PARKING SPACE MONITORING SYSTEM

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Abstract

This report presents the design for a parking space monitoring system which uses infrared (IR) sensors to check the occupancy of a spot. The IR sensors control LEDs (present at each parking space) which indicate whether a space is vacant (green LED) or occupied (red LED). The data from all the sensors in the system is wirelessly transmitted via RF to a central hub which aggregates the data and outputs the processed data to an LCD display for visual inspection. The use of IR sensors, in conjunction with visual LED and LCD displays, was confirmed to be successful in implementing an effective parking space monitoring system upon integration of the various submodules discussed in this report.

Contents

1. Introduction

Finding an open parking space in a crowded parking lot is often a long and frustrating endeavor. This irritation frequently stems from being unable to know where the open spots are, forcing drivers to wander aimlessly aisle by aisle, floor by floor, until finding a vacant spot. Our solution consists of a system that monitors the occupancy status of each spot in the lot and displays that information to the driver. In this document, the design of each submodule in the system is explored in detail to explain how the parts come together to create a successful monitoring system.

1.1 Background

An IBM survey conducted in 2011 found that over "30 percent of city traffic is caused by drivers searching for a parking spot" [1]. Additionally, drivers spend on average 17 hours a year looking for a parking spot [2]. And in the country's largest cities, such as New York City (one of the best known cities for traffic and parking difficulty), that number can rise to over 100 hours annually. Typical parking lots do not present incoming drivers with any data or visual markers regarding the vacancy/occupancy of spots. In large and crowded parking lots, it is often very difficult to easily identify where the open spots are because other vehicles block them. This system would provide drivers with useful data to make finding a spot much easier.

While attempts have been made to put parking lot systems in place to perform the function of identifying vacant spots [4][5][6], most notably outside the U.S.A, similar systems have yet to fully integrate themselves into American life. The marketability of such a system has yet to develop fully, so it is important that our solution be somewhat cost-effective in order to incentivize the installation of such systems in parking lots. The time wasted and potential pollution concerns associated with driving around searching for spots must be addressed and our goal for this project is to design and implement a system which helps reduce the magnitude of the problem.

1.2 High-Level Requirements

- IR proximity sensor must be able detect the presence of a vehicle and toggle connected LED light bulbs between RED (occupied) and GREEN (vacant)
- Proximity sensors must be able to send their data via RF transmission to a central data hub to be processed
- The processed data aggregated from all the proximity sensors must be displayed in visual format to the user (driver) via LCD display.

2 Design

2.1 Power Supply

2.1.1 Design Procedure

There are three distinct voltage levels used in the entire system: 3.3VDC, 5VDC, and 120VAC. While the idea of creating our own power supply was entertained, it was ultimately decided that the power supply was a secondary part of the system and not a priority of this project. The decision was made to have a simple 120VAC to 5V converter supply the necessary 5V output to the system, while the LEDs (which required 120VAC) would be given that voltage directly from the wall output.

The RF transceiver chips used in this system require a voltage of 3.3V, so it was initially decided to use a voltage divider circuit to output 3.3V from the 5V output already present in the system. This decision was made because it was believed to be the most cost-effective and simplest way to implement a 3.3V supply. However, during implementation, the alternative solution of using a voltage regulator proved to be more effective as the voltage divider circuit failed to provide the proper current to the RF chips (see Verification section for more details). Therefore, the voltage divider was replaced by a voltage regulator (regulating the output to 3.3 V) in the final design.

2.1.2 Design Details

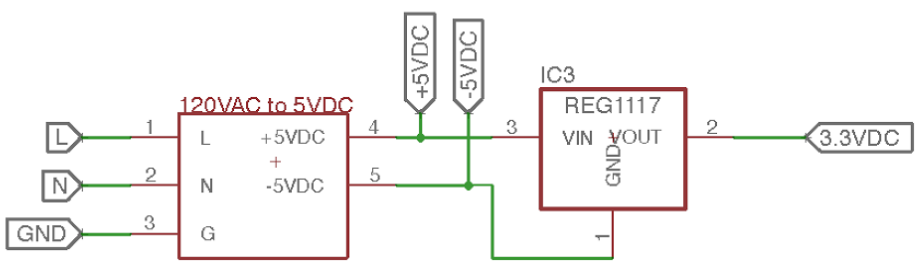

Figure 1: Power Supply Schematic

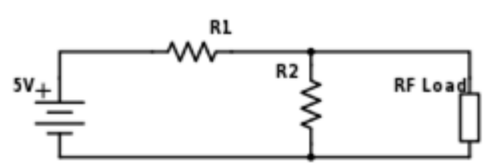

Figure 2: Voltage Divider Circuit for 3.3V

Figure 1 shows the circuit schematic for the power supply in our system. The voltage regulator maintains a steady 3.3V output for the RF transceiver chips. The initial design proposed a resistive network to generate the 3.3V. Figure 2 shows the proposed voltage divider circuit.

With the voltage divider circuit in place, the measured current output going to the RF chip did not exceed 14 mA. Referencing the RF chip datasheet, the peak current draw of the RF chip is 115 mA. It is immediately clear that the voltage divider circuit does not provide the proper current to the RF chip.

Therefore, the decision was made to replace the voltage divider with a voltage regulator which did allow for an appropriate current output to the RF chips.

