wall source, we have the period of the desired output signal at 16.66ms, which is calculated by computing the inverse of 60Hz. Our lightbulb is modeled as R1 (circled in pink), so the lightbulb will receive the chopped waveform (pictured in figure 4) coming out of the triac on the neutral connection. The other end of the lightbulb is the 120V/60Hz AC wall source, which we will call the 'hot' line.

2.2.4 Voltage Step Down

As pictured in figure 5, the U2 component TPS71433DCK is the linear regulator selected to output a 3.3V/50mA output. It will take the secondary output from the flyback converter and step the 5V down into the desired 3.3V. This portion of the subsystem will provide power to the ambient light sensor.

Requirements	Verification
• Flyback converter should output 5V ±10%	• Connect a differential probe across flyback voltage output • Connect the circuit to the 120V AC mains • Monitor the output voltage for 5 minutes and ensure that the value is between 4.5-5.5V
• Flyback converter should function from 5V-120V input	• Connect an oscilloscope differential voltage probe across the output terminals • Connect the circuit to a single phase AC variable voltage source • Vary the voltage on the voltage source from 5-120V in 5V increments for 3 minutes each • Monitor the output voltage and ensure that the value is between 4.5-5.5V

Table 1: Sensor subsystem requirements and verification

2.3 Sensor Subsystem

This subsystem will detect the surrounding environment to provide data to the microcontroller. Based on this data, the microcontroller will be able to output control signals to allow the light to turn on and also adjust the power of the light.

2.3.1 Ultrasonic Sensor

This component is intended to prevent obstructions of the ambient light sensor from rapidly changing the light level. If an obstruction (like a person) is detected in front of the switch, a high signal will be output and the light control will pause and maintain the current light level until the obstruction is removed. After the obstruction is removed, the output will change back to a low signal and the circuit will resume monitoring the ambient light level and controlling the light level.

2.3.2 Luminosity Sensor (Ambient Light Detection)

This subsystem will detect the existing ambient light and adjust the power to the overhead lighting to match the desired light level. The power level adjustment will be triac controlled to only pass a portion of the AC mains waveform to the lights. The sensor has I^2C data output, which can connect to a I^2C controller on our microcontroller to read the data.

We will be using an Arduino and special testing modules to test the sensor subsystem. This will allow for easy connection of the Arduino and output to the console on a laptop.

Requirements	Verification
• The ultrasonic sensor must be able to accurately detect a person between the heights of 5' and 6' within 1 m.	• Connect the Arduino 5V to the VCC pin, analog out to trig pin, analog in to echo pin, and ground to ground pin. • Start the custom Arduino module. Check the console to ensure that there is a connection. • Have a person stand in front of the sensor at distances ranging between 5-50cm in 10cm increments. • Verify that the distance calculated from the output of the ultrasonic sensor is accurate to the actual distance of the person.
• The luminosity sensor must be able to detect the typical brightness in a room from 100-4000 lumens.	• Connect the Arduino 3.3V to the VCC pin, ground to GND pin, and I^2C data and clock pins to the corresponding ports on the Arduino • Cover the sensor and verify that close to 0 lumens is measured. • Gradually increase the light level and verify that the lumens measured increases as the intensity of light shined on the sensor inscreases.

Table 2: Sensor subsystem requirements and verification

2.4 Control Subsystem

This subsystem will provide the control for the light. By taking in data from the sensors and user interface controls, the microcontroller will vary the power that the light receives. The microcontroller will intake data from the sensors using an analog to digital converter.

2.4.1 Microcontroller

The microcontroller is responsible for handling the inputs from the User Interface and Environment subsystem and controlling the power to the light. It will first set the operation mode based on the user override switch and whether obstruction is detected by the ultrasonic sensor. The microcontroller will interface with the ultrasonic sensor using an analog to digital converter. If the override switch is on, the system operates as a simple switch. If not but there is an obstruction, the system will hold the current light power level until the obstruction clears. In normal operation, the microcontroller will utilize inputs of the luminosity sensor and the desired light level switch to run a control loop that adjusts the power sent to the light to approach the desired light level received by the luminosity sensor. The light control will continue to adjust to reach the desired level unless it reaches a limit by the minimum or maximum power levels available to the light.

Requirements	Verification
• Microcontroller must be able to interface with user interface and light bulb simultaneously	• Connect jumper wires to triac to connect to a power meter • Vary luminosity sensor input from 100-4000 lumens and set ultrasonic sensor readings between 5 and 100 cm. • Manually test each combination of user input and environment sensor possibilities through unit tests through Arduino. Check Arduino console at each combination to verify sensors are reanding. • The output should be verified by measuring the power delivered to the light bulb.
• Microcontroller must allow the triac to conduct to allow for power siphoning, while ensuring the light stays off	• Connect a voltage probe across the microcontroller and another voltage probe across the light bulb connection to view waveforms throughout the operation of the light bulb. • Vary the light bulb dimming output from the lowest (2 W) to highest setting (9 W) to ensure the entire range behaves properly and power is always delivered back to the control circuit.

