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PRELIMINARY ANALYSIS OF STABILITY AND CONTROL OF A QUADCOPTER UNDER GUN-SHOCK LOADING

By

Jordy Amar Zikri
11201501016

Presented to the Faculty of Engineering
In Partial Fulfilment Of the Requirements for the Degree of

SARJANA TEKNIK
In
AVIATION ENGINEERING

FACULTY OF ENGINEERING

BSD City 15345
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APPROVAL PAGE

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STATEMENT BY THE AUTHOR

I hereby declare that this submission is my own work and to the best of my knowledge, it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma at any educational institution, except where due acknowledgement is made in the thesis.

Jordy Amar Zikri	
Student	Date

ABSTRACT

Preliminary Analysis of Stability and Control of A Quadcopter
Under Gun-Shock Loading

by

Jordy Amar Zikri

Triwanto Simanjuntak, PhD, Advisor

In this thesis, the problem of stability and control of a quadcopter under gun-shock loading was preliminary studied. The gun-shock loading was due to a firing gun mounted on the quadcopter and approximated as an impulse. At first, A CAD model of quadcopter mounted with a gun was developed to obtain a reliable estimate of inertia properties and built the simulation model using XCOS/SCILAB. This thesis used the DJI Phantom 2 Vision and Pistol P-3A Kal.7.65 as the base model of the quadcopter and the mounted gun. Here, we considered the single impulse working on the point of action of the impulse was in the z-directional axis of the quadcopter. Hence angular momentum by the impulse was only in the pitch and roll directions. Moreover, this thesis also reports an attempt to implement PID control on the non-linear dynamics of the quadcopter under the gun-shock loading. In this thesis, the PID control tuning was divided into three methods. The first tuning method was manual PD tuning (trial and error). The second tuning was the PID tuning with the Ziegler Nichols method. And the third tuning was the Ziegler Nichols method with manual tuning. The PD tuning method had the best rise time and settling time, but the Ziegler Nichols with manual tuning had the best steady-state error, and it was the closest to the initial condition after the gun was fired.

Keyword: *quadcopter, stability, control, PID, gun-shock*

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List of Abbreviations

UAV	**U**nmanned **A**erial **V**ehicle
COG	**C**enter **O**f **G**ravity
CAD	**C**omputer **A**ided **D**esign
RPM	**R**otation **P**er **M**inute
ESC	**E**lectronic **S**peed **C**ontrol

Dedicated to my parents

CHAPTER 1
INTRODUCTION

1.1 Background

A drone or unmanned aerial vehicle (UAV) is a flying vehicle without a pilot inside it. Typically, a UAV was flown by a pilot using a remote control or an on-board computer for an automated flight. UAV has a more complex composition than a model aircraft. That is in the same category as small aircraft. UAV and model aircraft have the same composition that consists of airframe and propulsion system, but the similarity ends there. A drone has added composition because UAV has some mission to be fulfilled. The added components are a task system, a communication link system, and a ground control system (Quan, 2020).

UAVs can be classified into two types. The first type is a fixed-wing type. The wing fixed permanently. The second type is a rotary-wing type. The lift supplied by the rotors directly. Multicopter is a type of helicopter that supplies the lift directly, but instead of just one or two rotors, it has three or more rotors. These two drone types have their advantage and disadvantage. The fixed-wing type has a more excellent range by using a single battery than the rotary-wing type. Fixed-wing also has a stability advantage because of the design of the airframe. The fixed-wing type also has safer recovery because it can glide by using the fixed-wing(Quan, 2020)

On the other hand, the rotary-wing type has more excellent maneuverability, and it can hover in place, navigate narrow areas even perform vertical take-off and landing. Rotary wing type is also more comfortable to operate. It has an even lower price than the fixed-wing type. The advantage of vertical take-off and landing makes the rotary type UAV more compact because it does not require a runway to take off and lands. Figure 1.1 is an example of an unmanned aerial vehicle in the rotary-wing type.

FIGURE 1.1: Unmanned Aerial Vehicle
(*Price of Drones: How much do Drones Cost?*, 2020)

Fixed-wing UAV is one type of UAV, just like an airplane fixed-wing aircraft fly using the lift generated by the fixed-wing and the forward motion of the UAV. Fixed-wing UAVs can be divided into three types. The glider type, the quadcopter, does not have an engine and propeller. It flies by launching it through the air. The self propeller type, it has a rotor and it by an electric engine or internal combustion engine. The third type is the combination of the two. It can glide and have an engine. The fixed-wing type maneuver, just like an airplane it has aileron, elevator, and some type even have flaps(Quan, 2020).