2.2 Proximity Sensor Module

2.2.1 Design Procedure

The choice of sensors was a key part in the initial design because it is at the core of our system functionality. The design choice was between ultrasonic and infrared (IR) sensors because both could be useful as proximity detectors. The ultrasonic sensors were more expensive, but had a more reliable and larger range of detection. IR sensors were cheaper, but more limited in their detection range. Upon finding IR sensors with a range of 80 cm, it was determined that an 80 cm range was sufficient for the system. Therefore, the IR sensors were chosen because they were more cost-effective.

The design of the system contains a relay unit in order to best facilitate the switching of LEDs from the microcontroller units (MCU) based on the IR sensor outputs. The MCUs contain on-board analog-to-digital converters which allow us to convert the analog IR sensor output to digital input for the relays.

2.2.2 Design Details

2.2.2.1 IR Sensors

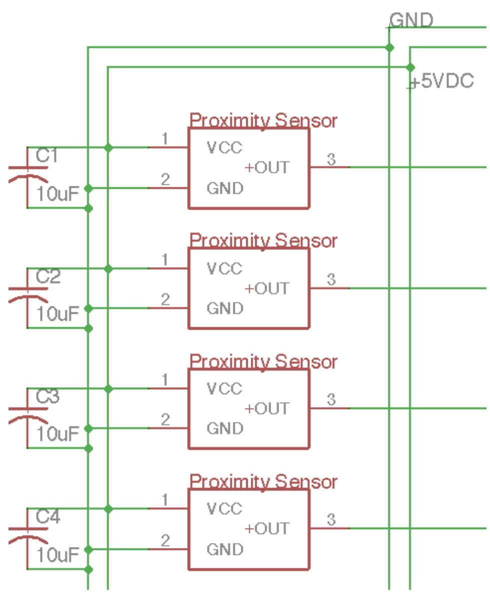

Figure 3: Proximity Sensor Schematic

The Sharp GP2Y0A21YK0F analog IR sensor was chosen as the proximity sensor in the system. A single IR sensor is placed at each parking spot in the system to monitor occupancy or vacancy and together, the multiple sensors make up the entire sensor network. The IR sensor is powered from 5Vdc, and its output is connected to one of the inputs of the SPDT relay.

Figure 3 shows the circuit schematic with all four proximity IR sensors. As a short note, decoupling capacitors were required between the power and ground lines of the IR sensors in order to reduce noise which could affect the sensor.

Table 1: IR Sensor Voltage Measurements

Distance	Voltage Output
5 cm	2.9 V
10 cm	2.1 V
40 cm	~0.5-0.6 V
80 cm	0.35 V
No blocking	25-45 mV

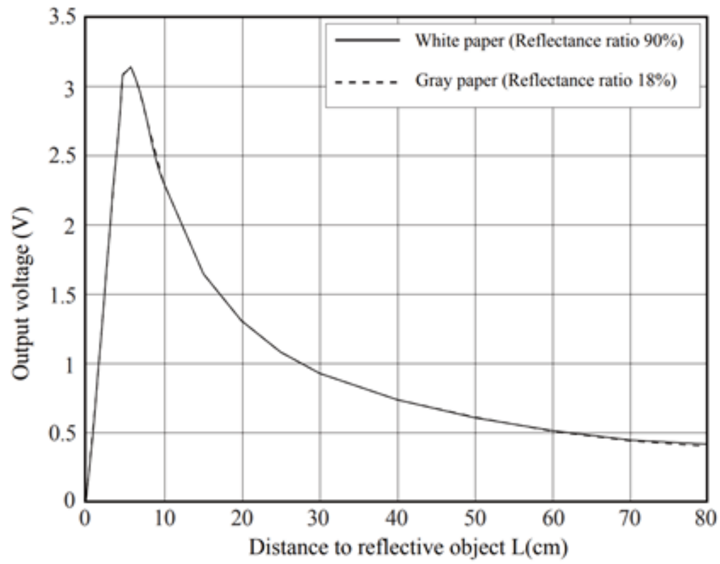

Figure 4: IR Sensor Voltage Characterization [9]

Figure 4 shows the IR characterization as taken from the sensor's datasheet. At the maximum distance required by our system (80 cm), the measured output voltage of the sensor was 0.35V. Due to these readings, a threshold of 0.25V was chosen as the switching point. Table 1 lists the measured output voltages at various other distances.

