AUTOMATIC DOG DOOR

By

Nicholas Cain

Ryan Prodoehl

Kamil Zabawa

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TA: Yuchen He

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Abstract

Our senior design project was focused on constructing an automatic dog door. Standard rubber dog doors offer no form of locking mechanism, meaning the dog can leave when it desires and poses security threats to the homeowner. We used a similar mechanical set-up to standard dog doors, but applied a locking system that will keep is secure from burglars and unwanted animals when not in use. The “automated” part of this door is through the locking mechanism which is triggered through a RFID tag on a dog’s collar. The door will immediately lock following the use of it by the dog. The system also allows for user customization on what conditions they find acceptable for their dog to go outside in (weather/time of day).

Contents

1. Introduction

1.1 Objective

In the U.S., approximately 44% of all households own a dog [1] - with dogs comes responsibilities, such as having to get up from the couch after a long day of work to let the dog out as it needs. We believe we can provide comfort and ease to the typical american household by having an automatic doggy door that opens when the dog approaches the door so the owner does not have to worry about getting up. Our solution will also allow for dogs to use the door even if the owner is not home while minimizing security risks.

1.2 Background

Most household owners that own a dog and a backyard can get annoyed with having to get up constantly to let their dog out. Another common issue is the dog not going out enough during the day due to the owner being stuck at work. The current solution to both of these problems is the use of a rubber door that the dog can use at free will. The main issue with using a rubber dog door is that burglars are more than welcome to crawl through the space [2]. This poses serious safety concerns to dog owners and results in them not purchasing a dog door.

Our solution of an electronic automatic doggy door can tackle both these problems at once while also providing additional features for user customizability. Upon an owner's configuration, a dog would be able to use this automatic door while keeping security under control through the use of an RFID chip in the dog's collar to ensure door use is restricted to the dog only. There already exists some on the market [3], but most are expensive and use ultrasonic sensor technology. Our solution uses different technology (RFID and IR), remains cheap, and also includes an application to provide the owner fuller customization.

1.3 High-Level Requirements

1. Door unlocks <u>only</u> when a dog is approaching within a meter, based on RFID and IR sensors, and locks within 3 seconds of dog leaving.
2. Door remains locked if dog attempts to use the door outside the bounds of the user's customization (weather and time). If the dog is outside when the door is locked due to user's settings, the door should unlock and allow the dog back in but not vice versa.

2 Design

The foundation for our new design utilizes a wooden doggy door and frame. It is modelled off the 'flap' style of dog doors that use a rubber flap that the dog can go through. The actual circuit design is powered by a 120V wall outlet, which is transformed to 12V DC using a power adapter. This 12V is connected to a relay controlling a magnetic locking mechanism for the door. This power adapter is down regulated to 5V to power the sensors, the microcontroller, and the RFID reader. It will also be down regulated to 3.3V to power our Wifi module. The sensors send analog data to our microcontroller that tells of the weather conditions, and whether the dog is entering or leaving the house. The RFID reader sends a digital signal to the controller telling whether or not the tag on the dog's collar is nearby, and therefore where or not the door should be unlocked. The microcontroller also communicates with the Wifi module which, allowing it to read from a server where user settings are stored, such as whether or not to let the door open during rain, completely lock the door, etc. Finally, the microcontroller sends out a 5V output to a relay to control the locking mechanism on the system.