A quadcopter is a type of UAV. It classified as a rotary drone type with four spinning rotors. A quadcopter uses two clockwise directions and two counter-clockwise direction rotors to operate. For a quadcopter to be stable, it needs a couple of directional rotors due to the gyroscopic effect. When the rotors rotate in 1 direction, only the quadcopter rotates in the opposite direction and the quadcopter yaws. Quadcopter only moves using the four rotors by changing the rpm. The upward and downward movement uses the four rotors at the same pace, speeding up the rotors will go up and slow down the rotors will bring down the quadcopter. For forward, backward, left, and rightward movement, the quadcopter uses the same sequence. For example, if the quadcopter wants to move forward two rotors in the front decrease, the speed and two rotors in the back increase the speed the quadcopter tilt forward, then the quadcopter moves forward. For backward, leftward, and rightward movements use the same sequence. Yawing motions in the quadcopter use the speed variable in the two different directions of the rotors. In clockwise yawing, the counter-clockwise rotor speeds up then the quadcopter yaw in the clockwise direction(Quan, 2020).

In recent years UAV becomes the tool for many projects and industries. Drone used to be one of the military and tech people use for many years. Gradually, as UAV becomes more affordable, more people use it for many purposes. As technology also progressing the collision avoidance system getting better, even the average person can pilot it. Nowadays, drone use in many projects from making a movie to surveillance for the military.

UAV has become more accessible nowadays. Civilians use drones in plenty of ways today. The most use industry to use UAV is aerial photography. Before drone becomes an option for aerial photography, they use a helicopter to do it. Helicopter flying at low altitude is a dangerous thing to do. When a drone comes over, especially the quadcopter, quadcopter hovering makes the photography easier, and by the collision avoidance system getting better, even tight spaces quadcopter can go(*38 Ways Drones/UAVs Impact Society: Fighting War To Forecasting Weather | CB Insights*, 2020). Figure 1.2 is a DJI Phantom 2 Vision that is an everyday use as an aerial photography drone.

FIGURE 1.2: DJI Phantom 2 Vision
(*The story of drone pioneer DJI*, 2020)

The construction industry also begins to use drones technology. Now 3d mapping even gauging the soil can use the drone technology. When somebody wants to sell property, drones also have parts to be useful. Drones can do mapping of the neighborhood before making some property in the area. Mining use drones to assess constant measurement and assessment of physical material.

In some other ways, the drone also becomes useful for the airline industries. For example, Airbus now has a drone subsidiary called airbus aerial. It provides services for exterior aircraft mapping and created 3d models for the aircraft. In some parts of the world, drones also have been considered as transportation. In Dubai, they have tested drone as a taxi. Its vision works like GO-JEK or GRAB by having an app on the phone, and instead of taxi drones will come and takes the passenger to the destination (*38 Ways Drones/UAVs Impact Society: Fighting War To Forecasting Weather | CB Insights*, 2020).

Traditionally drones are used in military and defenses. Because the cost to develop one of them, use to be so expensive, and the only state of the art technology can use to develop one. Drones now use in much military application where dangerous jobs for people like surveillance even as a strike drone to strike down the enemy from afar. Drones, also called UAV, is a broad term in military and defense. There are several more terms. Unmanned combat aerial vehicle (UCAV) is a UAV that carries missiles and bombs. Unmanned aerial system (UAS) is a UAV that has everything, including the ground-based terminal, control stations, a complete UAS, usually have several drones and control stations.

UAVs in the military divided into several types. The first type is the MALE drone (medium-altitude long-endurance drone). This type of drone can fly from 10,000 to 30,000 feet. Its designs to orbit in a specific area. UCAVs usually in this type of drone. The next type is the HALE drone (high altitude long endurance drone). This drone can fly up to two days at one time. Its designs for flying in altitude exceeding 60,000 feet. Surveillance and spy drone are in this category. There is also a MAV drone (micro air vehicle drones). A micro drone in the palm-size usually for surveillance ahead or checking corners for enemy combatants. There are many others like mini-drones, tactical drones; then, there is a kamikaze drone. Kamikaze drone is a drone that carries explosives, and it will explode by impacting the enemy into the enemy.

