Quadcopter Demonstrator

***Abstract*— The popularity of quadcopters is increasing as the sensors and control systems are getting more advanced. This project is start with the design and construction of test rigs having in mind a list of objectives to be fulfilled by it. Objectives are to investigate the sensors and control systems needed to balance a quadcopter in one axis without the uncertainties of a flying platform. Sensors were tested one by one before implement in control system. Different PI control algorithms have been implemented using microprocessor.**

Keywords—component; quadcopter; sensors; control system

I. INTRODUCTION

A quadcopter is a multi-copter that is lifted and propelled by four rotors. Quadcopters are classified as rotorcraft, because their lift is generated by a set of revolving propellers. Quadcopters generally use symmetrically pitched propellers. Altering the rotation rate and pitch of one or more rotor for controlling the motion of vehicle, that way changing its torque load and thrust characteristics.

Early in the history of flight, quadcopter configurations were seen as a possible solution to some of the problems in vertical flight; efficiency issues originating from the tail rotor and torque-induced control issues, which can be eliminated by counter-rotation. This causes the rotational forces induced by each rotor to cancel each other out.

Advantages of quadcopters over helicopters are that they do not require mechanical linkages to vary the rotor pitch angle when they spin. Quadcopters require less maintenance. They use four smaller rotors which allow them to store less kinetic energy. This reduces the damage in case of accidents.

Figure 1. A Quadcopter

Because of their capability to manoeuvre in dangerous locations while allowing their human operators to be at a safe distance the use of unmanned aerial vehicles (UAVs) has grown in the military. The larger UAVs are providing a reliable long duration, cost effective, platform for reconnaissance as well as weapons. Hence they have grown as an indispensable tool for the military.

The Quadcopter is capable of being distantly operated to fly for specific pre-determined missions. Some missions may be like examination of a difficult to reach location, rapid deployment video from the location of a fictitious campus incident, or like surveillance video along a pre-planned track around campus. Quadcopters are used in search, rescue and surveillance operations, construction inspections and many more other applications.

II. MAJOR COMPONENTS USED IN QUADCOPTER

A. Overview of quadcopter

Quadcopters use fast on board motor control to take care of stability. Quadcopters can navigate in three directions using only four motors. And the high reliability of brushless motors makes them a simpler, more reliable.

A quadcopter has four propellers arranged in a cross configuration or square pattern. Two propellers rotate clockwise and the other two propellers rotate counterclockwise, so the quadcopter gets lifted into the air without any net angular momentum. Movement in the x and y directions is attained by tilting the quadcopter such that the thrust forms a horizontal component. Figures below present how the thrust of different propellers can be modified, allowing the quadcopter to move. The platform of the quadcopter is same as that of a helicopter with respect to its mobility; however, it is simple to construct and can be operated with ease because the blades of the propeller are fixed-pitch.

The figures also show how a quadcopter can control its pitch, row and yaw angles. In figure 2, the quadcopter is level and still because of the equal thrust provided by the motors (the red propellers rotate clockwise and the green propellers rotate counterclockwise). If one of the pairs generates a difference in thrust, as indicated in figure 3, then the quadcopter will roll or pitch about the other axis. In another case, if one pair of motors rotates faster than the other pair, as indicated in figure 4, then the quadcopter controls its yaw angle.