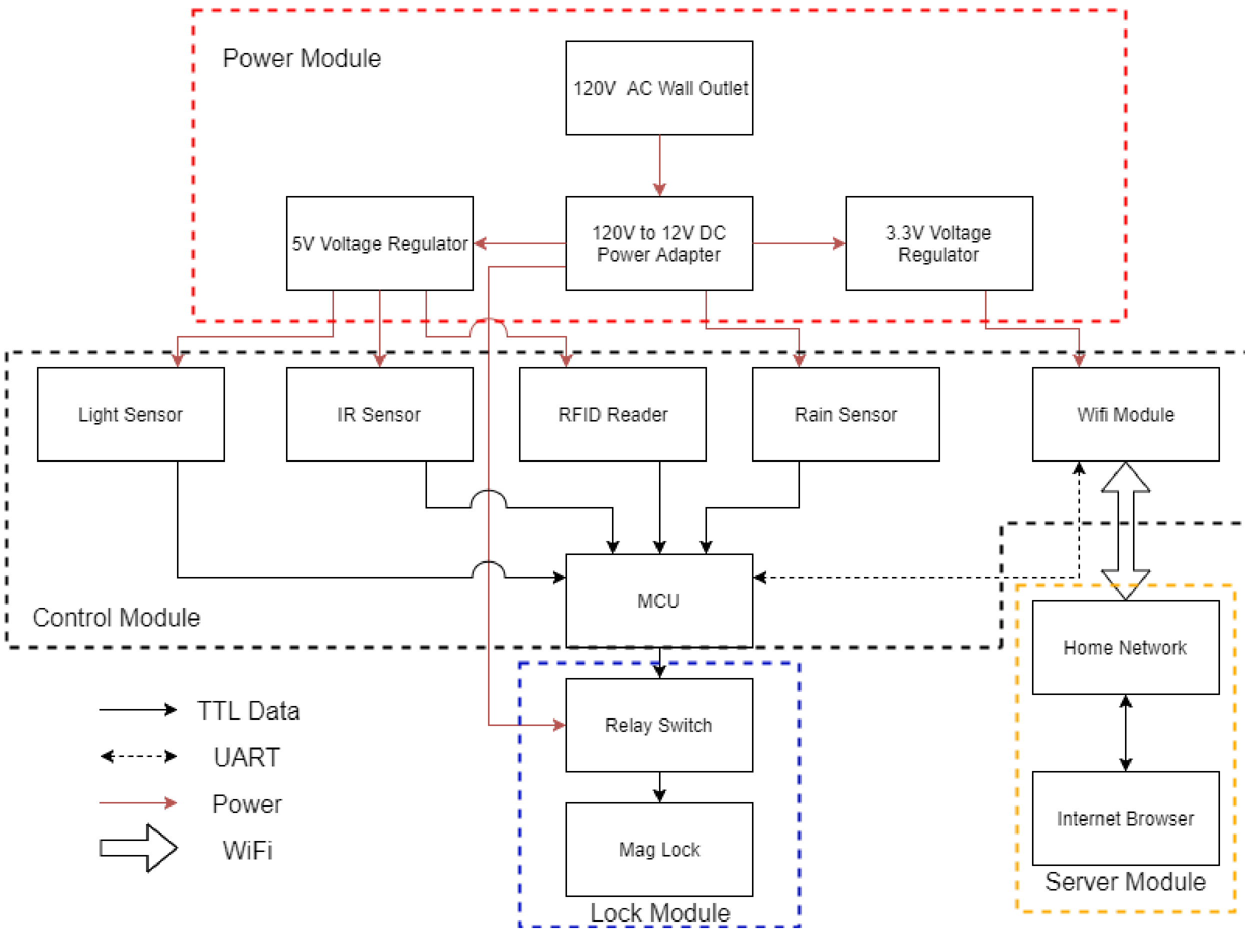


Figure 1: Block diagram of system architecture

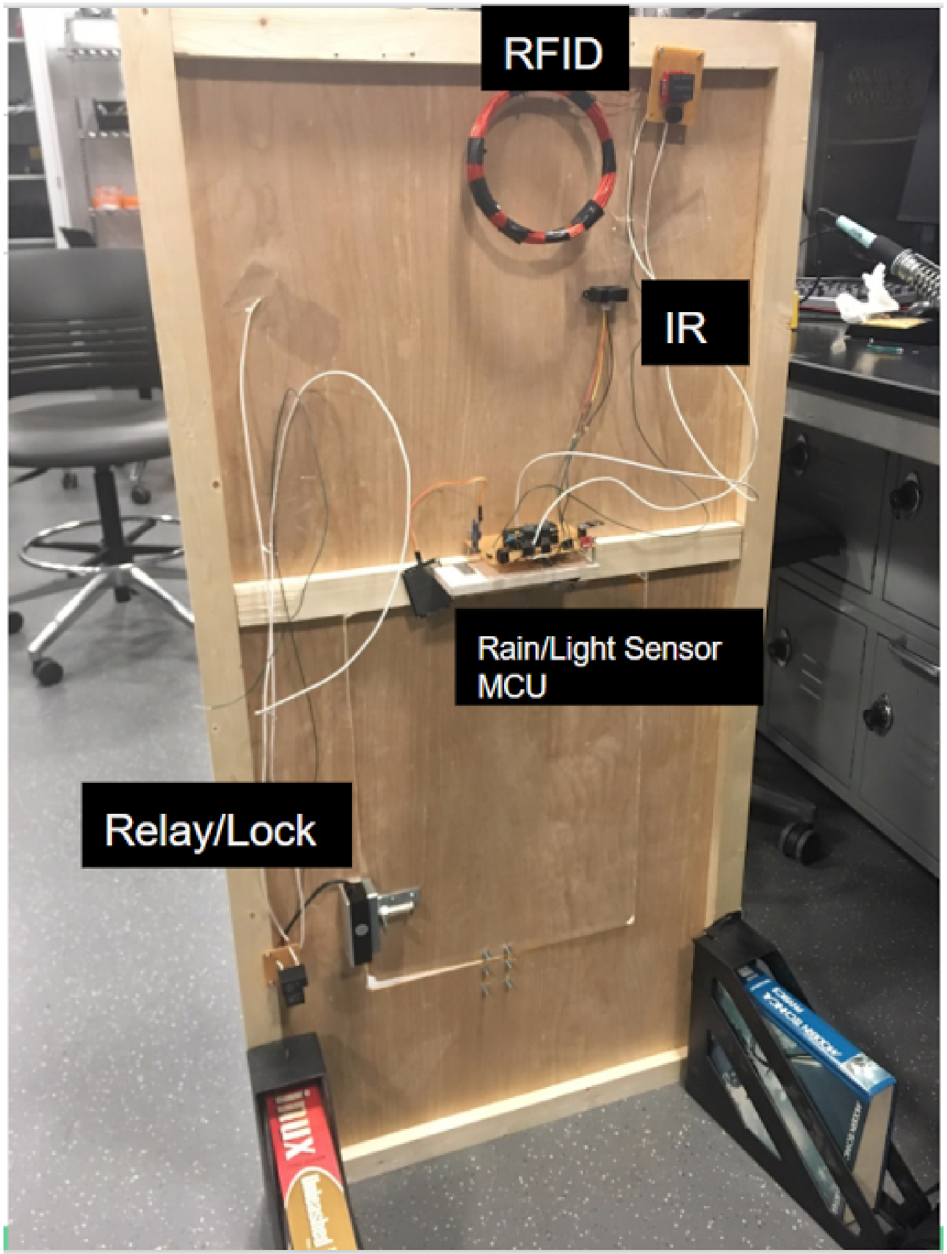


Figure 2: Finished dog door system with sensors, main control unit, and lock mechanism labelled