There are several examples of drones used in the military. The US military might be the most famous for using drones in warfare conditions. They have The Black Hornet mini-drone, palm-size drone use for surveillance. It works in a day, even at night. Because of its small profile, the drone is hard to detect. US military also has surveillance drones, the RQ-4 Global Hawk surveillance drone. This drone can fly up to 30 hours at a time, and it claims that this drone works on all-weather conditions with large resolution imagery; it can gather large areas of land. The famous drone of us might be the MQ-9 Reaper. This UAV classified as a strike drone in UCAVs. It has a payload of 4.500 pounds, and if the Reaper has a light payload, it can fly over 40 hours with a distance of 1,200 miles. This drone is the one that strikes the general of Iran Qassem Soleimani(Roblin, 2020; *Qassem Soleimani death: The capabilities of MQ-9 Reaper drone*, 2020). Figure 1.3 is a Reaper Drone which uses commonly in the US military, and also the same type that Strike Qassem Soleimani.

FIGURE 1.3: Reaper Drone
(*MQ-9 Reaper Drone PNG Images & PSDs for Download | PixelSquid - S111959003*, 2020)

Most of the military drones nowadays is a fixed-wing drone. With fixed-wing drones similar in shape to a traditional aircraft, not only is it cheaper to build than a quadcopter one but it also more reliable because of many uses over the years. The multicopter also has some problems, particularly in its stability. Because of its shape multicopter is naturally unstable aircraft and it is hard to mitigate it. As technology progress and the computer becomes more sophisticated, the quadcopter control also becomes more manageable, and in recent years military drone using quadcopter as a base start to be researched. Because of simple multi-copter design, it is easier to maintain than the fixed-wing UAV.

There are several products of a multi-copter with a gun already on the market. The first example is from the USA, the TIKAD drone by Duke robotics. The TIKAD drone arm with a machine gun and a grenade launcher. Duke robotics says that the drone uses various unique suppression fire and stabilization solutions. This drone also has robotic gimbal with 6 DOF (degree of freedom). It can carry and stabilize drone up to 3 times the weight of the gimbal.

Turkey, in late 2019 also has its armed multi-copter. The drone called SONGAR drone. It develops by asisguard. The songar drone uses a modified automatic rifle. It has a mission radius of 10 km with an operating altitude of 2800 meters. The drone can be used in the day or night operations. It equipped with an automatic shooting stabilization system, on drone machinegun system, and a ground control station. This drone uses when an enemy combatant ambushes soldiers. The soldiers fly the drone, then the drone searches enemy position and returns fire while the soldiers are in covers(*Turkey acquires machine gun-toting octocopters with anti-recoil systems*, 2020).

China also has begun testing on an armed drone for urban warfare. The mini quadcopter named Tianyi drone is in development by the Tianjin ZhongWei data system. The quadcopter will have an operational range up to 5 km and a flying altitude of 6 km. the quadcopter will be equipped with an infrared, laser detector, and even up to two 50 mm rockets. It is claimed that the drone will be suitable for asymmetrical combat, counter-terrorism, special forces operation, and street battles(*China tests Tianyi mini-UAV for urban warfare | weapons defence industry military technology UK | analysis focus army defence military industry army*, 2020).

There is also an armed quadcopter, but it is not made by the military. In 2015 a student named Austin Haugwouts. He uploads a video on youtube. The quadcopter in the video attach by a semi-automatic handgun and firing it. In the video, we can see that the quadcopter after getting a recoil start to stabilize automatically(CNN, 2020). Figure 1.4 is a SONGAR drone. A Turkish company manufactures this drone, and it is a type of armed octocopter.

FIGURE 1.4: SONGAR Drone
(*Turkey acquires machine gun-toting octocopters with anti-recoil systems*, 2020)

A quadcopter is inherently unstable because it flies and turns only by using its rotor and angle of attack. When quadcopter is in hover condition, it just flies up using the same rotor speed. If somehow the quadcopter is given and angle of attack, it will move on that angle. In outdoor flight, there always be a disturbance, especially from the wind. When wind disturbs the quadcopter to make the quadcopter stay hover, it will need a stability and control technique.

Stability in aviation can be divided into two types, static stability and dynamic stability. Static stability also divided into three types, positive static stability, neutral static stability, and negative static stability. Positive static stability is when a quadcopter is in hover, and it experiences some disturbance like the wind. The quadcopter will stabilize itself. Neutral static stability is quadcopter at hover condition and is blown by the wind; it follows where the wind blows. Negative static stability is the opposite of positive stability. Meaning when the quadcopter is given a disturbance, not only it goes along with the disturbance it even makes the disturbance bigger.

The dynamic stability is also divided into three positive dynamic stability, neutral dynamic stability and negative dynamic stability. The positive dynamic stability is when the quadcopter moving, then take the finger off the controller quadcopter, will gradually come to hover. The neutral dynamic stability is instead of stopping or hovering the quadcopter still moving. In the negative dynamic stability, when the controller takes the finger off the controller, it will move even faster(*The 3 Types Of Static And Dynamic Aircraft Stability*, 2020).