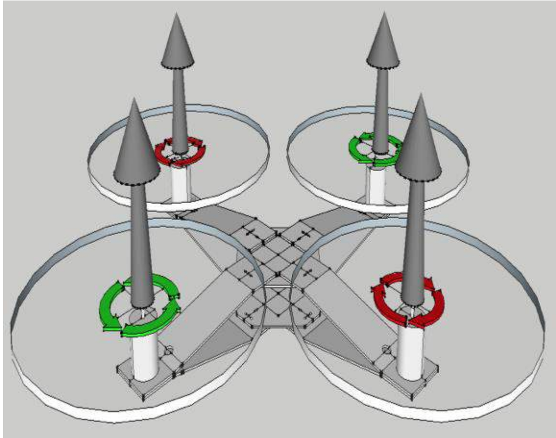


Figure 2. Condition for level

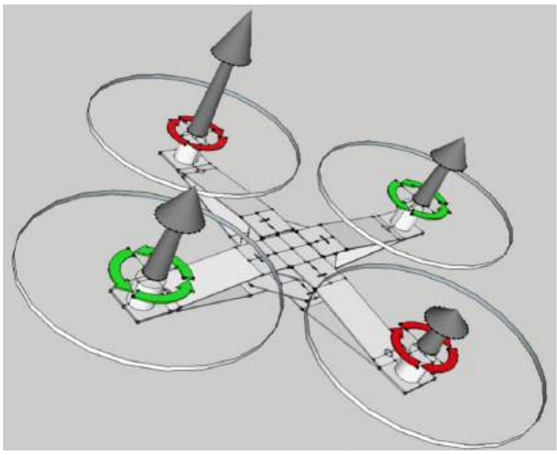


Figure 3. Condition for roll

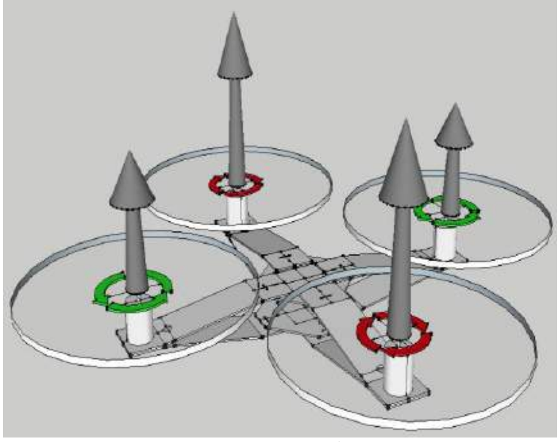


Figure 4. Condition for yaw

B. *Solid state sensors*

1) *Accelerometer*

Accelerometers are sensors that are used for measuring and analysing acceleration. They measure proper acceleration by measuring weight per unit of mass, a quantity of force, or g-force. Accelerometers can be used on a separate basis, or in combination with a data acquisition system. Accelerometers are offered in several forms.

Accelerometers will have one to three axes(X,Y,Z), with the multiple axes typically being perpendicular to each other. These devices work on many working principles. Accelerometers are recommended for different systems including aircraft control.

Figure 5. ADXL212 accelerometer

The accelerometer used in the project is ADXL212 from Analog Devices. The ADXL212 is ±2*g* dual axis with pulse width modulated (PWM) digital outputs. It is a high precision, low power, complete dual axis accelerometer with signal conditioned and duty cycle modulated outputs, all on a single monolithic IC chip. The ADXL212 contains a polysilicon surface-micromachined sensor and signal conditioning circuitry to implement open-loop acceleration measurement architecture. The output signals are duty cycle modulated digital signals proportional to the acceleration. The ADXL212 is capable of measuring both positive and negative accelerations to ±2 *g* [1]. A functional block diagram of the ADXL212 is shown in figure 6.

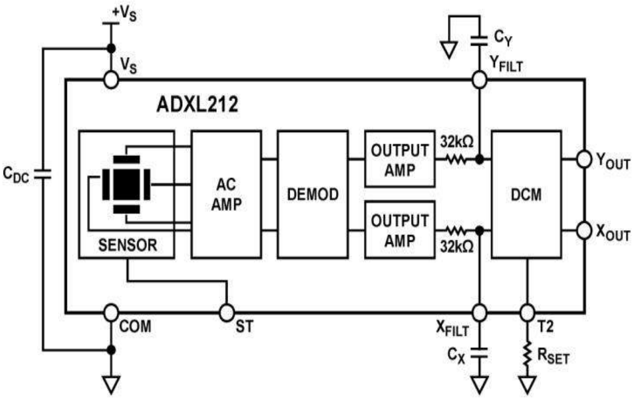


Figure 6. ADXL212 Functional block diagram

2) *Gyroscope*

A Gyroscope is defined as a device which utilizes the angular momentum of a spinning mass (rotor) to sense angular motion of its base about one or two axes orthogonal to the spin axis.

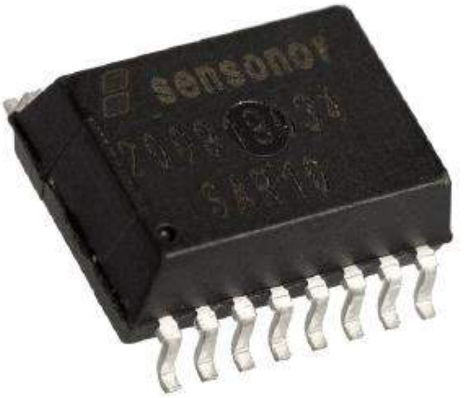


Figure 7. SAR10 gyroscope

The gyroscope used in the project is SAR10 from Sensonor. The SAR10 contains a butterfly gyro MEMS die and a BiCMOS mixed mode ASIC housed in a miniature SOIC plastic package. The gyro die is built as a triple stack consisting of a bottom glass die with metalized patterns defining excitation and detection electrodes, a middle micro machined mono crystalline silicon die with the oscillating masses, which also represent a common opposite electrode, and a third top cap glass die. SAR10 has sensitivity of ±250 º/s range [2].