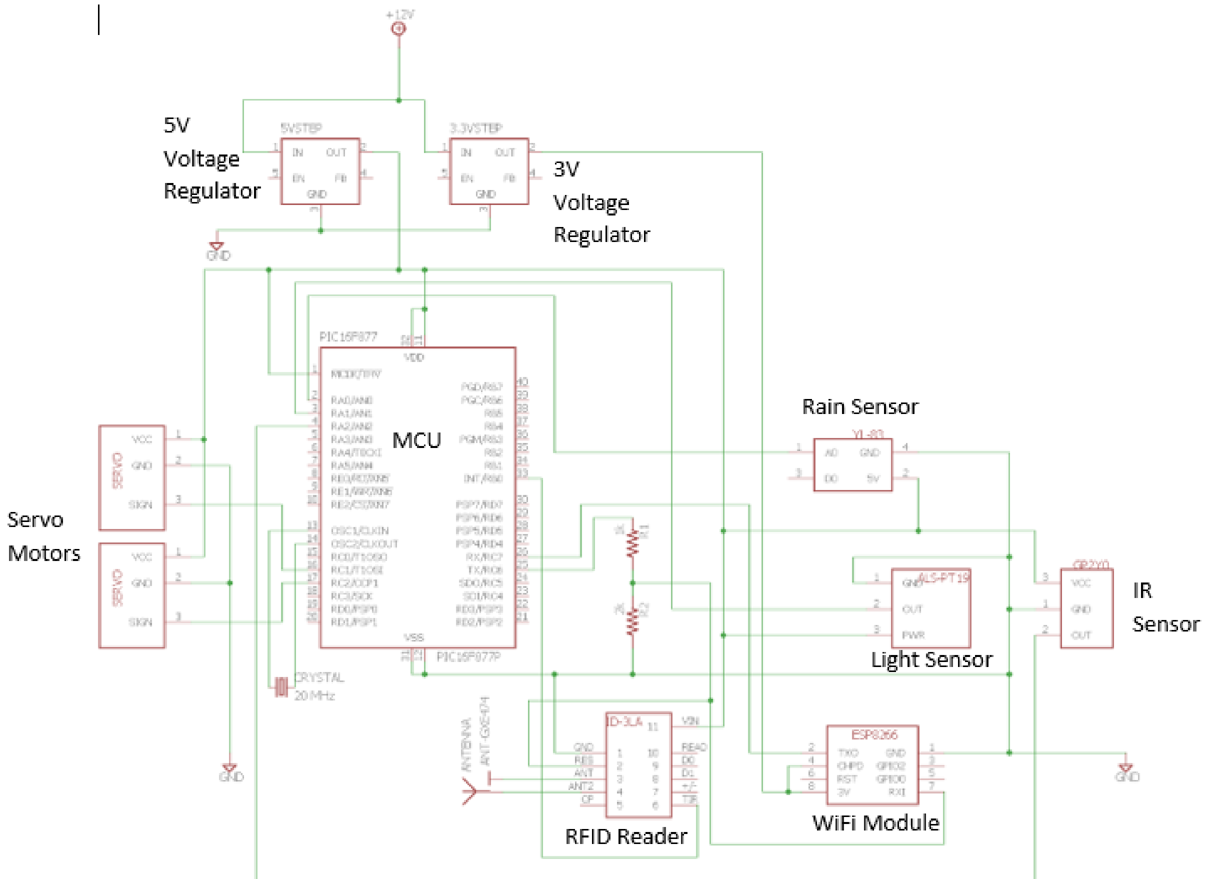


Figure 3: Full circuit schematic with individual sensors and parts labelled

2.1 Power Supply

Powering the system is handled by a ADP-12V2A AC to DC power supply that plugs into a wall outlet. This is a high-quality, well-reviewed adapter, mitigating any risk of electrocution.

2.1.1 Voltage Regulators

Since our components in the circuit operate at differing voltage levels, we use two voltage regulators to step down from the 12V adapter. A LD1117V33 is used to step down to 3.3V and a L7805 is used to step down to 5V.

2.2 Sensors

Our system uses a set of several different sensors in tandem to determine whether or not the door should be allowed open. All sensor schematics can be found in Appendix B.

2.2.1 Rain Sensor

A rain sensor is utilized to detect basic weather conditions outdoors. Our rain sensor is the YL-83 rain detector, which has a supply voltage of 3.3VDC ± 10% [5]. It provides an analog output from 0.75-3 volts based on how wet the module is. This analog value is sent to the microcontroller, where it is then converted to a digital value by the microcontrollers analog to digital converter module. From there, the microcontroller can sense if it is raining, and use the user settings found in the WiFi module to determine if the door should become unlocked when a tag is in range.

2.2.2 Light Sensor

A light sensor is used in our design to determine if it is day or night, which the user can then specify if they want the door to open during nighttime hours through the user application. The sensor used will be the ALS-PT19 Analog Light Sensor. It requires a supply voltage of 2.5-5.5 volts. It provides an analog output from 0-5 volts based on surrounding illuminance [6].

2.2.3 IR Sensor

A key concern is an owner's pet being locked outside, regardless if the tag is in range, if the dog is already outside when the door switches to a lockout state. An IR sensor is utilized outside on the dog door, facing one's backyard. If the tag is in range, and the IR sensor picks up that the dog is on the outside, it will override any locking conditions, and allow the door to open. This helps ensure the safety of the animal, and ease of mind for the owner. The sensor used is the Sharp GP2Y0A41SK0F. It requires a supply voltage between 4.5-5.5 volts. It provides an analog output of 0-3 volts, dependant on distance from sensor to object [7].

2.3 RFID

2.3.1 RFID Reader

The RFID reader we chose for our design is the ID-3LA. It uses an IC design, and needs an external antenna for tag detection. We chose this IC for two main reasons: it is one of the lowest cost RFID readers on the market, and the use of an external antenna allowed us to create an antenna that is larger than IC package itself, giving us a much higher tag detection range than the other models in the line. By choosing this route, we were able to get a detection range of 8 inches, or approximately 20 centimeters. Whereas many other RFID readers only use data lines to communicate the value stored on the RFID tag, this reader also features a TTL data output that is active high when a tag is in range. This allowed us to simplify our control logic for the design, while also leaving room for us to utilize the data transmission in future designs to track which dog is going outside if a family has multiple pets, and offer greater security.

2.3.2 RFID Antenna

The antenna attached to the RFID reader is continuously transmitting a signal at a frequency determined by the antenna's reactance. The tag on the dog's collar has a LC circuit embedded within that needs to be tuned to the same frequency as the transmitter. If the antenna signal is propagating at the resonant frequency of the tag, an effect of electromagnetic induction undergoes which sends the data of the tag back to the antenna and thus the reader. This allows us to know if the dog is near the door or out of range - the distance and effectiveness of our reader is directly related to the antenna we construct. Our antenna needs an inductance value that will provide the same resonant frequency in the reader circuit as the resonant frequency embedded in the tag.

The equations found in Appendix C.1 model the inductive reactance and capacitive reactance in general. Our chosen RFID reader has a built in 1n2 (.0012 μF) capacitor that is used to help tune to a frequency the resonant frequency of 125 kHz. The antenna effectively acts as an inductor, and when the capacitive inductance is equal to the inductive reactance, our system will be operating at resonant frequency. Simply setting the equations equal to one another and plugging in 125 kHz into for our frequency value and 1n2 for our capacitance, the inductance can be solved for which is 1.333 mH.