Quadcopter inherently lean-to negative stability. It will need some stability and control techniques to make a quadcopter become an armed quadcopter. In this research, we will use the PID control technique to stabilize the quadcopter; Proportional Integrated Derivative Controller (PID) is included as feedback to form a control loop. The measures an error value continuously as the difference between the target setpoint (SP) and a calculated process variable (PV) and applies a correction based on proportional, integral, and derivative terms.

1.2 Problem Statement

A quadcopter is inherently unstable. When quadcopter is given a shock loading in this paper case, a gun, and becomes an armed quadcopter, the quadcopter is expected to maintain its stability. Initially, the quadcopter is at a hover condition then the gun is fired by the quadcopter. The motion after firing the gun is analyzed.

Using the Xcos block to simulate quadcopter motion and classical control theory to analyze. the PID controller can be used to control the quadcopter's motion, so when instability happens, it can be controlled.

There are several questions that this paper wants to investigate. First, when the gun is fired, and recoil is acting on the quadcopter, what happens to the quadcopter stability? Does the quadcopter becomes unstable and directly fall, or does it have time to stabilize itself? The next question is, how much time is needed to turn an unstable quadcopter to become stable?

1.3 Research Goals

This research aims to understand what happened to the quadcopter when it is given a shock loading (impulse). In this paper, the impulse is modeled on a gun. Then the quadcopter is controlled by a PID control.

The objectives of this research are:

- To create representative physical modelling of an armed quadcopter based on DJI Matrice 100;
- To model mathematically the translational, and rotational momentum generated by the recoil effect;
- To design/implement PID control to the non-linear equation of motion.

The results of this research are expected:

- To be use in designing armed quadcopter stability.
- To contribute for initial research in quadcopter defense purposes in indonesia.

1.4 Research Scope

There are several things in this thesis that need to be paid some attention.

- X-configuration quadcopter.

- Two rotors rotate clockwise, and the other two rotate counter-clockwise, hence the gyroscopic effect is negligible.
- The quadcopter has a rigid structure and almost symmetrical shape.
- The location of mounted gun is aligned with the z-axis of the body frame.
- Initially the quadcopter is under equilibrium condition.
- The control is applied immediately (no delay).

1.5 Research Approach

Steps that will be taken for this thesis are:

1. Determine the base quadcopter and do the physical modelling.
2. Determine the base gun and do the gun physical modelling.
3. Derive the equation of motion of a quadcopter.
4. Make the XCOS model using the derived equation of motion and use the quadcopter's physical parameters.
5. Test by simulation the quadcopter basic motions: roll, pitch and yaw.
6. Use the gun physical modelling as a impulse disturbance to the quadcopter.
7. Implement the PID controller to control the quadcopter.

CHAPTER 2
LITERATURE REVIEW

2.1 Theoretical Perspective

A quadcopter is an inherently unstable system. A control technique is needed for the quadcopter to become stable. One of the most popular control technique to date is the PID control technique. The proportional integral derivative (PID) control technique is a closed-loop system. In closed-loop control, the system compares the input and output of the system, and it can adjust the system automatically. The example of a closed-loop system is a cruise control of a car. A car is set at 60km/h when there is an uphill the car will slow down. The closed-loop control system takes it into comparison, and it will speed up the car to be 60km/h. The PID control technique is more complicated than the traditional closed-loop system.(*How Does a PID Controller Work? - Structure & Tuning Methods*, 2020).

There are several advantages of a PID controller. The first advantage is It only acts on the error between the signal that is desired and the controlled signal. Therefore, no further measurements are needed for internal states. The second advantage is Besides specific structural properties of the plant/process, and the tuning involves little plant information. The tuning may be done by trial and error, or a table of views. There is not much expertise required for tuning, so few middle-skilled technicians can efficiently perform the task. The third advantage is If properly tuned, it is efficient and robust against certain typical uncertainties. The fourth advantage is Easy to implement in hardware (via filters) and easy to implement with microcontrollers, PLC. A middle-level programmer can write no complex codes to build.

The controller is not really appropriate in general for nonlinear plants or in layman language; the controller may not be able to provide the optimal output for a changing environment/operating point in high-end applications like fighter aircraft, submarines, precision robotics.

