

# Collision Avoidance Protocol for Package Delivering Quadcopters

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## ABSTRACT

In this paper, a possible collision avoidance protocol for the programming of a quadcopter is explored. It is taken into assumption that the quadcopter is to be programmed with the application to deliver consumer products of small weight and must traverse an urban setting without collision against any type of infrastructure.

## Keywords

Quadcopter, collision, guidance, system, protocol, Arduino, programming

## 1. INTRODUCTION

### 1.1 Problem Statement

Quadcopters require extensive hours of practice to be able to properly control due to their use of four separate motors to achieve flight. The purpose of this project is to ease the use of quadcopters by means of formulating a programming protocol and an array of sensors for a quadcopter to avoid collisions. This programming protocol is to be implementable to the programming of a quadcopter remote control, so as to avoid a user accidentally navigating the quadcopter into an obstacle, or within the programming of an automated robot.

### 1.2 Motivation

The formulation of this project is inspired by the concept application of a quadcopter by Amazon as a product-delivery system. In early 2015, Amazon, a shipping company, announced that they would be offering 1-hour delivery in select cities through the use of drones.



Figure 1. Amazon package delivery quadcopter

Amazon initially dismissed the concept due to public statements indicating drones would be targeted by citizens as “present

hunting”, Amazon announced on March 2015 the beginning of their 1-hour delivery program. Though the program has already been launched, the group members in this group project are motivated in researching a possible solution for a problem Amazon engineers must have encountered in the formulation of their final product.

## 1.3 Literature Survey

### 1.3.1 Quadcopters

Quadcopters are 6 degree of freedom unmanned air vehicles (UAVs) which generally use 4 rotary blades for propulsion. Compared to other UAVs, quadcopters have the advantage of increased stability while hovering (in comparison to controlled helicopters) and maneuverability in close quarters or tight turns.

### 1.3.2 PID Control Method

The PID control method is an algorithm used in the stabilization of a signal input, which may be used in the application of a quadcopter to stabilize the quadcopter according to a certain reading, such as its altitude. Using this method, a desired speed or position is set in the programming of the quadcopter. Sensors are used to measure the actual speed or distance and an error  $e$  is calculated.

$$(1a) \quad e_i = (v_{desired})_i - (v_{measured})_i \quad \text{or}$$

$$(1b) \quad e_i = (x_{desired})_i - (x_{measured})_i$$

The motor response  $u(k)$  is then altered according to three parameters P, I, and D which can be set constants or be variable for rapid response and stability.

$$(2) \quad u(k) = K_p e(k) + K_I \sum_{i=0}^k e(i) + K_D (e(k) - e(k-1))$$

The  $K_p$  term modulates the signal according to the error in measurement, while the  $K_I$  term relates to the sum of recent errors and  $K_D$  corresponds to the rate at which the magnitude of the error has changed. The purpose of this method is to have a diminishing and minimum error within a certain time. The time and precision in which the quadcopter stabilizes depends on the initial values given the PID terms.

## 2. QUADCOPTER MOTION STUDY

### 2.1 Statics

In order to develop a safety procedure to avoid collision with objects, the dynamics of the Quadcopter must be analyzed. It is important when the system detects an object to give a series of

outputs that will make the vehicle to avoid it without creating unsteady flying dynamics. Usually, Quadcopters collide in the direction of motion because of the difficulty of maneuverability. For this reason, only that type of analysis will be developed in this document.

To start the Quadcopter analysis, the static study is pertinent in order to understand how the forces and moments of inertia cancel each other. The sum of the forces in the vertical direction must be equal to zero. This means that the thrust created by all the helices must equal the weight of the vehicle in order for it to remain stationary in the direction of gravity. Figure 2 is a drawing of a Quadcopter as seen from the front plane. As shown, Figure 2 only has two helices for easiness of visualization.