There were a variety of ways to go about reaching an inductance of this value. The equation for the inductance of an air-core inductor can be seen in Appendix C.2. We manually wrapped two inductors (Appendix C.3) with different radii to see the differences in inductance. The first, and most optimal creation, was a circular inductor with a diameter of 5 inches. The second, was a square wrap with a 3 inch diameter. We used an oscilloscope and LC circuit configuration to measure the phase difference between the built inductor and an off the shelf capacitor, and this phase difference was plugged into a series of polar equations provided by Tektronix to deduce the inductance value [8]. These values were then reconfirmed with an old LRC meter in the lab. The circular wrap provided 1.55 mH while the square was at 800 mH. The built-in capacitor helped tune these values, and since the circular wrap was closer to the ideal value of 1.33 mH, it provided a further range than the square while also using a smaller amount of turns. The measured distance was 9 inches when powered through a 5V generator, but when attached to our circuit it only provided around 6 inches of distance due to the voltage regulator dipping in output. Overall, both of these inductors worked for our desired needs, and a professionally wrapped antenna would have only increased our max distance by a few inches at most, which would not have made a difference in terms of unlocking in time for the dog.

2.4 Microcontroller

Our design features a PIC16F877A microcontroller as the central control unit. This model was originally chosen due to its two hardware PWM output pins that we will use to control our servo motors, its USART communication pins that will allow us to communicate with our WiFi module, and therefore with our server that will be storing our user settings, and due to its many general I/O pins that allow us to read our sensors and RFID readers, while offering room for future expandable/utility. The PWM outputs ultimately proved unnecessary, due to our switch to a maglock design. The chip was programmed by both the ICD2 debugger, and the PICKIT3 debugger. The MCU also can handle up to a 20Mhz clock speed, sourced from an external oscillator, which allows for rapid code execution and quick communication with the WiFi module. Table 1 below shows the functionality of the program run by the microcontroller. Figure 4 below outlines the the code that is contained on the microcontroller. The block “Poll sensor data” and below it constitute the control loop, while the blocks above it outline the necessary MCU configurations.

Table 1: Truth Table for Logic States

Raining?	Nighttime?	Total Lock Out?	Lock during rain?	Lock during nighttime?	Tag in range?	Locked/Unlocked
X	X	X	X	X	F	Locked
X	X	T	X	X	X	Locked
T	X	X	T	X	X	Locked
X	T	X	X	T	X	Locked
X	F	F	F	X	T	Unlocked
F	X	F	X	F	T	Unlocked
T	T	F	F	F	T	Unlocked

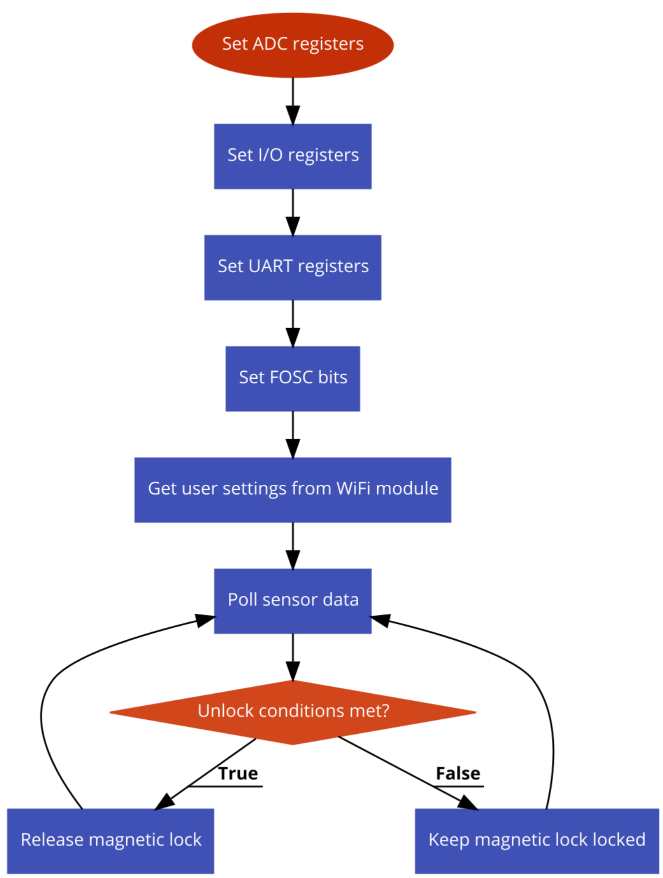


Figure 4: Flowchart for the microcontroller's code base

2.5 WiFi Module

Our design features the ESP8266 Wifi module. It was chosen due to its low price point, while not sacrificing on any crucial features. While other modules could offer high data transfer speeds, it wasn't an important factor in our choice, due to the small amount of data the module has to send to our microcontroller.

The module uses 2.4 GHz WiFI, which is the most widely used standard band, and also IEEE 802.11 b/g/n specifications for WLAN communication, which is also one of the most widely used standards. This allows the module to connect to any standard home WiFi configuration, and allows it to act as a server that any device also on the home network can reach through an internet browser. The module can host most web server files, such as HTML, CSS, JavaScript, and more. This means it can send simple data, in our case the user settings, to any connected device that wishes to access it. Figure 5 below shows our user settings page.