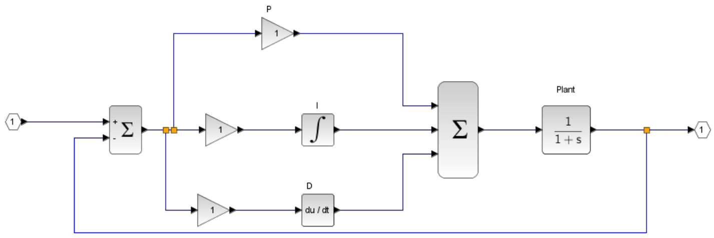

FIGURE 2.1: PID Controller Diagram

To control a process variable (system output), the PID controller uses proportional integral and derivative gain. They obtain input from process output and compare it for calculating the error signal with setpoint value. The PID control uses the three controllers or two controllers to work, and individually they also have their advantage and disadvantage. Figure 2.1 is a PID Controller Diagram what PID block is made of.

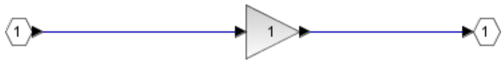

FIGURE 2.2: P-Controller

The proportional or P-controller produces output that is proportional to the current $e(t)$ error. It compares the desired or set point to the actual value or process value of feedback. For the output, the resulting error is multiplied by a proportional constant. If the error value is zero, then the output of this controller is zero. The advantages of proportional mode are the ability to minimize the wasted time from stiction and backlash, minimize rise time, minimize peak error, Minimize integrated error. However, the proportional mode disadvantages may cause abrupt changes in upset output operators, abrupt changes in output upset other loops and amplification of noise. Figure 2.2 gives a P-controller diagram.

Because of the limitation of the P-controller where an offset between the process variable and the setpoint still exists, I-controller is required, which provides the necessary action to remove the steady-state error. It spreads the error over time until the error value hits null. It retains the value to the final system of control at which error is zero. Where a negative error occurs, integral control decreases its efficiency.

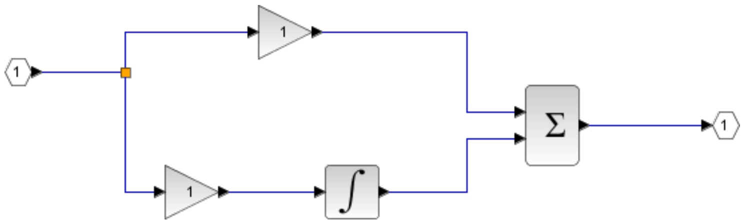

FIGURE 2.3: PI-Controller

It restricts reaction speed and affects system stability. Response pace is increased with decreased integral gain. Integral Mode Advantages are Eliminate offset, Minimize integrated error, Smooth movement of output Integral Mode Disadvantages are Limit cycles, Overshoot, Runaway of open-loop unstable reactors.Figure 2.3 is a PI-Controller diagram.

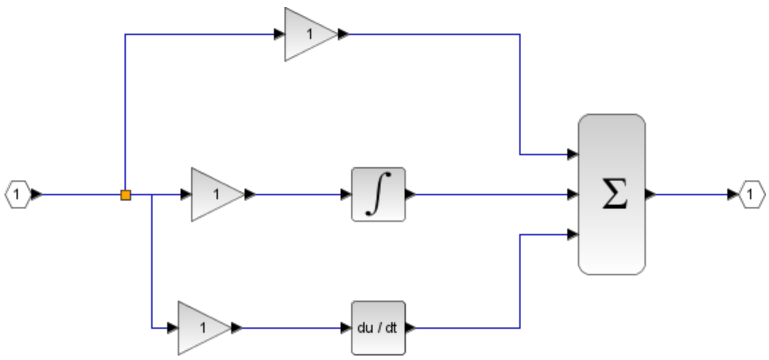

FIGURE 2.4: PID-Controller

I-controller is not capable of predicting possible error behaviours. So, it usually responds until the setpoint is changed. D-controller surmounts this issue by predicting potential error behaviour. Its output depends on the rate of time-related change in error, multiplied by the derivative constant. It gives the output kick start while increasing the machine response. Derivative mode advantages are the ability to minimize the wasted time from stiction and backlash, minimize rise time, minimize peak error, and minimize integrated error. While the disadvantages it may produce are abrupt changes in upset output operators, abrupt changes in output upset other loops and amplification of noise.

Before PID controller functions, it must be tuned to match the process dynamics to be controlled. Designers give the default values for terms P, I and D. Different types of tuning methods are designed to tune the PID controllers who require a lot of operator attention to select the best additive, integral, and derivative gains values. Figure 2.4 is a PID-Controller diagram.