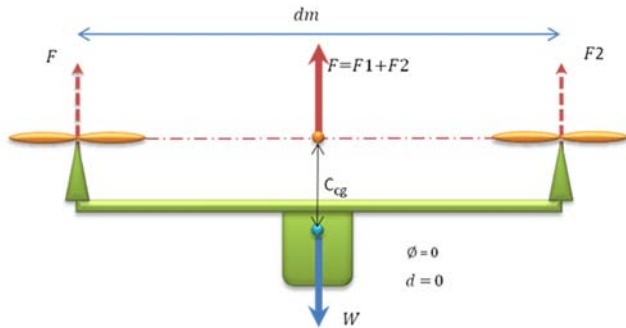


Figure 2. Quadcopter Static Equilibrium

## 2.2 Dynamics

Next, it follows to analyze the moment created by the spinning helices. As known, every spinning object has a rotational moment of inertia. For this reason, in order to cancel the torque created by changing the velocities of the helices, it is needed for two pairs of helices to rotate in a different direction. This can be appreciated by Figure 3. Making all the helices rotate in the same speed will create static equilibrium. On the other hand, by increasing the velocity of the helices in the x axis and decreasing the velocities of the y axis will create torque by the axis of the center of gravity. This will make the Quadcopter to rotate. This can be done in a way that the sum of the forces is equal to the weight of the vehicle in order to not change in elevation.

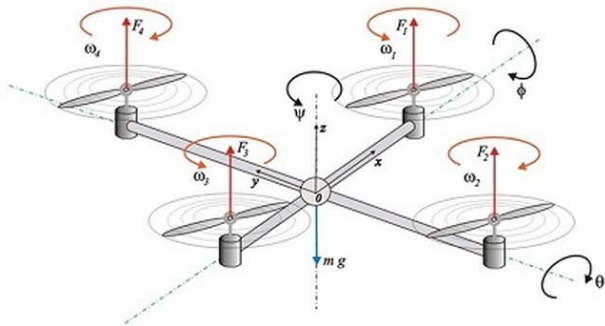


Figure 3. Direction of Forces and Velocities

Now that static analysis is explained, it follows to make the dynamic study. Usually, there are two flying dynamics that Quadcopters use. The “+” and the “X” configuration this two configurations can be appreciated in Figure 4. The flying characteristics between the two are different, but the principle is the same. On the “+” configuration and using Figure 4 as a reference, by increasing the thrust in the left and reducing it on the right will create a moment about the green axis.

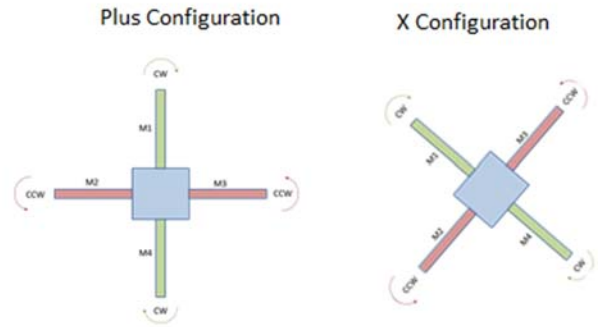


Figure 4. "X" vs. "+" configuration

This moment will make the vehicle to tilt to the right at an angle making the thrust to be on that same direction. This thrust will then have components in the vertical and horizontal plane, making the Quadcopter to move to the right but not to increase in elevation. Figure 5 is a graphical representation of this principle.

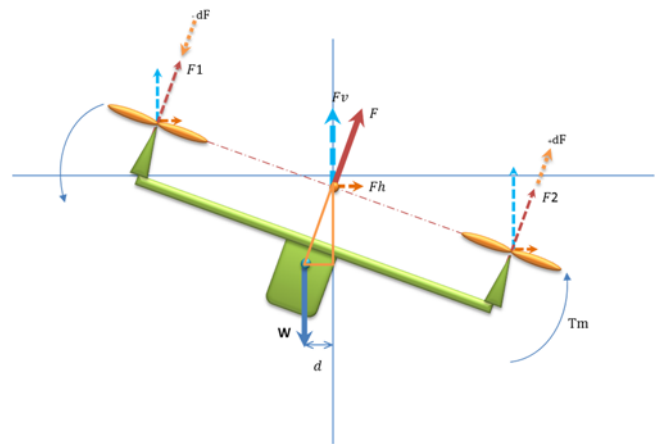


Figure 5. Forward Motion

However, the difference in thrust force must be by the same amount in order to balance the vertical loading as well as the moments of inertia so the device does not spin about the center of gravity. This flying configuration will be used if the obstacle is predominantly closer to a blade, as shown in Figure 6.