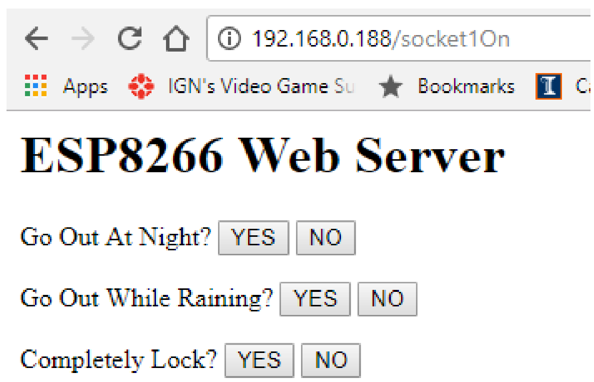


Figure 5: **Web Applet for controlling user settings**

2.6 Magnetic Lock

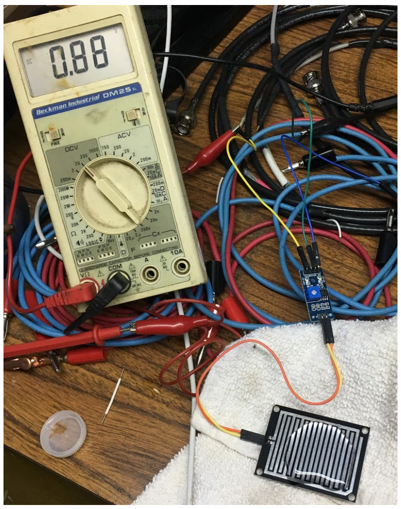
Our initial planned designed was to use two servo motors driving a deadbolt-style lock. Upon the actual construction of the door, we found the servo motors would pose a lot of possible mechanical issues. Instead, we opted to use a AGPtek 130LBs Electromagnetic Lock [9] which is specifically designed for door access. This magnetic lock operates on 12V DC and draws 110 mA, which made it perfect to use straight from the barrel jack of our wall adapter. There are only two wires to the lock, which is power and ground so it is either on or off. We grabbed an off-the-shelf relay (JQX-115F [10]) to be used in tandem with the microcontroller to set off the locking mechanism. The relay switch needs 5V to toggle, which the PIC is capable of outputting. The main inputs to the relay were connected to 12V from the barrel jack and the other pin was left in an open-circuit configuration. The coil of the relay was hooked to the PIC, and the output of the relay was directly connected to the maglock. Once the system is powered on, the relay is pushing out 12V keeping the door constantly locked. For the PIC to unlock the door, it sends a 5V output to the switch, allowing the relay to toggle, and for the door to be effectively unlocked. The door will remain unlocked until the PIC drops back down to 0V.

3. Design Verification

3.1 Sensors

3.1.1 Rain Sensor

The rain sensor was designed to output 4V when completely dry, and for the voltage to linearly drop as water covered more area of the sensor. This makes sense since the water will increasing the continuity of the sensor, effectively decreasing the resistance which is directly related to the voltage. Our measurements confirmed the sensor to be functioning properly.



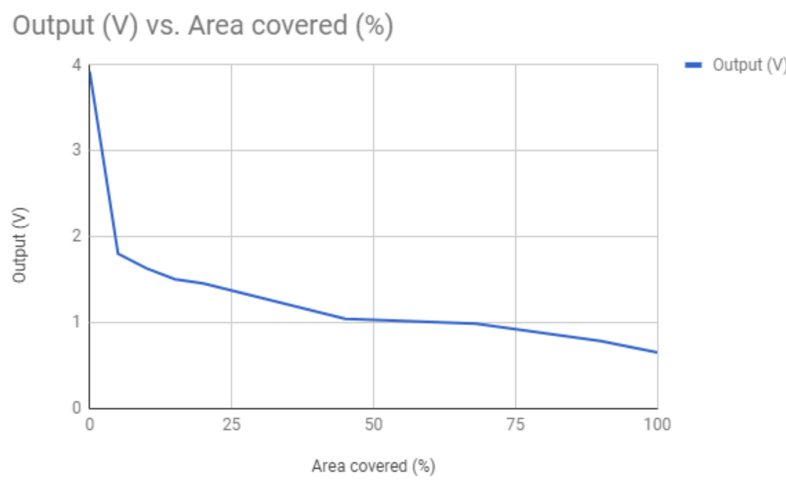


Figure 5: Rain sensor output voltage vs. water coverage

3.1.2 Light Sensor

The light sensor provides a 0 to 3 V analog output reading depending on the amount of light the photodiode picks up. For our purposes, we gave the user of letting their dog out at all times, or day-time only. We could provide further customization of specific times by picking up the amount of light (dusk/sunset will be naturally dimmer).

Table 2: Light Sensor Measurements

Input	Analog Out
"Night"	~0 V
"Sunny Day" (Senior Lab lights on)	2.5 V
"Dawn/Dusk" (Lights dimmed by pointing in darker area)	1.65 V

3.1.3 IR Sensor

The IR sensor was able to begin detecting objects within 2 feet. For our purposes, we're limited by the range of the RFID sensor which was from 7 to 9 inches. This so happens to be exactly where the IR sensor peaks in value. The sensor would easily be able to detect if a body was in the range, and we would use these analog readings to determine which side of the door the dog is on.

Table 3: IR Sensor Measurements

Distance (in.)	Analog Out (V)
Null	.26
0	.57
2	1.9
4	2.4
6	2.9
8	2.7
10	2.5
12	2.1
14	1.8
16	1.6

3.2 RFID

The RFID sensor document states that a maximum distance of ~11 inches can be achieved through a perfectly wrapped 1.333 mH inductor. We practiced wrapping smaller inductors to get the hang of manually making one, and made two working antennas that could connect to the sensor (pictured in Appendix C). As explained earlier, the diameter and number of wraps are inversely related, so the maximum reading distance did not vary too much since diameter is not the only determining factor.

Table 4: RFID Antenna Values

Shape	Diameter	Measured Inductance	Maximum Distance
Circular	5 in = .127 m	1.55 mH	8.5 in
Square	3 in = .076 m	~ 800 mH	7 in

3.3 Microcontroller

The planned communication method for the microcontroller with the WiFi module was the Universal Asynchronous Receive Transmit protocol. Both the microcontroller and the WiFi module are listed as being able to communicate through this protocol up to a baud rate of 115200, with baud rate being how many symbols a module can transmit per second. However, communications at higher rates can sometimes be faulty due to interference or other outside influences. Therefore, it was crucial to test communication at multiple rates to ensure proper communication. A sample message was transmitted through UART to an LCD screen from the microcontroller, which was initialized to increasing baud rates. If the message displayed properly on the screen, transmission at the initialized baud rate was successful.