Trial and error method: It is a simple method of PID controller tuning. The controller can be tuned whilst the machine or unit is running. In this process, we must first set Ki and Kd values to zero and increase the proportional term (Kp) until the oscillating behaviour of the device is reached. Once it is oscillating, adjust Ki (Integral Term) to avoid oscillations and finally adjust D to get a fast reaction.

Ziegler-Nichols works first the Ki, and the Kd turns to zero. The Kp is gradually increased until the system becomes critically stable. When the loop oscillated with constant amplitude is when the critically stable system is achieved. The Kp value is called final gain, Ku, and the period associated with such amplitude is called the final period, Pu. By using Table 2.1 and Ku and the Pu, the Kp, Ti, and Td can be obtained. Then the Ki and Kd can be obtained by using Table 2.2 The PID value is Kp, Ki, and Kd. Figure 2.5 is an example of the critically stable wave that use in Ziegler-Nichols.

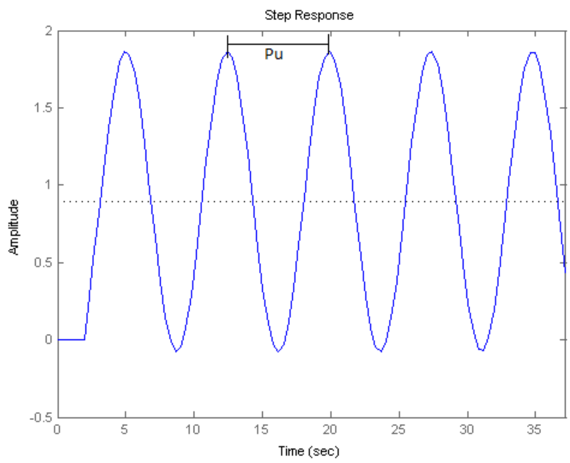

FIGURE 2.5: Critically Stable Wave

	Kp	Ti	Td
P	0.5Ku	-	-
PI	0.45Ku	Tu/1.2	-
PID	0.6Ku	Tu/2	Tu/8

Table 2.1: Ziegler-Nichols 1

	Ki=Kp/Ti	Kd=KpTd
P	-	-
PI	0.54Ku/Tu	-
PID	1.2Ku/Tu	0.075KuTu

Table 2.2: Ziegler-Nichols 2

2.2 Newtonian Mechanics vs Lagrangian Mechanics

Classical or often referred to as Newtonian mechanics, is how a scientist describes equation in motion with just a few equations. The mechanical study of motion everyday objects and the forces that affect them is called classical mechanics. Nearly all of it built on Isaac newton's mechanical law and principles. It includes Newton's First Law of Motion, Newton's Second Law of Motion, Newton's Third Law of Motion, Newton's Law of Universal Gravitation, Law of Conservation of Energy.

Lagrangian mechanics, which is $L = T - V$. it says that kinetic energy minus potential energy. Lagrangian mechanics is derived from the principle of least action. Lagrange says any physical system will follow a path of least length it derived from Any system undergone some change it will behave in such a way that action is minimized. Unlike newton mechanics, Lagrangian mechanics doesn't consider all the forces on the object; instead, it uses the difference between kinetic energy and mechanical energy.

Newton mechanics is used in this thesis. It is chosen because the quadcopter is a rigid body. The simulation begins when the quadcopter is at an equilibrium condition, then the gun that the quadcopter fired produce an impulse that affects the quadcopter. Newton's Euler equation can be used to calculate it.

2.3 Free-Body Diagram (FBD) of a Quadcopter and Its Explanation

FIGURE 2.6: DJI Matrice 100
(*M100 | 3D CAD Model Library | GrabCAD*, 2020)

The figure 2.6 is shown the free body diagram of DJI matrice 100. DJI matrice 100 is a quadcopter from a company called Da Jiang Innovation (DJI). The quadcopter was launch on the 6th of July in 2015. The quadcopter has a diagonal wheelbase of 650 mm, and it has a payload of up to 1 kg, it also has flying time up to 40 minutes. The DJI matrice 100 also comes with two developer kits to make apps.

The quadcopter has 6 degrees of freedom. It can go translational motion the movement along the x, y, and z axes of the quadcopter. The quadcopter also can turn on the axes. The Moment on the x-axis is when quadcopter roll, Moment on the y-axis is for the quadcopter to pitch, and Moment in the z-axis is for the quadcopter to yaw.