2.2.2.2 4-Channel Relay Module

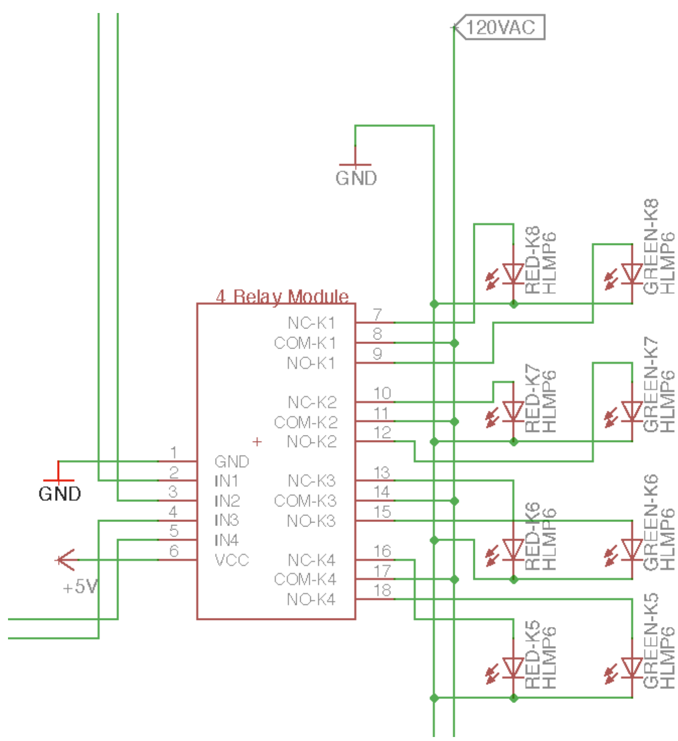

Figure 5: 4-Channel Relay Schematic

Figure 5 shows the 4-channel relay schematic. The relay module used in this project was part number B00KTEN3TM, which was a four channel relay, allowing us to control up to four parking spot LED pairs. The relay, in the normally open position, allowed 120VAC to the green LED and switched when its input was a digital 0 (indicating occupancy). When in the normally closed position, the relay allowed 120VAC to the red LED, meaning that only one of the LEDs would be on at a given time. Because the relay operated using mechanical switches, it was easy to verify the switching by listening to the sound of the switch moving.

2.3 LED Module

2.3.1 Design Procedure

LED bulbs powered by 120VAC were chosen to be the main visual display at each parking spot. These bulbs were chosen over small LEDs (powered at 5V) because of their brightness and visibility. The choice of a relay to control switching of the LEDs allowed us to have the most control over the LEDs using the MCUs.

2.3.2 Design Details

For each parking spot, there is a red and green LED which visually displays the status of parking space to approaching drivers. These LEDs are powered by the relay module which switches between the LEDs as directed by the MCU signals which change depending on the IR sensor readings.

2.4 Slave RF Transceiver Module

2.4.1 Design Procedure

In order to meet the high-level requirement for wireless transmission of data, the choice was made to use RF transceiver chips broadcasting at a frequency of 2.4GHz. The NRF24L01 chip was chosen because of its cost-effectiveness and long range transmission (1000+ meters line-of-sight). The processing of data and the analog-to-digital conversion (ADC) necessary in the system required the use of a microcontroller, which was chosen to be the ATMEGA328P chip, a popular microcontroller chosen for its robustness and compatibility with existing Arduino hardware and libraries.

The slave transceiver modules are associated with multiple parking spots, so that the transmission consists of a binary array with data from each parking spot.

2.4.2 Design Details

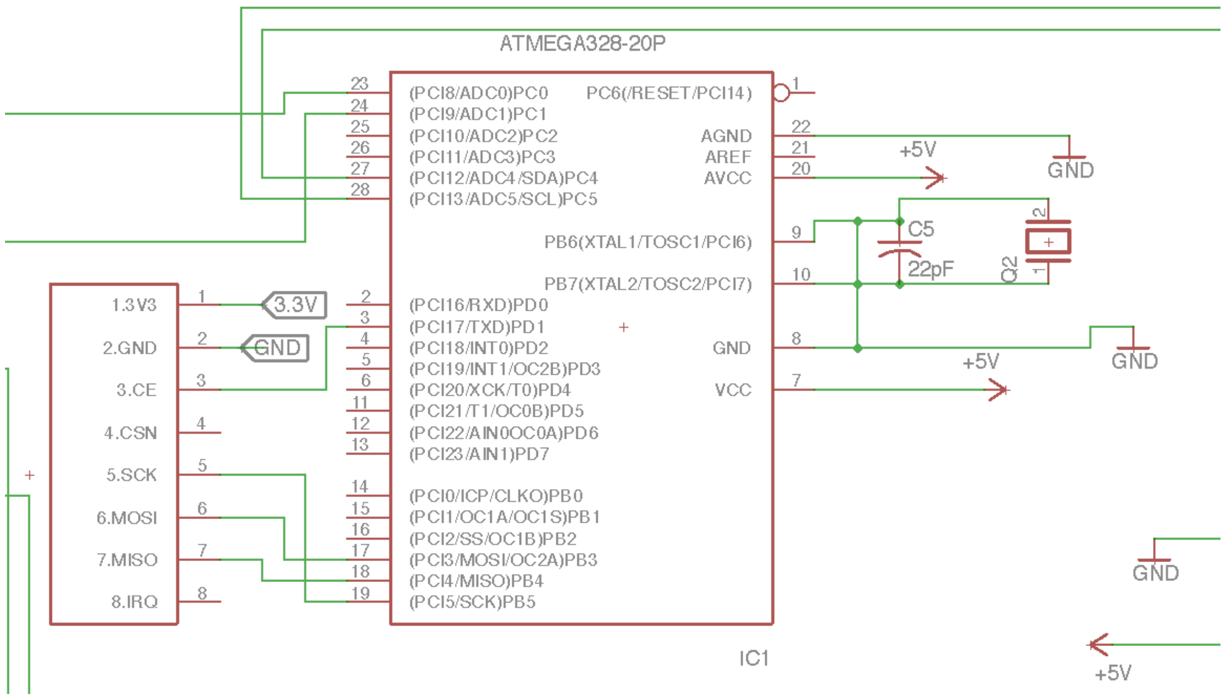

Figure 6: Slave/Master RF Module Circuit Schematic

The connection of the RF chips and the MCU is shown in Figure 6. One major design aspect of the slave RF system was implementing a proper RF protocol for the slaves to follow. A simple polling scheme was created that the master (explained further below) and slave transceiver modules would follow. The slave waits for permission to be received from the master before transmitting. After receiving permission, the slave transmits its data to the master and loops back again to wait for permission. While it is a simple protocol, a fair amount of testing was required to smooth the timing between master and slaves.