Table 5: UART Baud Rates

Baud Rate	Message Transmission
9600	Successful
19200	Successful
57600	Successful
115200	Successful
230400	Unsuccessful

3.4 WiFi Module

Our original design called for using the TX and RX pins on the ESP8266 to communicate with the microcontroller through UART. This was changed to utilizing simple DIGITAL_HIGH or DIGITAL_LOW signals on the GPIO pins on the ESP8266 for simple boolean logic from our hosted webpage. These were confirmed working by connecting them to LED's and setting our server to output off the GPIO pins, turning the LED's on and off.

We also tested the module's response time. As long as the device was within range, it would give a <30ms response time when communicating with the module. This is shown in Figure 6.

```
:\Users\Kamil>ping 192.168.4.1

inging 192.168.4.1 with 32 bytes of data:
eply from 192.168.4.1: bytes=32 time=1ms TTL=128
eply from 192.168.4.1: bytes=32 time=9ms TTL=128
eply from 192.168.4.1: bytes=32 time=1ms TTL=128
eply from 192.168.4.1: bytes=32 time=23ms TTL=128

ing statistics for 192.168.4.1:
    Packets: Sent = 4, Received = 4, Lost = 0 (0% loss),
pproximate round trip times in milli-seconds:
    Minimum = 1ms, Maximum = 23ms, Average = 8ms
```

Figure 6: **Response times from computer to ESP8266**

4. Costs

4.1 Parts

Table 6: Part Cost Table

Part	Cost (prototype)	Cost (bulk)
12V DC Power Supply	$5.10	$1.20
Rain Sensor (YL-38)	$5.80	$0.50
Light Sensor (ALS-PT19)	$2.50	$2.00
IR Sensor (Sharp GP2Y0A02YK0F)	$14.95	$6.00
RFID Sensor (ID-3LA)	$25.95	$15.00
125 kHz Assorted RFID Tags	$3.00	$0.50
Magnetic Lock (AGPTek 60kg)	$20.00	$20.00
Microcontroller (PIC16F877A - PDIP)	$4.94	$0.75
WiFi Module (ESP8266)	$6.95	$0.75
5V Voltage Regulator	$0.95	$0.25
3.3V Voltage Regulator	$0.95	$0.25
Resistors, Capacitors, Crystals, Sockets	$5.00	$0.50
Building Materials	$8.00	$3.00
Total	**$114.09**	**$54.70**

4.2 Labor

Our fixed development costs were estimated to be $40/hour, 10 hours/week for three people. We considered approximately 9 weeks worth of work during the semester:

$$3 \cdot \$40/hour \cdot 10\,hours/wk \cdot 10\,wks \cdot 2.5 = \$30,000$$

5. Conclusion

5.1 Accomplishments

A majority of our project functioned as expected: all of our sensors communicated properly to the pins of the PIC via analog measurements. The fully constructed door/flap and magnetic lock worked perfectly to secure the flap when powered on. The RFID range on the antenna was within an acceptable threshold and the PIC detected the external interrupt.

5.2 Uncertainties

While our sensors and door worked great, we ran into issues upon integration with the PIC and the full system. The PIC we used required the use of an external oscillator as a clock. We ran into issues with our debuggers being faulty and deduced the problem to reside in the pins of our external oscillator not being close enough to the IC itself, causing issues when attempting to run the software. This issue was compounded by us using a perforated board rather than a PCB. The solution to our problem would be to either re-print a larger PCB to account for the external changes we made (magnetic lock, buzzer for RFID, etc) or to upgrade to a modern PIC with a built-in oscillator.

Another issue we ran into was the range on the RFID sensor was reduced when we ran off the fully-integrated perforated board. After debugging, we found the issue to reside in our 5V voltage regulator only outputting around 4.3V. We ran the regulator through a power generator and the output returned to 5V, so the problem resides in a weak soldering joint from the 12V barrel jack on the perforated board to the regulator input. The other regulator worked just fine in the board which confirmed our theory. This problem only affected the RFID range, since 5V would create the largest amount of magnetic field within the inductor increasing the maximum distance. The distance went from 8.5 inches down to 6, which still worked for demo purposes.

5.3 Ethical considerations

The principal safety hazard is potential injury to the user of the door. Adhering to the IEEE Code of Ethics, #1: “to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment” [9], we must ensure that any dog entering through our flap cannot be injured. Due to our design structure, there is never a possibility of a dog being stuck in the door frame since the flap must be be back in its original position for it to successfully lock. The biggest concern is that the dog is outside and the door does not unlock, rendering the dog trapped until the user comes to manually open the door. We have a workaround for this fault by giving priority to any RFID tag that is read from the outside to always unlock the door on approach. The user’s settings on time and weather restrictions are only taken into account when the tag is on the inside of the door and attempting to exit. An IR sensor facing outdoors determines if the tag is being read from either outside or inside.

Following from the locking of the door, the security of the home is possibly at risk when the door is momentarily unlocked since an intruder could attempt to enter (IEEE Code #3). Our implementation of the locking mechanism allows for magnetic lock to immediately lock the door flap back into place once the dog has passed through it. An intruder would have to wait for a tag to be present near the door and prevent the flap from closing once it is unlocked and hold the flap open. For the concern of the door being broken into: we're using a lock with 130 pounds of holding force, our dog door poses the same security threat as a regular front door to a house. If an intruder can break our dog door, they can break the window/main door.

Another area of issue is that part of the electrical system is outdoors, moisture could cause damage to the system (apart from the specific rain sensor). An enclosure will be created in the future for all relevant electrical components that must be kept out of moisture. This follows IEEE's code #5 of improving our understanding of technology by ensuring no danger is at hand. This enclosure will adhere to IP64 guidelines for this system.

5.4 Future work

Our project is very modular in design, and offers much room for expansion in the future. The biggest potential for future improvement resides in the RFID system. The RFID tags can hold small amounts of rewritable data, which can be read by the RFID sensor and sent to the microcontroller. By giving every pet in your house a tag with unique data on it, individual pets can be tracked and have different settings applied to them. This system would allow the user to gain statistics on when their pets go outside, how often, etc. This also offers greater security against potential intruders, as you can lock out any tags that don't hold identifying data for one of your pets.