Table 3: Control subsystem requirements and verification

2.5 Tolerance Analysis

For the rectifier portion of our circuit, we want to guarantee that the DC output is a steady supply with close to little voltage ripple at twice the line frequency. As mentioned earlier in the subsystem requirements, the smoothing capacitor is responsible to control this tolerance parameter. The smoothing capacitor, also referenced as the DC link capacitor, should be about 2-3uF per watt of input power for a universal input range of 85-265Vrms. The minimum voltage across the smoothing capacitor is modeled as below:

$$V_{DCmin} = \sqrt{2 * (V_{linemin})^2 - \frac{P_{in} * (1 - D_{ch}}{C_{DC} * f_L}}$$

Dch is the DC link capacitor charging duty ratio as illustrated in the figure below.

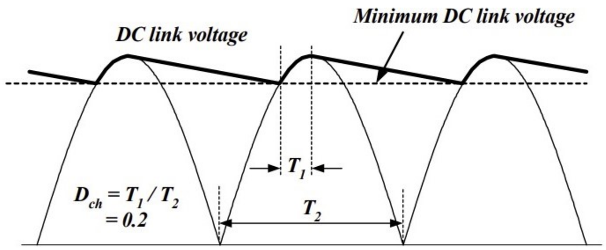

Figure 7: DC Link Capacitor

The actual voltage ripple can be calculated with the parameters below as well.

$$V_{ripple} = \frac{I_{DC}}{2fC}$$

For the flyback converter, we want to make sure that the transformer does not go into saturation. The zener-diode clamp circuit on the primary side ensures that when switching through the MOSFET, high voltage spikes that could damage the switch can be avoided. If the transformer goes into saturation, the switch can also be damaged from the increasing rate of the supplied current. This is why well-calculated switching control and well-calculated transformer sizing is needed to keep the transformer unsaturated. The switches should be sized based on the switch stress. The following equations are guidelines for defining this tolerance.

$$I_{swpk} = \frac{I_{in}}{D}$$

The peak switch current is calculated as a ratio of the current coming into the primary side over the duty ratio. If the current across the switch

$$V_{ds_max} = V_{DC_max} + V_{sn2}$$

To decrease the voltage switch stress, the maximum duty ratio D can be reduced. However it could also cause voltage stresses on the secondary sides' diodes. In general, it is best to set the maximum duty ratio so that the nominal voltage across the switch is 65-70% of the MOSFET voltage rating.

With the following information, we will size our MOSFET to meet these specifications.

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Parts

This is our parts lists that we have purchased to assemble our project.

Description	Part Number	Unit Cost ($)	Quantity	Total Cost ($)
atmega328p MCU	ATMEGA328P-PU DIP28	7.70	1	7.70
Override switch	SW-T3-1A-A-A3-S1	0.88	1	0.88
Analog to digital converter	MCP3021A2T-E/OT	1.42	1	1.42
3.3 V linear regulator	TPS71433DCK	0.18	1	0.18
Diode	ES2CA-13-F	0.73	5	3.85
Triac optoisolator	MOC3021	0.54	1	0.54
Triac	583-BT136	0.67	1	0.67
Ultrasonic sensor	3942	3.95	1	3.95
Ambient light sensor	ALS-DPDIC17-78C-L749/TR8	2.78	4	11.12
Switching controller	UCC28720D	1.65	1	1.65
Transformer	750314178	2.83	1	2.83
1 uF cap	CL05A105KP5NNNC	0.10	3	0.30
16 MHz crystal	16M20P2/49SMT	0.16	1	0.16
330 Ω resistor	RC0603JR-07330RL	0.10	1	0.10
360 Ω resistor	RC0603JR-07360RL	0.10	1	0.10
470 Ω resistor	ERA-3AEB471V	0.35	1	0.35
47 nF capacitor	C0603C473K4RECAUTO	0.18	1	0.18
22 Ω fuse resistor	EMC2-22RKI	0.65	1	0.65
Diode switching bridge	RH06-T	0.18	1	0.18
Transformer	750314178	10.65	1	10.65
Flyback controller	UCC28720	0.53	1	0.53
3.3 V linear regulator	TPS71533DCKR	0.91	1	0.91
Schottky diode	SS110-TP	0.35	1	0.35
Diode	BAS316,115	0.15	1	0.15
Test point (red)	5000	0.42	4	1.68
Test point (black)	5001	0.42	4	1.68