The SAR10 function is based on the excitation of a reference motion in the butterfly structure. An angular rotation of the device will generate Coriolis forces, whose frequency equals that of the reference motion and whose resulting vibration amplitude is a measure for the angular rotation [2]. SAR10 uses a SPI (serial peripheral interface) interface to communicate with other applications. A SPI interface enables easy and effective communication between the SAR10 and the application. SAR10 functional block diagram is shown in figure 8.

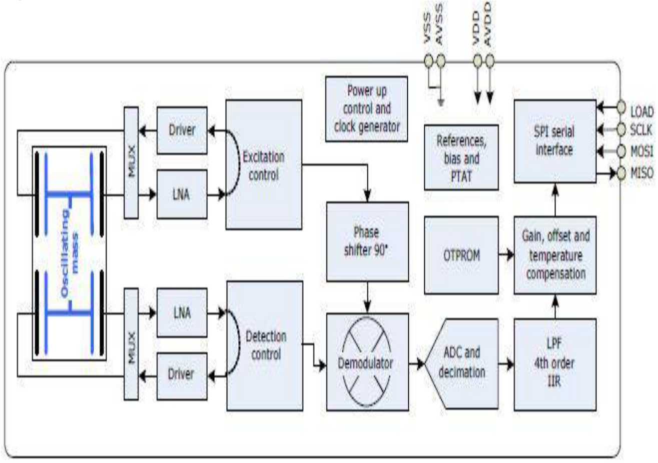


Figure 8. SAR10 functional block diagram

3) *Comparison*

The gyroscope can sense rotation, and an accelerometer cannot. The major difference between a gyroscope and an accelerometer is that a gyroscope measures or maintains orientation, based on the principles of angular momentum, whereas an accelerometer measures vibration. Another difference is that a gyroscope gives a sign of the change of angular rate, whereas an accelerometer provides linear acceleration.

The 2 axis accelerometer provides the direction of gravity on the balancing instrument. Usually a gyroscope measures angular position with respect to the principle of rigidity of space of the gyroscope.

Both gyroscope and accelerometer have their separate characteristics and functions. Either of these can be critically important when properly used.

Accelerometers measure linear motion and gravity. Accelerometers identify and measure the electrical current that develops from muscular action. The measured magnitude of the signal in accelerometer is subjective to gravity. This is not similar with gyroscope. Information pertaining to bandwidth and frequency is available to the level of zero frequency in case of gyroscopes, which is not similar with an accelerometer. A single integration is adequate to realize angular displacement in the case of gyroscopes, whereas a complex double integration is essential in the case of accelerometer. Signal to noise ratio is high in the case of gyroscope, but in accelerometers, mostly a low signal to noise ratio is obtained.

C. Motors

Quadcopters have 4 motors with a propeller each. Most quadcopters uses brushless DC motors to drive the propellers. Brushless DC motors are used because they are weigh less and can operate at very high speed.

Brushless DC motors, also known as BLDC motors, are synchronous electric motors which electronically commutated. BLDC motors are similar to normal DC motors; they use the coils and magnets to drive the shaft. BLDC motors lose the brushes and the commutator when switching the direction in the coils. BLDC motors have three phases of driving coils on the inner of the motor, which are fixed and surround the shaft. On the outer layer of the motor, it contains the magnets which are mounted on the conventional motor shaft. So the coils are fixed, which means wires can go directly to them and, therefore, there is no need for a brush.

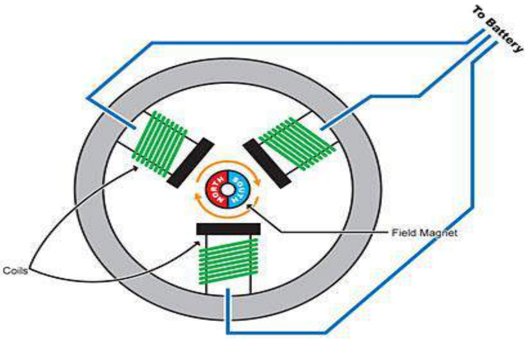


Figure 9. Brushless DC motor internal

BLDC motors compare to brushed DC motors in their use of much higher speeds; they can operate at above 10,000 rpm (revolutions per minute) under loaded and unloaded conditions. BLDC motors lose the brushes, which means they are more reliable and have longer life expectancies. BLDC motors are more efficient as there are no power losses. More efficiency, reliability, power and small size that BLDC motors offers makes them the ideal choice for quadcopters.