The quadcopter produces thrust using the four motors and the four rotors. The quadcopter also affected by gravity and its weight. For the quadcopter to fly, the thrust from the quadcopter has to exceed the force that gravity and weight. In this case, with the quadcopter weight at 2355 g and the maximum payload of 1245 g, so the quadcopter thrust has to exceed the maximum take-off weight of 3600 g, then the quadcopter can take-off. To make the quadcopter hovering, it must have thrust equal to the quadcopter weight, and then it will hovers.

The quadcopter flies using only four propellers. The propellers also fix in place, meaning it cannot change its angle, so for the quadcopter to manoeuvre around, it needs the variation of the thrust of the propeller to moments, then it can go around even turning. For the quadcopter to move forward, it has to pitch forward first by making the back propeller faster and slowing the front propeller the propeller pitching forward. Then by increasing the same amount of thrust gradually, the quadcopter will move forward. The same technique also uses in backward, leftward, and rightward movement. Then for the quadcopter to yaw, the amount of clockwise and counter-clockwise rotors must be adjusted. For the quadcopter to yaw clockwise, the clockwise rotor direction will speed up, and the counter-clockwise direction motor will be slowed down then the quadcopter will yaw clockwise. It is the same for the counter-clockwise yaw motion, but instead of the clockwise direction motor speed up, it is the counter-clockwise rotors that speed up.

2.4 Assumptions

A gun in this research is assuming to be attached to a quadcopter of DJI matrice 100. The quadcopter has a payload of up to 1 kg, and the gun with a fully loaded magazine is assumed to have 800 grams of weight. There is a leftover payload of 200 grams for the attachment of a gun to the quadcopter. The quadcopter is a rigid body meaning the quadcopter stays the same shape and will not bend. A quadcopter is a naturally unstable system. It can move easily by a disturbance and will have a difficulty to come to stable naturally. Because of that electronic system controller is needed with a control algorithm in the onboard computer to stabilize the quadcopter. The quadcopter centre of gravity is assumed to be at the centre of the quadcopter so that it will be stable.

This research is assuming the quadcopter at hover condition. It has the same amount of thrust and weight ratio. Then the gun that is attached to the quadcopter is fired. The quadcopter assumes to experience a disturbance because of the gun recoils. When the disturbance happens, the quadcopter will move opposite the direction of the bullet, and by using a control algorithm, the quadcopter can balance itself and make it stable.

2.5 Propulsion Modelling

For a quadcopter, fixed-pitch propellers are often used. Propeller performance depends on its thrust T and torque M.

$$T = C_T \rho \left(\frac{N}{60}\right)^2 D_p^4 \tag{2.1}$$

$$M = C_M \rho \left(\frac{N}{60}\right)^2 D_p^5 \tag{2.2}$$

N (RPM) is the propeller speed, Dp (m) is the diameter of the propeller. CT and CM are dimensionless thrust coefficient and a torque coefficient, respectively.

the air density ρ (kg/m3), which varies to the local altitude h (m) and the temperature Tt (Celsius), is written as

$$\rho = \left(\frac{273P_a}{101325(273+Tt)}\right)\rho_0 \tag{2.3}$$

where the standard air density $\rho_0 = 1.293(kg/m^3)(273K)$ the atmospheric pressure Pa is obtained as

$$P_{\mathrm{a}} = 101325\left(1 - 0.0065\frac{h}{273+T_t}\right)^{5.2561} \tag{2.4}$$

The height of a quadcopter varies, so h and Tt are treated as constant in the performance evaluation. the coefficient lift is

$$\begin{aligned} C_{\mathrm{T}} &= f_{C_{\mathrm{T}}}\left(\Theta_{\mathrm{p}}\right) \triangleq 0.25\pi^3\lambda\zeta^2 B_{\mathrm{p}} K_0 \frac{\varepsilon \arctan\frac{H_{\mathrm{p}}}{\pi D_p} - \alpha_0}{\pi A + K_0} \\ C_{\mathrm{M}} &= f_{C_{\mathrm{M}}}\left(\Theta_{\mathrm{p}}\right) \triangleq \tfrac{1}{8A}\pi^2 C_{\mathrm{d}}\zeta^2\lambda B_{\mathrm{p}}^2 \end{aligned} \tag{2.5}$$

where the coefficient drag

$$C_{\mathrm{d}} = C_{\mathrm{fd}} + \frac{\pi A K_0^2}{e} \frac{\left(\varepsilon \arctan \frac{H_p}{\pi D_p} - \alpha_0\right)^2}{\left(\pi A + K_0\right)^2} \tag{2.6}$$

C_l is coefficient lift, α_{ab} is absolute angle of attack of the propeller, K_0 is $K_0 \approxeq 6.11$, A is $A = \frac{D_p}{c_p}$ is an aspect ratio of where c_p is the blade average chord length. the drag coefficient ε is correction factor that arise due to downwash, the ostwald factor e is selected from 0.7 to 0.9, α_0 is the zero lift angle of attack, C_{fd} is zero-lift drag coefficient.