100 Ω resistor	RC0805FR-07100RL	0.10	1	0.10
4.99 kΩ resistor	CPF0603F4K99C1	0.20	1	0.20
20 Ω resistor	CPF0603F20RC1	0.19	1	0.19
127 kΩ resistor	RC0402FR-07127KL	0.10	1	0.10
499 Ω resistor	CPF0603F499RC1	0.20	1	0.20
40.2 kΩ resistor	CPF0603F40K2C1	0.20	1	0.20
5.6 Ω resistor	RC0805JR-075R6L	0.10	1	0.10
2.2 uF capacitor	CKG57NX7T2W225M500JH	3.79	1	3.79
1 uF capacitor	CL10A105KO8NNNC	0.10	3	0.30
10 pF capacitor	06033C100KAT2A	0.20	1	0.20
1 uF capacitor	CL21B105KBFNNNE	0.11	1	0.11
220 uF capacitor	10TPE220ML	2.37	1	2.37
Diode	CGRM4007-G	0.37	1	0.37
82 V zener diode	MMSZ5268BT1G	0.24	1	0.25
Banana plugs	CT2230-0	1.40	2	2.80
0 Ω jumper	RMCF0603ZT0R00	0.10	1	0.10
22 pF capacitor	06035A220JAT2A	0.10	1	0.10
1 kΩ resistor	ESR03EZPF1001	0.15	2	0.30
10 kΩ resistor	ESR03EZPJ103	0.14	2	0.28
Potentiometer	P120PK-Y25BR10K	0.93	1	0.93

Table 4: Parts list

3.1.2 Labor

According to the Grainger College of Engineering, the average salary for an electrical engineering graduate is $80,296 [7]. This translates to an hourly rate of about $38/hour.

Labor Category	**Spencer**	**Michael**	**Christine**
Circuit Design	25	25	40
Board Design	30	15	20
Software Design	3	15	3
Assembly & Soldering	5	5	5
Test & Verification	20	20	20
Documentation	40	30	30
Total	**123**	**110**	**118**

Table 5: Labor breakdown

3.1.3 Total Cost

Based on the labor hour estimates, the labor cost total is \$38 per hr x (123+110+118) hrs = \$13,338

Totaling up table 4 the total parts cost is \$65.75.

3.2 Schedule

- Week of 2/20: Write Design Doc and test circuit simulation
- Week of 2/27: Design review and begin PCB design/preliminary parts order
- Week of 3/6: Review board layout/routing, first round PCB order, order other parts, writing initial software
- Week of 3/13: Spring Break
- Week of 3/20: Soldering, test/debugging, ironing out software bugs
- Week of 3/27: Assess PCB and software, edit and order in second round PCB if necessary
- Week of 4/3: Debug continued, assemble in housing and test, more software debugging as necessary
- Week of 4/10: Finish hardware/software debug and documentation, prepare paper and presentation
- Week of 4/17: Prepare demo presentation and do mock demos
- Week of 4/24: Final Demo

4 Ethics and Safety

We will be following the IEEE Code of Ethics in the development of our project. Section I.1 specifies to hold safety in the highest regard [4]. The goal of our project is to make users' lives more convienient. We want to ensure that our project does not injure users in the process of installing it. As such, we will write appropriate warnings and include correct procedures for installing our device in a safe manner.

The primary source of danger in our project is the power system, specifically the connection to the 120V AC mains. As little as 50 to 150 mA could cause death [8], so it is paramount that the user understands safe protocol for installing our project. While developing the project, we will always ensure that the power is off before connecting or disconnecting any components. Our project will also include safety documentation for the user very clearly list these steps to ensure their safety.

Another possible danger is the circuit shorting and causing an electrical fire. From 2015-2019 there were an average of 46,700 home electrical fires [2]. To protect our users we decided to use a flyback converter for our AC-DC power converter system. The flyback converter provides galvanic isolation between the AC mains input and the circuit output. Due to this topology, the output side of the transformer is isolated from high current [6]. The input side of the power system will be protected by the usual circuit breakers that are included in home circuits.

Section I.5 specifies to seek critique of technical work and work to correct any errors, and section I.6 specifies to improve our technical competence. We intend to verify our designs with TAs and other students with experience in the power electronics and circuit design areas. By consulting with others, we can achieve better, safer designs with lower chance of failure.

As our project is a light switch, we do not believe that there are major ethical concerns beyond the power system is as safe as possible. The device is entirely self-contained, and no data from the user is stored or shared.

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