As with the IR sensors, decoupling capacitors were placed between the 3.3V power lines and ground to the RF chips.

2.5 Master RF Transceiver Module

2.5.1 Design Procedure

The design procedure for the master RF transceiver module was almost exactly similar to the design procedure for the slave RF transceiver as use of the same RF chip was desired. The only difference in the master transceiver was in the implementation of RF protocol, which is explained in the next section.

2.5.2 Design Details

The connection of the RF chips and the MCU is shown in Figure 6. A simple polling scheme was implemented for the master which is illustrated in the FSM shown in Figure 7.

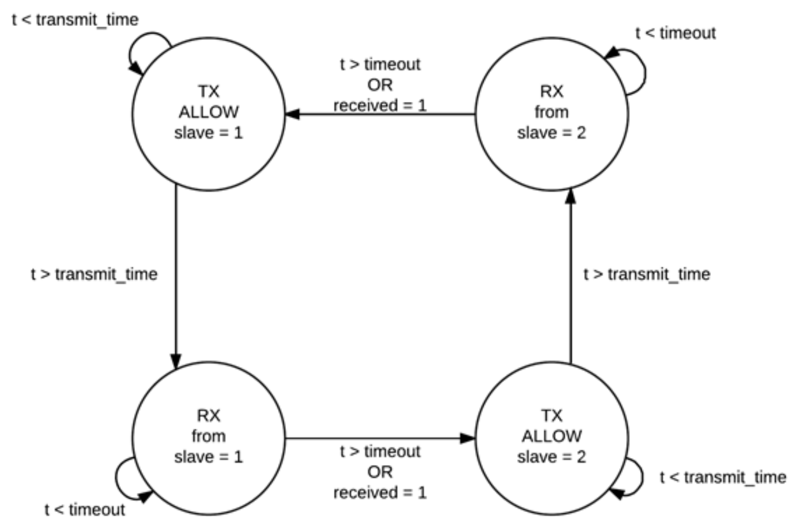

Figure 7: Polling Scheme FSM

The polling scheme works as follows: the master transmits permission to slave 1, slave 1 responds with data, master receives the data and then repeats for as many slaves in the system (for our project, there were two slaves). This solves the potential issue of having multiple slaves transmitting on the same frequency which can lead to dropped packets and data loss. As long as the master only allows one slave to transmit at a time, it should theoretically be able to avoid any data loss.

As with the IR sensors, decoupling capacitors were placed between the 3.3V power lines and ground to the RF chips.

2.6 Central Data Collection Module

2.6.1 Design Procedure

The Central Data Collection Module includes the Master MCU and the LCD. The purpose of the central hub is to aggregate the data sent from the slaves and display it through the LCD. In our project, we are using this data to display the number of open spots onto the LCD. The communication to the LCD is done using the LiquidCrystal Arduino library. This data could also be displayed through other mediums, e.g. a smartphone app. For the purposes of this project, it was suggested to skip the more complex software part and focus on hardware instead. But the implications of such an application certainly appear useful, as it would be nice to drive into a parking lot and use your phone to find the nearest vacant spot.

2.6.2 Design Details

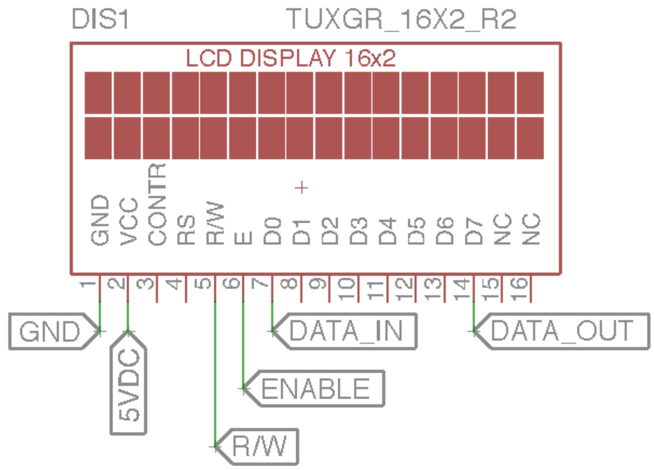

Figure 8: LCD Schematic

The schematic of the LCD is shown above in Figure 8. The design of the central hub is rather straightforward. There are only three major components that make up the master PCB: MCU, RF transceiver, and LCD. The RF transceiver is responsible for the smooth transfer of information between slaves and master. The MCU receives the data from the slaves using the RF transceiver and then uses this data to display the number of vacant spots onto the LCD.