Another potential area for improvement in the future is the use of a real time clock over an analog light sensor. Currently, the system is set up to only differentiate between day and night, not specific times of day. By switching to a real time clock, and passing the current time to the microcontroller, the user can set specific schedules for their pets. They would be able to set a weekly schedule, with specific times of the day that they would like for their animal to be able to go outside.

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Appendix A Requirement and Verification Table

Table A.1 System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. 22Enough voltage (~12V, ~5V, and ~3.3V) and current can be sustained across every component in the circuit for functional operation.	1. a) Read voltage and current levels across all components once the circuit is fully wired. The voltage supply for every component should fall within 5% of their respective optimal operating voltages.	**Y**
2. Rain Sensor provides an analog output from 1-3 volts based on 'wetness' of module.	2. a) Connect per datasheet specifications b) Measure output voltage when sensor is completely dry c) Take output measurements while adding water drops incrementally, noting voltage levels d) Note how wet module is when output voltage reaches max of 3v	**Y**
3. Light Sensor provides an analog output from 0-5 volts based on surrounding illuminance.	3. a) Connect per datasheet specifications b) Measure output voltage while in dark environment (as dark as possible) c) Gradually increase surrounding light level, measuring output voltage at different levels. d) Repeat a-c using varying light sources, i.e. sun vs. fluorescent light	**Y**

4. IR Sensor Must have an effective sensing distance of 0.5-1.0 meters. 5. IR sensor is strong enough to provide readable values for differing fur colors and types.	4. a) Connect IR sensor to power supply. b) Measure output voltage using multimeter at varying distances. 5. c) Find materials of differing colors and construction. d) Read the values returned by the sensor for each of these materials at varying distances. e) Verify that the sensor provides differentiable values for all types of fur color and type.	**Y**
6. Wifi Module must be able to pull XML data 7. Wifi Module able to send and receive 32 bytes of data in under 1 second. 8. Wifi Module must have a loss rate of < 1%	6. a) Set up simple .xml data on localserver on one of our devices b) Set up module per spec c) Ping our device to ensure connectivity 7. d) Connect ESP to WiFi network. e) Send data from different device on same network f) Measure latency 8. g) Repeat procedure from Requirement 5 for 10 times. h) Determine packet loss	**Y**
9. RFID sensor - ensure transceiver outputs with tag in range 10. RFID sensor- ensure range of at least 30 cm.	9. a) Antenna needs an inductance value of 1.333 mH per the RFID sensor. Construct circuit and measure inductance via values on oscilloscope. 10. b) Hook antenna to circuit c) Test receiver range at 10 cm increments with the TAG-IN-RANGE output pin	**Y**

11. MCU - Ensure the MCU can communicate through USART at a baud rate of 115200	11. a) Beginning at 9600, test the MCU with an increasing baud rate and ensure proper configuration through correct function calls, up to 115200 b) Call "printf" at each baudrate, and ensure that the message is correctly printed to a USART LCD screen.	**Y**