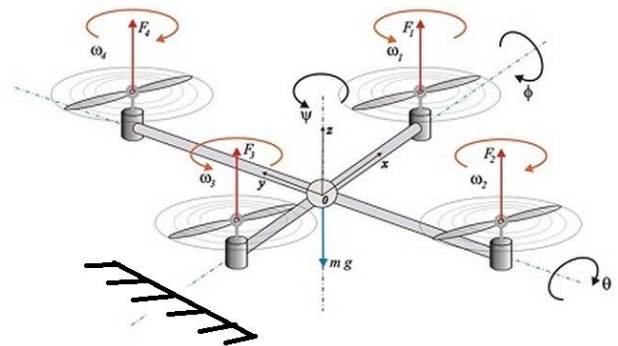


Figure 6. "+" configuration obstacle

For the “X” configuration flying dynamics, the rotation of the vehicle is not predominantly in a specific axis. Instead, it is at a 45 degree angle. Referring again to Figure 4, in order for the Quadcopter to move to the right, both helices of the left side must create a higher but equal thrust force. The helices on the right on the other hand, must reduce the force so the vertical components are equal to the weight of the device. This create force component

to the right making the device to move. Since both pairs decrease and increase by the same amount, the torque about the direction of gravity is zero. This configuration will be adopted if the obstacle is close to a complete side of the Quadcopter. As shown in Figure 7.

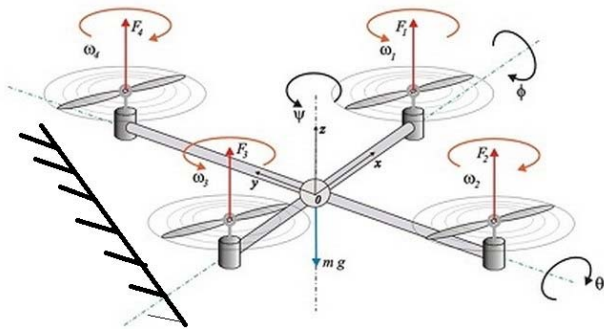


Figure 7. "X" configuration obstacle

### 3. SENSORS

As well as modern airplanes, redundancy in flight assistance devices is the main strategy to accomplish flight on a safety way for this project. Modern aircrafts accomplish safe flight through the constant use of redundant flight computers, generally three of these computers assist the pilots throughout the whole flight, each one of these computers is connected to a series of redundant sensors that make constant readings to different aspects of the aircrafts as well as external conditions, the average of these measurements is interpreted by each computer and then compared to the outcome of the same analysis from the other two. Taking this concept to a smaller scale, the appropriate way to accomplish a redundant sensor system will be to set modular units, meaning this the use of arrangements of sensors located on a specific position in order to measure the same target by two or more different methods. For the reach of this project the first approach was to use an arrangement composed by an ultrasonic sensor and an infrared sensor, nevertheless after some research it was determined to be ineffective.

The use of two distance measurement devices comes from the need to avoid miss readings caused by the conditions of the surroundings or the characteristics of the surfaces to avoid. It has been proven that ultrasonic sensors in order to receive an ample sound echo must be perpendicular to the surface or in angles not too deviated from the perpendicular position, even more when these surfaces are smooth or polished, they are also affected by changes in the environment and finally they have difficulties while reading low density targets like foam and cloth. Unfortunately, these weaknesses are similar to the ones found on the IR sensors and even more, IR sensors have shown to be unable to make precise readings on bright sunlight, the logic conclusion after this is the need to add a different type of sensor in order to cover the weaknesses of the ultrasonic sensor.

After some research it was determined that the best option to accomplish this task was to use laser based sensor. These sensors, different from the IR or the ultrasonic sensor, have shown a reliable performance on different environments, have a higher working range, they are much more precise and they can make precise readings despite of the angle of the target.



Figure 8. Laser Sensor

The capabilities of laser based sensors are much higher to the capabilities of ultrasonic sensors, nevertheless ultrasonic sensors are highly capable of giving a precise reading when they are perpendicular or almost perpendicular to the surface, becoming a practical solution to measure the distance with objects over and under the quadcopter, being one of these objects the floor, meaning this that the sensor can be used to measure the flight altitude when approaching the landing zone as well as the maximum flight altitude when flying on roofed areas.