2.7 Block Diagram

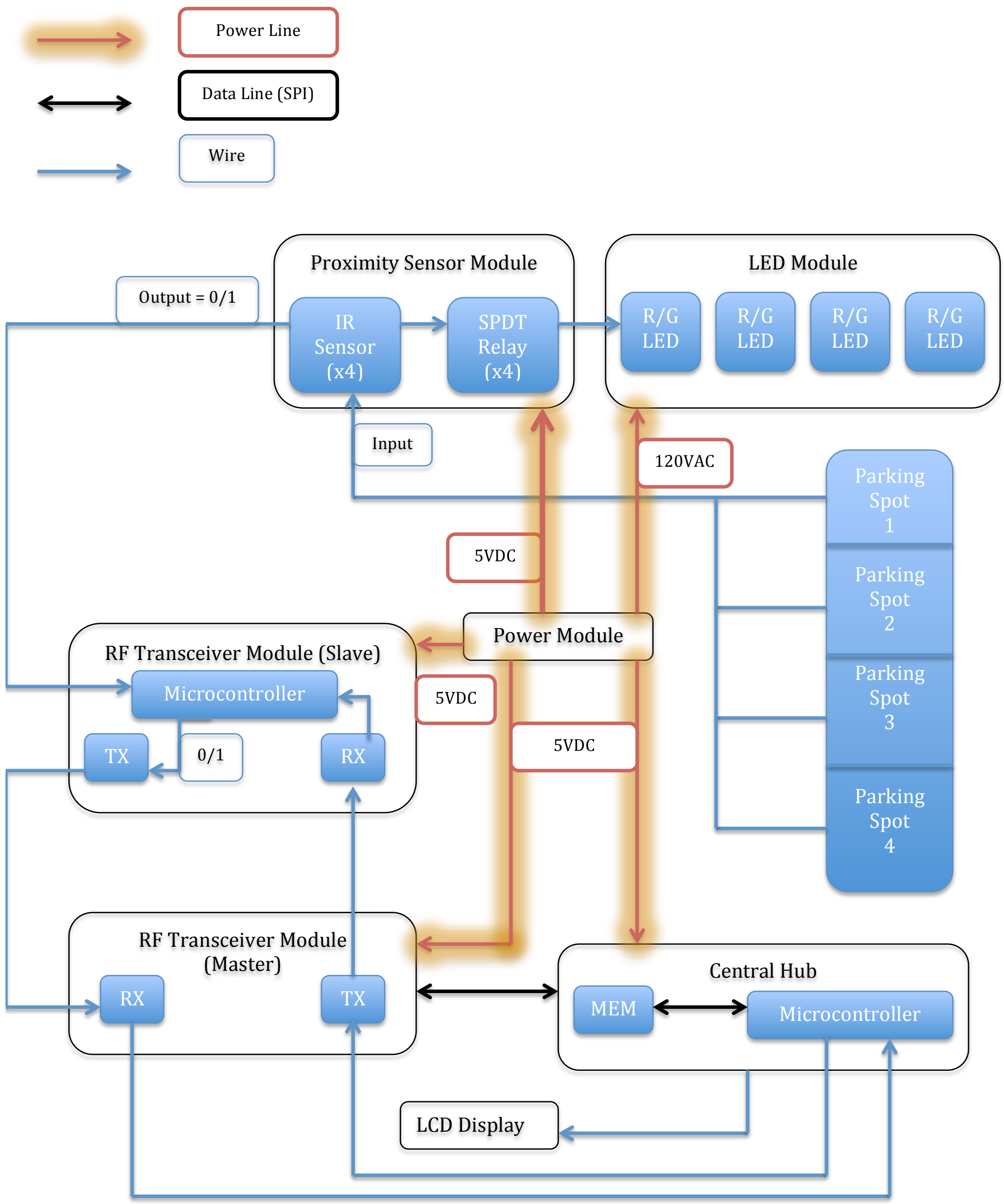

Figure 9: Overall Block Diagram

3. Design Verification

3.1 Power Supply

The power supply module is used to provide three different voltage levels: 120VAC, 3.3VDC and 5VDC. The 5V is supplied to the Proximity Modules, LCD, and RF transceiver module. The 3.3V is supplied to the RF transceiver chip in the RF module. Finally, 120VAC is used to power the LED bulbs. All of these voltage levels were verified using standard lab equipment (i.e. multimeter). We measured all 5V and 120 VAC to be accurate but the 3.3V was not steady. 3.3V (created using resistive network) is applied to the RF transceiver chip and when we measured the voltage, it came out to be around 2.37V which is outside of the RF operating range. This was due to the fact that we were using a resistive network to generate the 3.3V, but the RF chip has its own resistance that when connected to the resistive network changed the resistor ratios and thus caused the undesirable voltage drop. We solved this problem by using a 3.3V regulator that ensures steady 3.3V across it output terminals. We measured this voltage to be 3.3V and this completed our verification for power supply module.

3.2 Proximity Sensor Module

3.2.1 IR Sensors

The IR sensors are supplied with 5V input and they output a voltage relative to their detection distance. First, we needed to find the minimum voltage that the IR sensor will output when the vehicle is in 80 cm detection range. We measured the 80 cm voltage at ~0.25V and the 10 cm voltage at 3V. We verified this in the lab with a meter stick as well as by parking a vehicle at both marks (10 cm and 80 cm) and verifying the voltage is within 0.25V to 3V.