Appendix B Circuit Schematics

Figure B.1 Rain Sensor Schematic

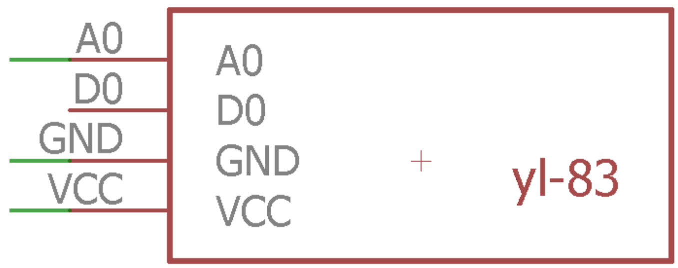


Figure B.2 Light Sensor Schematic

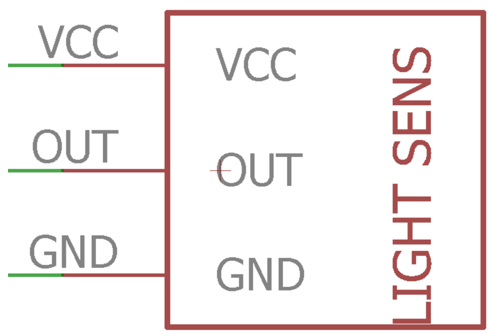


Figure B.3 IR Sensor Schematic

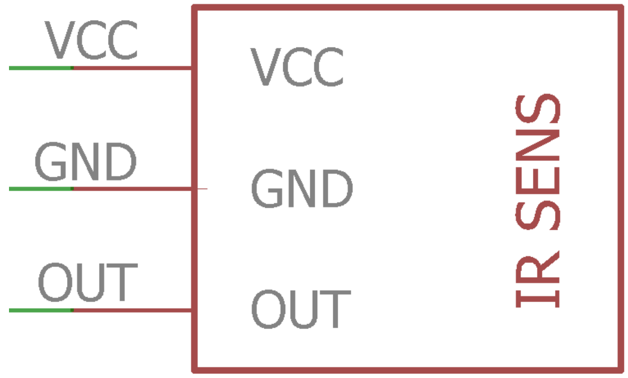


Figure B.4 RFID Schematic

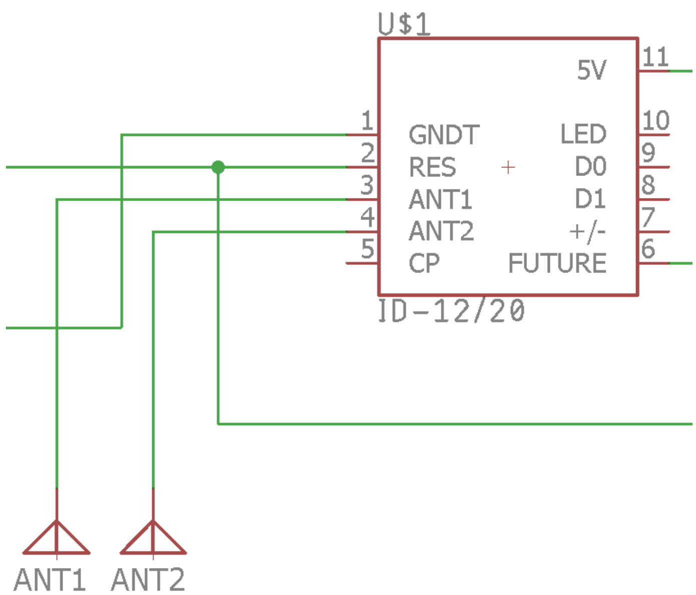


Figure B.5 WiFi Module Schematic

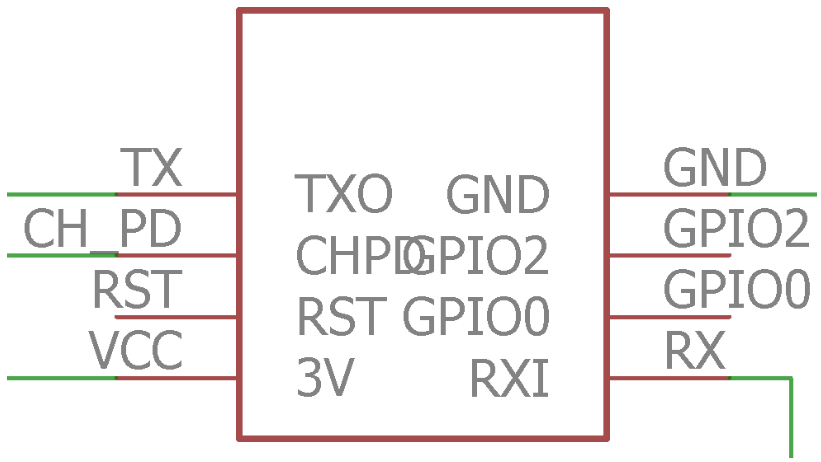


Figure B.6 Main Control Unit Schematic

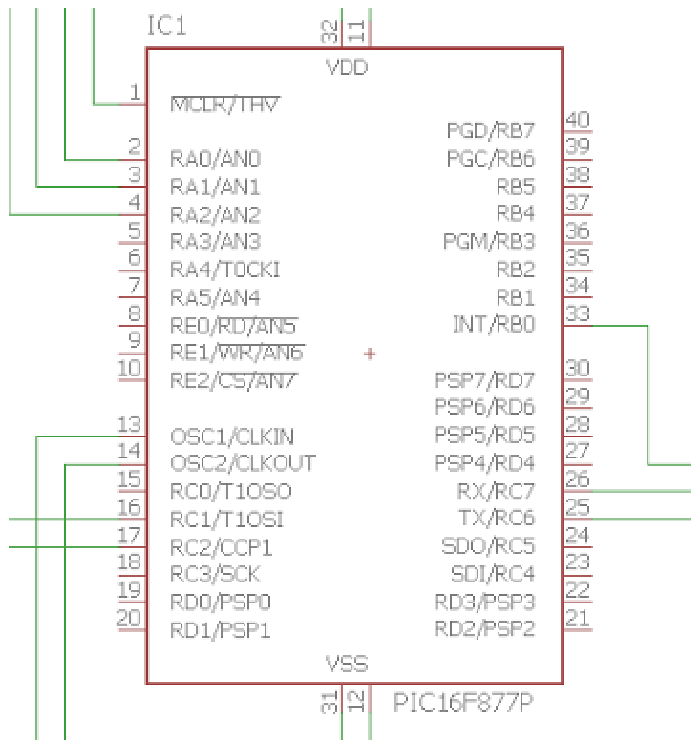
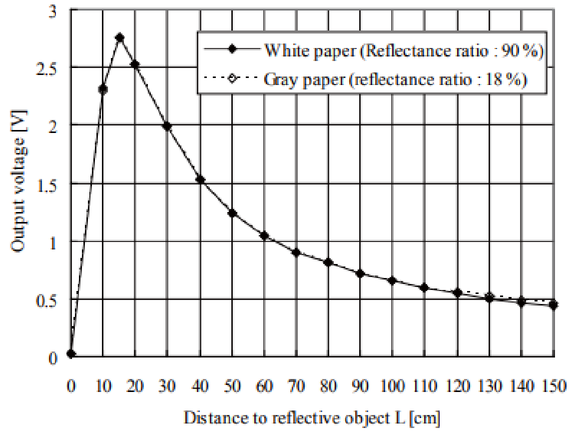
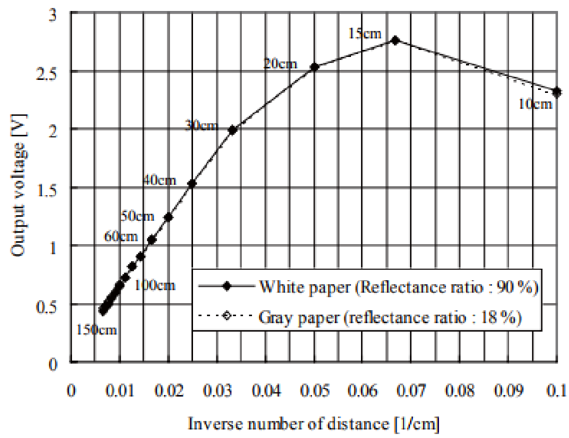


Figure B.7 IR Sensor Output Voltage vs Detected Object





Appendix C RFID Sensor Equations and Design

Equations C.1 Inductive and Capacitive Reactance for Resonant Frequency

$$X_L = 2\pi f L$$

$$X_C = \frac{1}{2\pi f C}$$

$$X_L = Inductive\ Reactance\ [\Omega]$$

$$X_C = Capacitive\ Reactance\ [\Omega]$$

$$f = Frequency\ [\text{Hz}]$$

Equations C.2 General Equation for Inductance of an Air-Core Inductor

$$L = \frac{31.6(Nr_1)^2}{6r_1 + 9l + 10(r_2 - r_1)}$$

$$L = Inductance\ [\mu\text{H}]$$

$$N = \#\ of\ turns$$

$$l = Length\ of\ coil\ [\text{m}]$$

$$r_1 = Radius\ to\ inside\ of\ coil\ [\text{m}]$$

$$r_2 = Radius\ to\ outside\ of\ coil\ [\text{m}]$$

Figure C.3 Manually Made Antennas (3in. square on left; 5in. circular on right)