The conceptual design of this modules is based on the idea of oscillation for the laser based sensors and static fixtures for the ultrasonic sensors, the idea of oscillating the laser based sensors is related with the movement of the quadcopter, just because it moves on three dimensions the sensors are required to take measurements on an angular range that not only includes panning left and right but also up and down. A spinning platform with up and down oscillation is the simple response to this issue only if the weight of this platform can be minimized. Locating one of this modular sensor units under each motor of the quadcopter will give the system enough redundancy to make it safe and user friendly, besides this, the use of a gyroscope located on the center of the device will give feedback information in order to determine the oscillation angles for the laser based sensors, as well as to control maximum tilt angle in the moment of flying away from an object.



Figure 9. Quadcopter

## 4. PROGRAMMING

### 4.1 Object Avoidance with Fuzzy logic

The navigation of the quadcopter is assumed to be via GPS tracking. The quadcopter will fly to the location designated by GPS. The quadcopter will continue on the path set by the GPS until sensors on the quadcopter pick up an object close or in the way of the quadcopter's current trajectory. Another assumption made is that the quadcopter is able to maintain stable flight while moving through the GPS path. The programming covered for this section is on obstacle avoidance. While the quadcopter is assumed to remain at a high altitude until it reaches its destinations, there are potential obstacles such as tall buildings as well as other quadcopters it might come in contact with in its path.

Through the use of fuzzy logic, the quadcopter can avoid these obstacles with cheap sensors and low end processors. Because these quadcopters need to cover a vast amount of area that is constantly changing, mapping out the entire path of a quadcopter would be difficult. Due the nonlinearity of the system, mathematical models requiring a large amount of computation proves a difficult method for obstacle detection within a constantly changing environment. There are several methods being researched for obstacle avoidance and quadcopter stability. In the work "Controlling of Quadrotor UAV Using a Fuzzy System for Tuning the PID Gains in Hovering mode," fuzzy logic was used to determine the values of the gains, which are input values developed to offset errors and to make nonlinear mathematical models of quadcopter dynamics solvable. Through fuzzy logic, a solution is found for these nonlinear equations at a fast pace for the required movement of a quadcopter. The proposed method will only use fuzzy logic.

Fuzzy logic offers a simple method to deal with this nonlinear system. It makes approximated decisions based on the scenario it is presented with. While mathematical models hold more accuracy, fuzzy logic controllers can make a decision faster and can deal with obstacles that are not defined in a system. One of the main goal for the program is not to define the exact amount of distance required to avoid the object, but to avoid the object within a certain time frame regardless of the offset in required distance. Distance sensors are placed on the sides and corners of the quadcopter to achieve this task.

Another important goal is to keep the quadcopter oriented in a way that it will return to a level plane with all motors. The quadcopter system is a highly unstable system. In order to prevent the quadcopter from destabilizing as it turns to avoid an object, a gyro meter is place on the top of the quadcopter. This sensor will also be implemented in the fuzzy controller. The gyro meter sensor will be used to determine the angles between the quadcopter and the turning axis. The fuzzy logic control will attempt to maintain a small angle between the two so that the quadcopter will able to avoid the obstacle while not becoming unstable. If the angle is too large, the quadcopter will not be able to return to its original stable state where the angle is 0.

### 4.2 Program Overview

The structure of this program will be as follows. The quadcopter will move away from approaching objects while maintaining an orientation. Once the object has been avoided, the quadcopter will reorient itself with all three axis and resume moving to the GPS location. Depending on which sensor detects an object, the fuzzy logic control will choose the inputs and the outputs. There are two scenarios considered in object detection. One scenario is if the

quadcopter approaches an object from its corner and the other is if the quadcopter approaches from the side.

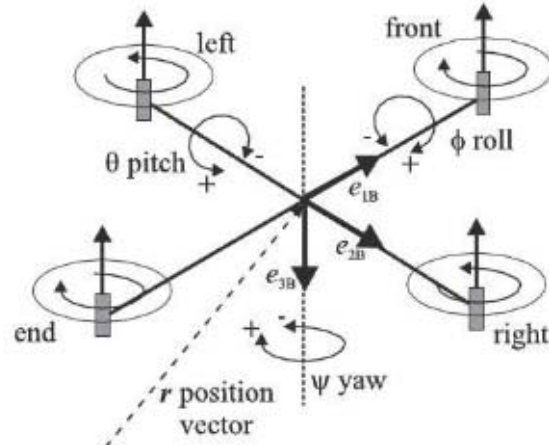


Figure 10. Schematic of Quadcopter

Using the figure above, if the quadcopter is approaching an object from the front corner, it will consider distance detection from the left and right distance sensors and the axis between them (roll axis) as inputs. There is only one output, however, it will manage both motors (left and right) between the input axis. The corners and axis selection depends on which corner detects the object. The corner that detects the object becomes the front corner. The left corner, right corner, and turning axis are then defined by the assigned front corner. The fuzzy logic program was developed through Matlab Simulink.