D. *Batteries*

Battery is the power source for quadcopters. Batteries have various types. However, for quadcopter two types can be used; nickel metal hydride (NiMH) batteries and lithium polymer (Li-Po) batteries. The one that is highly recommended is lithium polymer. Li-Po has higher specific energy around 120 Wh/kg while NiMH has around 70 Wh/kg. Li-Po weighs less than NiMH. Li-Po has lower resistance, which means less heat produce and more stability. Li-Po has a much slower discharge rate. Overall, Li-Po is more of an ideal choice because it is lighter and provides more power.

III. METHODS

A. *Testing rigs*

This project involves the design and construction of two test rigs. The first one is to measure the lift of the drive motors in one axis and allow different control strategies to be tried using the ADXL212 accelerometer as the feedback. The second one is for testing the SAR10 gyroscope. The first test rig contains the following components:

- Two DC motors
- Propellers
- Freescale MC9S08AW60 Microcontroller
- ADXL212 accelerometer
- Battery

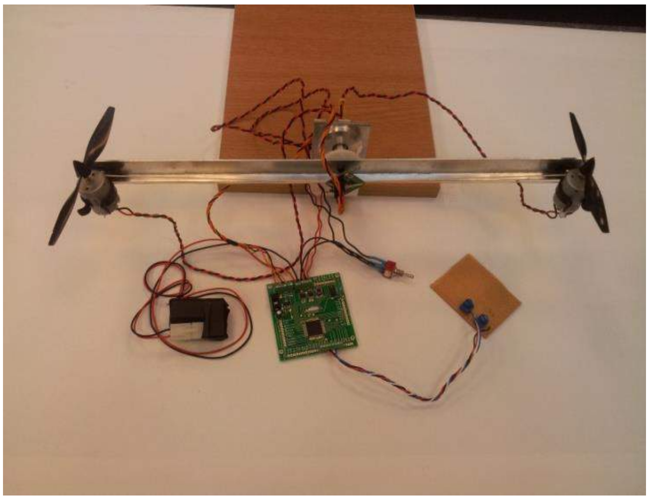


Figure10. First test rig

The second test rig contains the following components:

- Freescale MC9S08AW60 Demonstration Board
- SAR10 gyroscope
- Battery

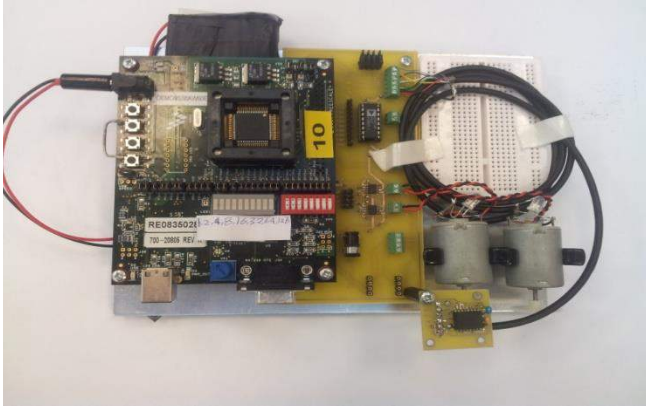


Figure 11. Second test rig

B. *PID controller*

Controllers are components that basically have an input of error signal and output signal. Controller modifies the error signal to give the required characteristics of the system output.

PID controllers use 3 basic algorithms: P - proportional, I - integrative and D – derivative. PID control is usually used where a disturbance occurs, the integral and derivative modes taking care of the large offset and the rapid change.

Combinations such as PI control are very often used in practical systems. PID controller is a natural generalization of a simplest possible controller.