3.2.2 4-Channel Relay Module

The relays are electrically controlled mechanical contacts. A relay has a coil that is de-energized in its normally open (NO) state. It needs a digital 0 to energize the coil and 1 to de-energize it. We verified this by using 5VDC from the power supply module as an input to the relay and verified it stayed in its normal state (i.e. NO). Next, we used the GND terminal from the power supply module as an input to the relay and verified that it energized the coil to its normally closed state.

3.3 LED Module

LED bulbs are mounted such that they are visible from a distance of 1m or more. We verified this visually. Another requirement is the correct switching of the LED bulbs given the correct relay input. We verified that the green LED is on when the input is digital 1 and the red LED is on when the input is digital 0. Another requirement is that only one light is turned on at any given time. This is verified by the normal operation of the relay since relays can only be in Normally Open(NO) position or Normally Closed(NC) position. It is physically impossible for both positions to be on.

3.4 Slave/Master RF Transceiver Module

3.4.1 Microcontroller

The Slave microcontroller is responsible for using the inputs from the IR sensors and converting them into digital 0s and 1s. 1 means occupied and 0 means vacant. One of the requirements is that the microcontroller should be able to do analog to digital conversion of the IR sensors input. We verified this in two ways. One way is that we used the microcontroller to monitor the data it receives and serial print it using UART. Another way we verified that is to observe the data using an oscilloscope and see it in the time domain. The results matched exactly with what was received by the microcontroller. Next requirement is that the slave microcontroller should only transmit when polled by the master. We verified this by setting a variable to a value of 1, then 0. We used if-else conditionals to switch between the two values the variable can take. We defined 1 to mean the slave MCU is allowed and 0 to mean it is not allowed. We used this convention to print the data on the serial monitor only when the variable is set to 1. We observed similar behavior using an oscilloscope.

3.4.2 RF Transceiver Chip

The RF transceiver chip is used as a medium for the wireless communication between the slave and master PCBs. We used single channel communication, which means that both the slaves and master are communicating on the same frequency. We used 2.4GHz as the frequency to transfer data and verified this by enclosing the RF transceiver in a Faraday cage and using the spectrum analyzer to observe the RF pattern. We saw only one peak at 2.4GHz which verifies our requirement that data is only transferred at 2.4GHz. Another requirement of the RF transceiver chip is that the input voltage to the chip needs to be 3.3V (+/- 0.3V), which is the recommended operating voltage of the chip. Initially, we used a resistive network to generate 3.3V and this verification failed. The output was measured at 2.47V using a multimeter, which is too low for the RF transceiver chip to work properly. We solved this problem using a 3.3V voltage regulator and verified that the output is a steady 3.3V using a multimeter.

3.5 Central Data Collection Module

3.5.1 Microcontroller

There are three requirements that needed to be verified for the microcontroller in the master unit. One is that the master MCU needs to store the data received from slaves in the onboard memory. We used the onboard flash memory space of 32 KB. We verified this by generating a test signal in a form of string of 1s and 0s. We stored this message in the onboard memory and then retrieved the same message from the memory.

Another requirement is that the master MCU needs to generate the polling sequence for the two slaves to make sure that both the slaves are not communicating at same time. We verified this by generating a test signal that alternates between 0 and 1 every five seconds. Slave 1 was allowed to transmit for five seconds and then slave 2 was allowed for the next 5 seconds, etc. We observed this pattern using both the serial monitor by connecting the MCU to an Arduino and by connecting the RF chip to an oscilloscope.

The last requirement is that the master is continuously updating the data displayed on the LCD. We verified this by displaying the actual data received from the slaves which we can change by blocking the IR sensors. The data was then verified visually on the LCD.

3.6 LCD Display Module

The LCD is used in this project to display the number of spots open on each floor. For simplicity purposes, we designed this project for 2 floors so we used a 16x2 LCD. Each row will display the words "Floor 1: X" and "Floor 2: X" where X represents the number of vacant spots. This was verified visually and we used the built in Arduino library to echo this information onto the LCD.

4. Costs

4.1 Parts

Table 2: Parts Costs

Description	Part No	Manufacturer	Quantity	Cost/unit	Total Cost
IR Analog Distance Sensor	GP2Y0A21YK0F	Sharp	4	$9.00	$36.00
Green LED Bulb 1W	PLT LED-A19-GREEN	PLT	4	$2.44	$9.76
RED LED Bulb 1W	PLT LED-A19-RED	PLT	4	$2.44	$9.76
Lamp Holder (Home Depot)	100356849	Leviton	8	$1.33	$10.64
Wireless Transceiver Module 2.4GHz	B06WLH4ZG6	Longruner	1 (Pack of 3)	$13.99	$13.99
4 Channel 5V Relay Module	B00KTEN3TM	JBtek	1	$6.99	$6.99
Atmega328p-pu Chip	B01263IMU8	Atmel	4	$4.12	$16.48
Standard 16x2 Character LCD Display	HC1624	Tsingtek	1	$3.90	$3.90
Misc. Caps, Resistors, Regulators	N/A	N/A	N/A	N/A	$10.00
Total				**N/A**	**117.52**

4.2 Labor

We assume our hourly salary to be $40/hour and 10 hours per week for each group member.

$$total = 3 \times \frac{\$40}{hr} \times \frac{10\ hr}{week} \times 16\ weeks * 2.5$$

$$total = \$48{,}000$$

5. Conclusion

5.1 Accomplishments

This project was, for the most part, successful. All the modules worked independently and also as a system. There were two testing scenarios that we had for our project. We tested it in the lab and the whole project worked as expected. The other scenario was to test the project in an actual parking lot, which offered significant challenges. We did the testing in an actual parking lot and the LED bulbs were operating correctly. However, the RF communication was not reliable, due to issues discussed in the next section. Overall, we can say that we did prove the concept by having a successful project in the lab environment. However, it is clear that further improvements must be made in order to implement the project in a real-world scenario.