### 4.3 Fuzzy Input

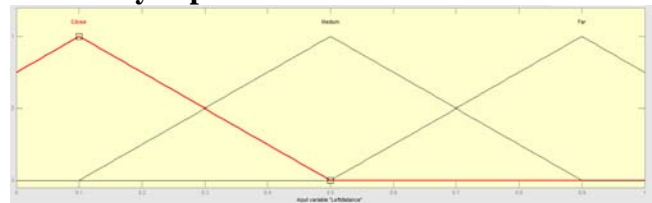


Figure 11: Left Distance Sensor Reading

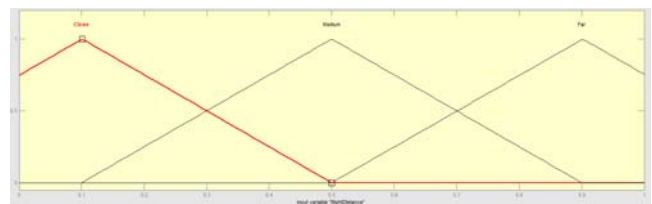


Figure 12: Right Distance Sensor Reading

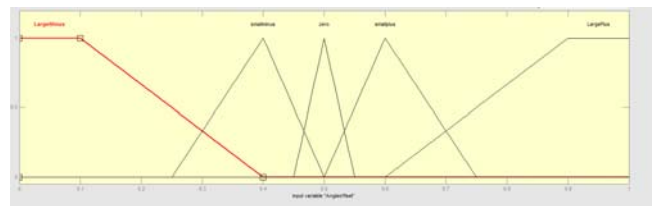


Figure 13: Angle Offset Sensor Reading

The three figures above are the input variables for the corner distance detection. The first two figures represent the left distance

sensor and the right distance sensor. These inputs determine the direction the quadcopter will take. The third input variable is the angle offset. The minus represents a negative offset with respect to the quadcopter and the axis perpendicular to the turning axis (pitch).

The positive offset is represented by the plus. The zero membership function tells the quadcopter that it is not turning fast enough, while the large plus and minus membership functions tell the quadcopter that it is turning too fast.

#### 4.4 Fuzzy Output

The output motors, chosen based on the assigned left and right corners, will adjust based on the inputs and rules.

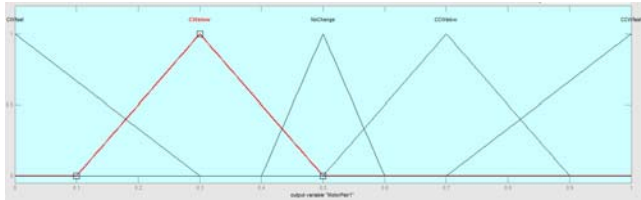


Figure 14: Desired Change in Quadcopter Orientation

The figure above shows the output variable for the motors. The counter clockwise and clockwise membership functions do not represent the direction of the motor turning. It instead signifies the desired change in orientation of the quadcopter about the turning axis. As an example, if the quadcopter needs to be turned counter clockwise, the right motor will increase its counterclockwise rotation while the left motor rotation would decrease by the same amount.

#### 4.5 Fuzzy Logic Rules

In order to connect these outputs and inputs, the rules were created. The following figure contains the current rules.