The proportional, integral, and derivative terms are summed to calculate the output of the PID controller:

$$\boldsymbol{u(t) = k_p e(t) + k_i \int_0^t e(\tau) d\tau + k_d \frac{d}{dt} e(t)} \quad (1)$$

k_p: Proportional gain

k_i: Integral gain

k_d: Derivative gain

e: Error

t: Time or instantaneous time

τ: Variable of integration

IV. RESULTS AND DISSUCSION

At the beginning of the experimental works, accelerometer and DC motors have been tested to make sure they function properly. An accelerometer has been mounted to the balance bar, and then switched on the power supply, so that the accelerometer can sense the two directions. Figure 12 shows accelerometer PWM waveforms on the X-direction and Y-direction. The first waveform shows there is no acceleration (0g) while the other two show positive (1g) and negative (-1g) acceleration. It also shows the operating frequency, which is 27.8 kHz.

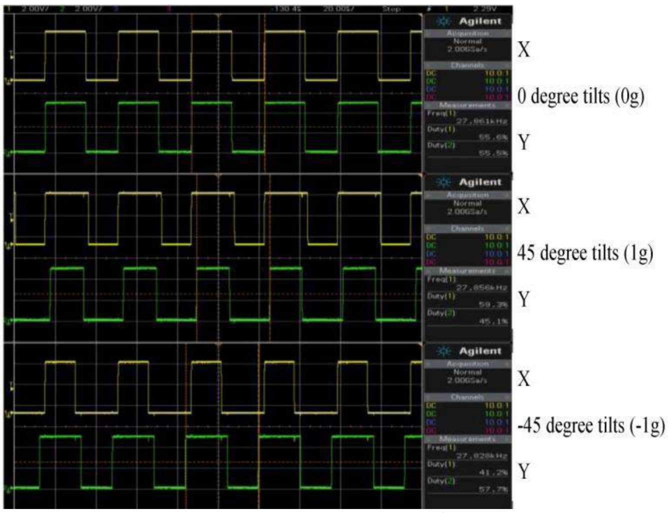


Figure 12 Accelerometer waveforms

DC motors have been mounted to the balance bar and connected to the MC9S08AW60 microcontroller. Figure 13 shows PWM waveform of the DC motors.

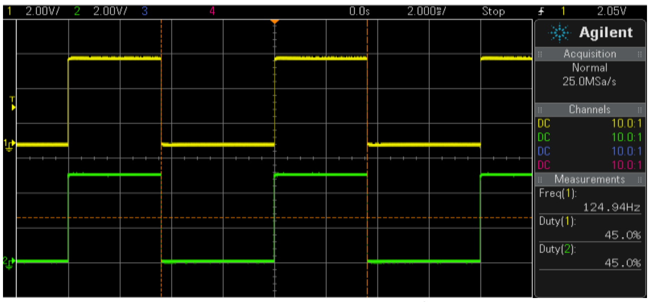


Figure 13 DC motors waveform

We introduce two potentiometers to perform cumulative and differential loop control. Now, we can balance the bar manually. We connect the accelerometer to the microcontroller as the feedback that replaces the cumulative and differential loop control. We have set the initial motor speeds as a one-off operation.

For a controller, we use a PI controller. We tried proportional algorithm and integral algorithm. We use rising and falling edge interruption of PWM signals. Then, we use the readings from the accelerometer to average the edges.

For the proportional algorithm, we measure the time difference between the rising and falling edges of the X and Y and average them. Then, we subtract the X value from the Y value or vice versa depending on if it has a positive or negative value. We scale the new value by shifting and rotating one byte to the left. After scaling, we add and subtract the initial motor speeds from the new value. Motor speeds will change according to the new speeds value. Figure 14 shows different PWM waveforms for proportional algorithms.

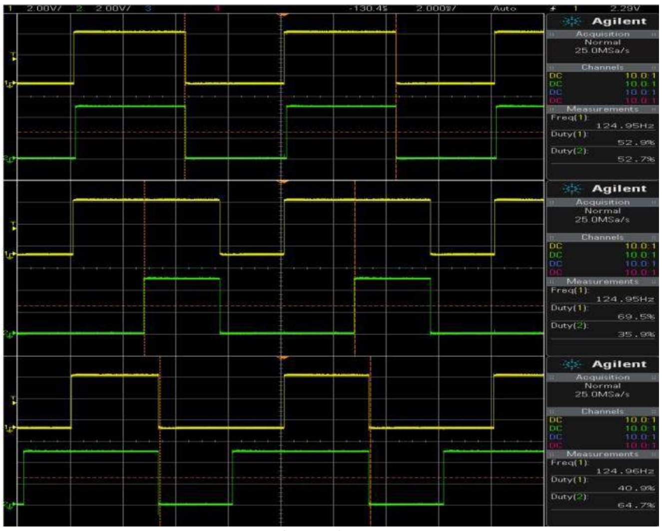


Figure 14 PWM waveforms for proportional algorithms

When we were testing the control, we found an oscillation disturbance of the platform. The motors try to be balanced, but they are never in a steady state position. For the platform to be stable, we need to reduce the oscillation and write sophisticated algorithms.