5.2 Uncertainties

As mentioned above, our group encountered some difficulties when attempting to implement the system in a real parking garage. The main issue was the unreliability of the RF transmission between master and slaves. Environmental hazards, such as rain and wind, led to the damage of power lines on the PCBs. This was verified in lab by connecting the entire system to an ammeter, which showed a total current draw of 450-500 mA. Our previous measurements in the lab of our fully-=functioning system had a current draw of about 700 mA. This proved to us that the power connections had been damaged on the PCB and that a broken connection was leading to reduced current draw, most likely to the transceiver chips.

Other potential uncertainties with the project stem from concerns with the hardware. As we discovered, it is necessary to have proper housing for the PCBs and IR sensors in order to reduce potential damage to the circuits and to reduce ambient light interference with the IR sensors. Shadows and other ambient light frequently caused “glitches” in our switching.

5.3 Ethical considerations

We did not encounter any major ethical concerns with this project. A detailed reading of the IEEE Code of Ethics [7] reveals we need to ensure we meet code #1 considering the safety of the public. This code was satisfied by minimizing the exposure a user has to dangerous voltages, and only allowing our system to be put into operation if it presents no physical hazards that have not already been accounted for. Any design flaw in our project that could present a danger would be immediately disclosed to any affecting parties (though we do not know of any such flaws). Similarly, reading over the ACM Code of Ethics [8], we need to ensure we meet code 1.2 which states to avoid harm to others. This was ensured by using the same methods to meet the IEEE code, guaranteeing safety to the public (and ourselves) at all costs. We can gladly state we did not have any further ethical or safety concerns throughout the project and have met all aforementioned ethical requirements.

5.4 Future work

A large portion of the design space for this system is yet to be explored in detail. For a real-world application, it is necessary to expand the sensor network. In this project, we worked with two parking spots per floor for a total of four parking spots. This was enough to prove the concept, but actual implementations would require support for a large number of spots. We also need to improve reliability with the RF transmission. The RF transmission failed due to the issues discussed earlier in this report and we found that one solution would be to have more reliable power lines. This could be done by using a power jack that ensures strong VDD and GND connections.

The data transmission protocol could also be further optimized, since with many parking spots, there would be a large amount of data being transmitted over the same channel. One way to solve this problem is by using different channels for different floors or to design a more sophisticated polling scheme to receive data from each parking spot in a sequence. Finally, future work could improve IR sensor reliability by using a case to shield against ambient light and prevent “glitches” in the switching of LEDs.

References

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Appendix A Requirements and Verification Table

Table 3: Power Supply - Requirements and Verification

Requirements	Verification	Verification Status (Y/N)
1. Must provide between 4.5-5.5 V to the slave and master RF transceiver modules and the central data collection modules	a. Measure open-circuit voltage output to central data collection module with a multimeter, ensuring that it is below 5.50 V b. Measure open-circuit voltage output to central data collection module with a multimeter, ensuring that it is above 4.50 V c. Add resistive load at output of power supply to central data collection module such that the voltage supplied to the microcontroller falls in range 4.50-5.50 V d. Repeat steps a-c for the slave RF transceiver module and the master RF transceiver module	Y
2. Must provide voltage of between 4.5-5.5V to the IR sensors in the proximity sensor modules	a. Measure open-circuit voltage output to proximity sensor module with a multimeter, ensuring that it is below 5.50 V b. Measure open-circuit voltage output to proximity sensor module with a multimeter, ensuring it is above 4.5 V c. Add resistive load at output to proximity sensor module such that the voltage supplied to the sensors falls in range 4.50-5.50 V.	Y
3. Must provide voltage of 120VAC (+/-5V) to the LED module	a. Measure open-circuit voltage output to the LED module with a multimeter, ensuring that it is 120VAC	Y

4. Must provide between 4.5-5.5 V to the LCD display module	a. Measure open-circuit voltage output to central data collection module with a multimeter, ensuring that it is below 5.50 V b. Measure open-circuit voltage output to central data collection module with a multimeter, ensuring that it is above 4.50 V c. Add resistive load at output of power supply to central data collection module such that the voltage supplied to the microcontroller falls in range 4.50-5.50 V.	Y

Table 4: Proximity Sensor - Requirements and Verification

Requirements	Verification	Verification Status (Y/N)
1. Must provide analog voltage output of >0.25V when vehicle is in detection radius of 80 cm.	a. Move vehicle into detection radius (within 80 cm) b. Verify that the voltage output of the IR sensor is greater than 0.25 V using a voltmeter.	Y
2. Must provide analog output of <0.25V when vehicle is not within detection radius of 80 cm.	a. Move vehicle outside of detection radius (>80 cm) b. Verify that the voltage output of the IR sensor is less than 0.25 V using a voltmeter.	Y