1. If (LeftDistance is Close) and (Angleoffset is zero) then (MotorPair1 is CWslow) (1)
2. If (RightDistance is Close) and (Angleoffset is zero) then (MotorPair1 is CCWslow) (1)
3. If (LeftDistance is Close) and (Angleoffset is LargeMinus) then (MotorPair1 is CWfast) (1)
4. If (RightDistance is Close) and (Angleoffset is LargePlus) then (MotorPair1 is CCWfast) (1)
5. If (Angleoffset is LargeMinus) then (MotorPair1 is CWfast) (1)
6. If (Angleoffset is LargePlus) then (MotorPair1 is CCWfast) (1)
7. If (RightDistance is not Close) and (Angleoffset is smallplus) then (MotorPair1 is NoChange) (1)
8. If (Angleoffset is smallplus) then (MotorPair1 is NoChange) (1)
9. If (RightDistance is not Close) and (Angleoffset is zero) then (MotorPair1 is CWslow) (1)

Figure 15: Rules for Fuzzy Logic Control

While there are only 9 rules, the reason for this is because the main deciding input is the gyro meter readings which would pick up the angle offsets. The other two inputs are used to change the direction of the quadcopter motion if it is moving closer to another object, while trying to avoid the one from the front. The fuzzy logic controller also does not consider all the sensors as inputs at one time. It only uses the sensors necessary to avoid one object at a time. If no objects are detected in either the left or right direction, the quadcopter assumes a small clockwise orientation to move to the right.

As for object detection from the sides, the same fuzzy logic controller is used however the inputs and outputs are defined differently. The side where the distance sensor is detected becomes the front. The left and right distances will become the sensor readings from the sides to the left and right of the front side. The axis selected will be the one going through the front and back sides. For the motor pairs the right motor will be the two motors to the right of the axis and the left motor will be the two motors to the left of the axis.

#### 4.6 Programming Discussion

There are several limitations to this design. Without distance detection on the top and bottom of the quadcopter, the quadcopter might come in contact with an object not covered by the current distance sensors on the corners and the sides. The design has not been tested, so the locations of the membership functions are not optimized as well as the values. Despite the lack of testing, a general idea of a method for the solution to quadcopter obstacle avoidance has been realized.

### 5. PROTOTYPE DESIGN

#### 5.1 Description of Prototype

A prototype circuit board was designed to test the performance of the programming protocol. The circuit board includes an Arduino UNO microcontroller powered by a USB cable to a laptop computer, four servo motors with propeller blades to simulate the motors in a standard quadcopter, and six ultrasound sensors to serve as sensory input for the quadcopter's surroundings. Control commands ("up", "down", "left", "right", "forward" and "backward") are given by a switch boxes.

#### 5.2 Prototype Design

The high cost associated with programmable quadcopters (averaging \$1,000) makes direct testing of a program on a quadcopter platform difficult for the time and budget restrictions for this project. However, preliminary testing can be conducted using servomotors and sensors in a breadboard as shown in the following figure.

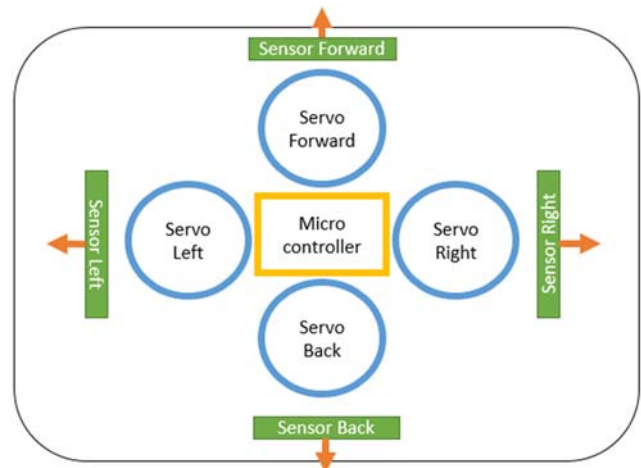


Figure 16: Breadboard layout

This form of preliminary testing is favorable to a low-budget project as cost would only involve the servo motors and sensors to be used. Allowing time and funds, the results from this preliminary test could be transferred into the platform of a programmable quadcopter.

### 5.3 Prototype Parts List

Table 1 includes the parts required for the construction of a prototype circuit used to test the programming of the quadcopter collision avoidance protocol.

Table 1. Testing circuit parts list

| Part                    | Quantity |
|-------------------------|----------|
| Breadboard              | 1        |
| Arduino UNO             | 1        |
| Switch                  | 1        |
| USB Cable               | 1        |
| Servo Motor with blades | 4        |
| Ultrasound Sensors      | 6        |
| Cables                  | 50       |

### 5.4 Discussion

Due to time constraints, a prototype circuit board was not manufactured yet, but this will be accomplished in the future.

### 6. ACKNOWLEDGMENTS

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