For integral algorithm, we measure the time difference between the rising and falling edges of the X and Y and average them. Then, we subtract the X value from the Y value or vice versa depending on if it has positive or negative value. We scale the new value by shifting and rotating two bytes to the right. After that, we add the left motor speed with the new value and subtract the right motor speed from the new value. Motor speeds will change according to the new speeds value. PWM waveforms for integral algorithms are showing in figure 15.

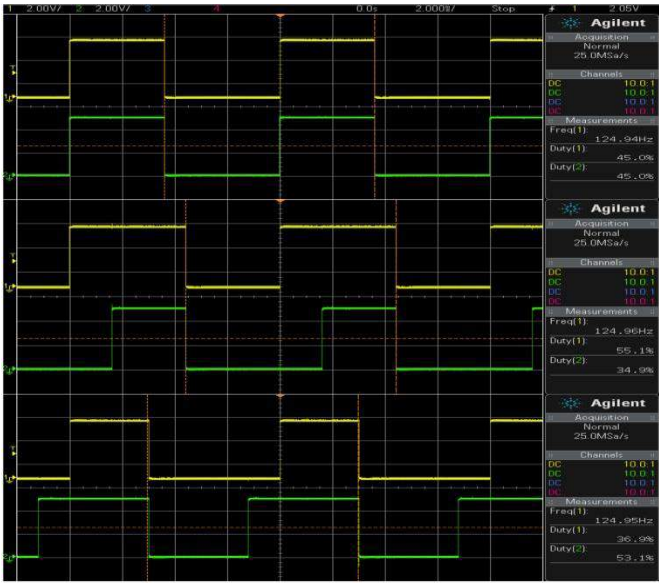


Figure 15 PWM waveforms for integral algorithms

Integral algorithms had problems. The motors were not able to balance the bar. Integral loops caused them to oscillate and behave violently, and eventually this reached the point where the bar flipped over. For a stable platform, we need to increase the gain for a much faster response. In order to do that, we need a faster microprocessor. Oscillation needs to be reduced.

Overall, proportional and integral algorithms worked, but it needs a lot of modifying for sophisticated algorithms. Proportional algorithm was better than integral algorithm in term of stability. Oscillation caused a lot of disturbance for the platform. We need a faster microprocessor for faster processing results and updating more quickly.

One of the problems we had during the project was vibrations. DC motors produce too much vibration, which affects the accelerometer. We tried reducing the vibration by various ways. The best way we found was to use elastic bands so we can take off the accelerometer from the bar.

Gyroscopes use an SPI interface. An SPI interface consists of four signals MOSI (master out, slave in), MISO (master in, slave out), SCLK (serial date clock) and load. The program works as follows. SPI transmit RARH (10000000). SPI receive date. We then averaged the date we received. We tested the gyroscope by using a spinning chair. We placed the device on the chair then spin it and read the output data.

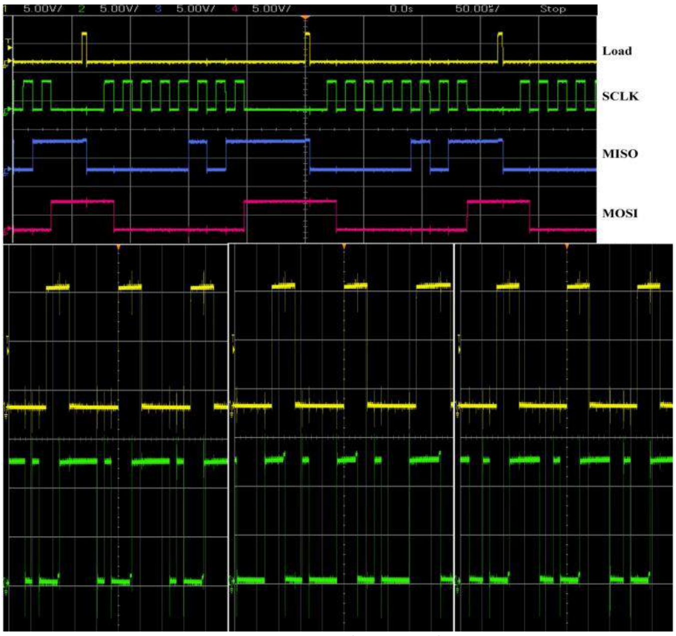


Figure 16 SPI interface waveforms

Figure 16 shows SPI interface waveforms. It shows the four signals load, SCLK, MISO and MOSI respectively. It is also shows different received data. For example, one of the signals transmits 10000000, and we received 11111010.