Table 5: 4-Channel Relay- Requirements and Verification

Requirements	Verification	Verification Status (Y/N)
1. Input must be a digital 0 to energize the coil and switch to the normally open position.	a. Apply digital 0 to relay input and use multimeter to verify continuity between N0 and COM relay terminals.	Y

2. Input must be a digital 1 to de-energize the coil and switch to normally closed position.	a. Apply digital 1 to relay input and use multimeter to verify continuity between NC and COM relay terminals.	Y
3. Relay will be supplied with 50 - 60 mA of input current to sufficiently energize the coil.	a. Apply digital 1 to relay input and use multimeter to verify 50 - 60 mA of input current.	Y

Table 6: LED - Requirements and Verification

Requirements	Verification	Verification Status (Y/N)
1. LEDs must be visible from a distance of 1m when on.	a. Provide 120VAC to LED b. Measure 1m distance from the LED c. Ensure that LED is clearly visible from viewer’s position	Y
2. Must display RED LED when connected 4 channel relay is in the normally closed position (digital 0 - analog 0V)	a. Force relay to the normally closed position b. Visually ensure that the GREEN LED is on	Y
3. Must display GREEN LED when the connected 4 channel relay is in the normally open position (digital 1 - analog 5V)	a. Force relay to the normally open position b. Visually ensure that the RED LED is on	Y
4. Must not have more than one LED in a pair visibly on at the same time	a. Toggle relay between the normally closed and normally open positions b. Visually ensure that both LEDs are not on together	Y

Table 7: Slave MCU - Requirements and Verification

Requirements	Verification	Verification Status (Y/N)
1. Must create a message containing the data from proximity sensors formatted in a binary array for transmission	a. Program microcontroller to output a message containing a series of 0s and 1s. b. Measure voltage signal in time domain at the output of the microcontroller to the transceiver to view signal on oscilloscope. c. Ensure that this signal is identical to the programmed signal of the microcontroller.	Y
2. Must transmit data message only when polled by the master RF unit (provided permission from RF to start transmitting)	a. Program microcontroller with an if-else conditional based on a set variable to emulate receiving permission from the master RF unit b. Verify that a voltage signal output from the microcontroller (using oscilloscope) is only generated when the variable is set to 1 (emulating that permission has been granted).	Y
3. Must convert the analog voltage output of the IR sensors to a digital equivalent (<0.25 is equivalent to 0, >0.25 is equivalent to a digital 1)	a. Apply voltage of 0V to the ADC pins of the microcontroller b. Measure corresponding digital output signal of the microcontroller using a multimeter, ensuring that it corresponds to a digital 0 c. Apply voltage of 2V to the ADC pins of the microcontroller d. Measure corresponding digital output signal of the microcontroller using a multimeter, ensuring that it corresponds to a digital 1	Y

Table 8: Slave/Master RF Transceiver - Requirements and Verification

Requirements	Verification	Verification Status (Y/N)
1. Must be able to transmit messages at 2.4GHz at 250 kbps	a. Generate a test message in the microcontroller for transmission and transmit this message using the transceiver b. Measure the transmitted RF signal using an oscilloscope/spectrum analyzer listening on 2.4GHz frequency, ensuring that the transmission received is identical to the generated message. c. Verify that the speed is 250 kbps (+/-5%)	Y
2. Must be able to receive messages sent at 2.4GHz at 250 kbps	a. Generate an RF signal at 2.4 GHz using an RF signal generator b. Measure the received RF signal at the transceiver using an oscilloscope, ensuring that the transmission received is identical to the generated message.	Y
3. Must operate at 3.3VDC	a. Measure open-circuit voltage output from resistive network using multimeter, ensuring that it is at 3.3V	N

Table 9: Master MCU - Requirements and Verification

Requirements	Verification	Verification Status (Y/N)
1. Must store aggregated data from master RF transceiver module in onboard memory.	a. Use function generator to emulate a data signal transmitted from master RF transceiver module to the microcontroller (binary array of 0s and 1s). b. View the stored data in memory to ensure	Y

	that the data matches the generated signal data	
2. Must generate a periodic polling sequence for the master RF transceiver to poll the slave units, switching between slave IDs every second.	a. Program microcontroller to generate periodic polling sequence b. View output signal of microcontroller to the master RF transceiver (via oscilloscope) and verify that the message contents are rotating periodically each second (with a timer) between different slave RF ids	Y
3. Must continuously output parking space data stored in memory to the LCD display via SPI	a. Program microcontroller to output a set of data to the LCD display b. Verify on LCD display that the data is correctly output continuously	Y
4. On-board memory must have at least 1KB of storage space for collecting data.	a. Fill 1KB of memory with verifiable, documented data b. Read data back and echo to UART terminal and ensure that data matches completely.	Y

Table 10: LCD - Requirements and Verification

Requirements	Verification	Verification Status (Y/N)
1. Must display the number of vacant spots on each level of the parking lot	a. Program microcontroller to output a set of data to the LCD display that indicates completely occupied b. Verify on LCD display that the data is correctly output as 0 vacant spots c. Program microcontroller to output a set of data to the LCD display that indicates	Y

	completely vacant d. Verify on LCD display that the data is correctly output as all vacant spots e. Program microcontroller to output a set of data to the LCD display that indicates half vacant f. Verify on LCD display that the data is correctly output as half vacant spots	