V. CONCLUSION

We have tested several control algorithms, but none of them has achieved a stable flight. We have resolved several issues encountered in this project. Altogether, a lot of work needs to be done in order to achieve stable flight.

For stable platforms, we need to use all the three modes of PID controller; we used the proportional and the integral modes only in this project. We need to write more sophisticated control algorithms and use a faster microprocessor than the Freescale MC9S08AW60. Also, we should increase the gain in terms of speed, processing and readings from sensors. Processing results from sensors is critical, so we need faster processing results and updating more quickly.

We tried several methods for testing the gyroscope, but none of them works properly. We transmitted RARH and RARL, but the received data got high value, which is not what we expected. The program needs modifying. Unfortunately, at this point we reached the end of our experimental works because the semester is nearly finished.

The project was more complicated than what we thought at the beginning. The project requires a better understanding of control system for sophisticated algorithms. It is also needs to use more efficient components.

REFERENCES

[1] ADXL212 data sheet, Anloag Davices.

[2] SAR10 series data sheet, Sensonor.

[3] Gabriel M. Hoffmann, Haomiao Huang, Steven L. Waslander, Claire J. Tomlin. Quadrotor Helicopter Flight Dynamics and Control: Theory and Experiment.

[4] Antal Turóczi. Flight Control System of an Experimental Unmanned Quad-Rotor Helicopter. 10th International Symposium of Hungarian Researchers on Computational Intelligence and Informatics.

[5] Inkyu Sa and Peter Corke. System Identification, Estimation and Control for a Cost Effective Open-Source Quadcopter. 2012 IEEE International Conference on Robotics and Automation. Minnesota. USA, May 14-18, 2012.

[6] Paul Pounds, Robert Mahony, Peter Cork. Modelling and Control of a Quad-Rotor Robot. Australian National University. Canberra, Australia.

[7] Teppo Luukkonen. Modelling and control of quadcopter.

[8] Samir Bouabdallah. Design and control of quadrotors with application to autonomous flying.

[9] Daniel Mellinger, Michael Shomin, and Vijay Kumar. GRASP Lab, University of Pennsylvania. Control of Quadrotors for Robust Perching and Landing.

[10] Pedro Castillo, Rogelio Lozano and Alejandro E. Dzul. Modelling and Control of Mini-Flying Machines.

[11] Inkyu Sa and Peter Corke. Estimation and Control for an Open-Source Quadcopter. Proceedings of Australasian Conference on Robotics and Automation. 7-9 Dec 2011. Monash University. Melbourne Australia.

[12] Ziegler, J.G, Nichols, N.B. Optimum settings for automatic controllers. Trans. ASME. vol. 64. pp. 759-768. 1942.

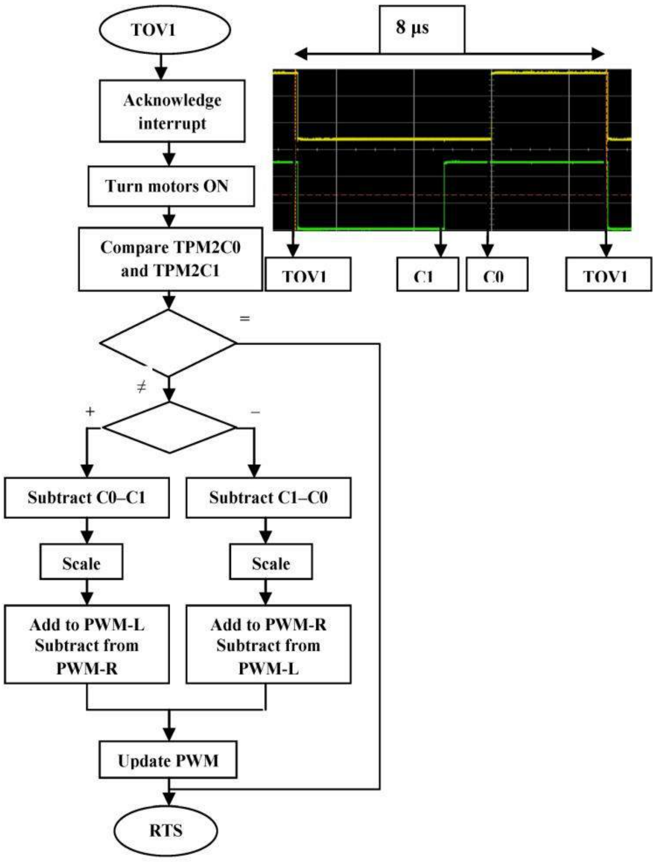
[13] Cohen, G.H., Coon, G.A. Theoretical consideration of retarded control. Trans. ASME vol. 75. pp.827-834. 1953.

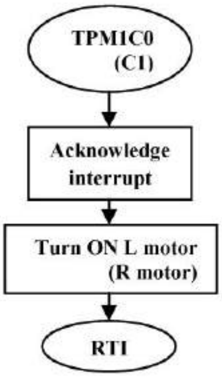
[14] Astrom, K.J., Hagglund, T. *PID Control – Theory, Design and Tuning*. Instrument Society of America. Research Triangle Park. NC. 2nd ed. 1995.

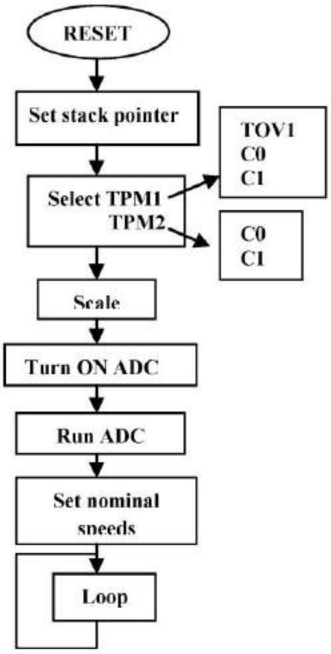
[15] Sung, Su Whan. Process identification and PID control. Wiley. NJ. 2009

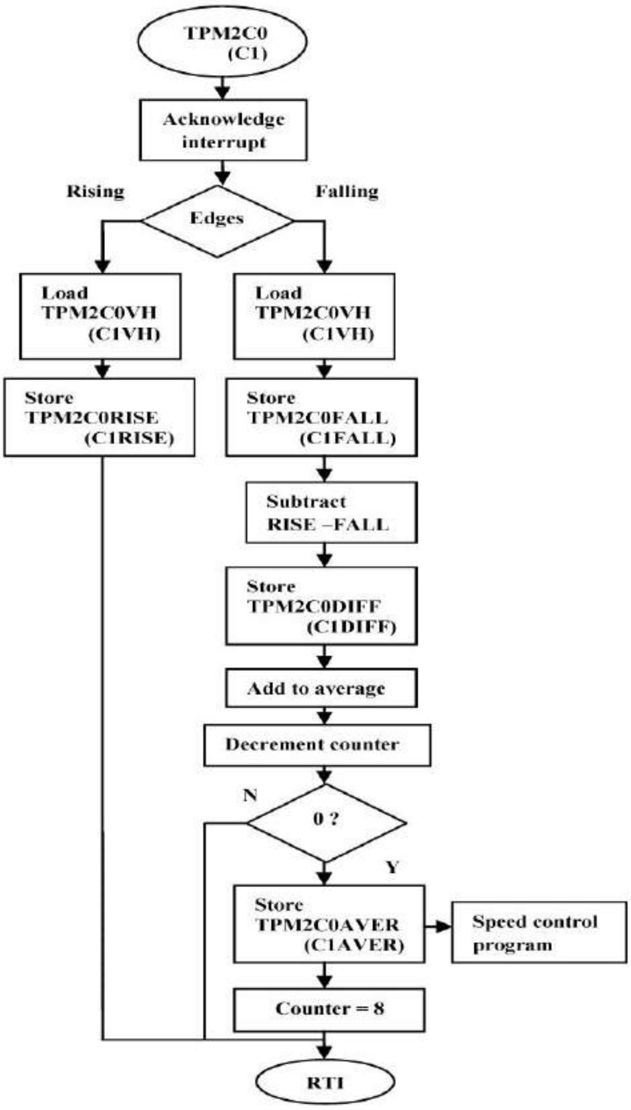
APPENDICES

A. Balancing flow charts









B. Gyroscope flow chart