2.6 Derive the Equation of Motion

The quadcopter structure is presented in Figure including the corresponding angular velocities, torques and forces created by the four rotors (numbered from 1 to 4).

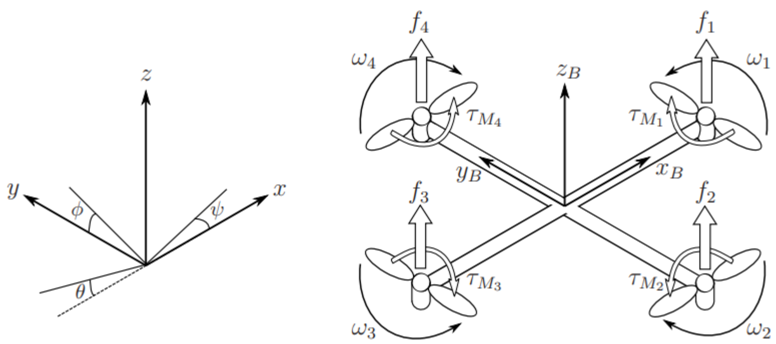

FIGURE 2.7: The Inertial and Body Frame of Quadcopter (Luukkonen, 2020)

The quadcopter's absolute linear position is described in the x, y, z axes inertial frame ξ. In the inertial frame, the attitude, i.e. the angular position, is defined With three angles from Euler η. Pitch angle θ is obtained by rotation of the quadcopter around the y-axis. Roll angle ϕ is achieved by the rotation around the x-axis and yaw angle the rotation around the z-axis produces ψ. Vector q includes representations of the linear and angular positions.

$$\xi = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \quad \eta = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}, \quad q = \begin{bmatrix} \xi \\ \eta \end{bmatrix} \tag{2.7}$$

The quadcopter's centre of mass is the origin of the body frame. V_B obtains the linear velocities in the body frame, and the angular velocities are obtained by ν.

$$V_B = \begin{bmatrix} v_{x,B} \\ v_{y,B} \\ v_{z,B} \end{bmatrix}, \quad \nu = \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{2.8}$$

From the body frame to the inertial frame, the rotation matrix is:

$$R = \begin{bmatrix} C_\psi C_\theta & C_\psi S_\theta S_\phi - S_\psi C_\phi & C_\psi S_\theta C_\phi + S_\psi S_\phi \\ S_\psi C_\theta & S_\psi S_\theta S_\phi + C_\psi C_\phi & S_\psi S_\theta C_\phi - C_\psi S_\phi \\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi \end{bmatrix} \tag{2.9}$$

Wherein $Sx = \sin(x)$ and $Cx = \cos(x)$. Therefore the rotation matrix $\boldsymbol{R}$ is orthogonal $\boldsymbol{R}^{-1} = \boldsymbol{R}^T$, which is the matrix of rotation from the inertial frame to the body frame. The transformation matrix for angular velocities from the inertial frame to the body frame is W_η, and from the body frame to the inertial frame is W_η^{-1}

$$\dot{\eta} = W_\eta^{-1}\nu, \quad \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & S_\phi T_\theta & C_\phi T_\theta \\ 0 & C_\phi & -S_\phi \\ 0 & S_\phi / C_\theta & C_\phi / C_\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{2.10}$$

$$\nu = W_\eta \dot{\eta}, \quad \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -S_\theta \\ 0 & C_\phi & C_\theta S_\phi \\ 0 & -S_\phi & C_\theta C_\phi \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{2.11}$$

Where In $Tx = \tan(x)$.If $\theta \neq (2k-1)\phi/2, (k \in \mathbb{Z})$, the matrix is invertible.

It is assumed that the quadcopter has a rigid body and a symmetrical structure. Thus the inertia matrix is the diagonal matrix I in which Ixx = Iyy.

$$I = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \tag{2.12}$$

In the direction of the rotor axis, the angular velocity of the rotor i denoted as ω_i produces force f_i. The angular velocity and the rotor acceleration also produce torque around the rotor axis τ_{M_i}

$$f_i = k\omega_i^2, \quad \tau_{M_i} = b\omega_i^2 + I_M\dot{\omega}_i \tag{2.13}$$

The influence of $\dot{\omega}_i$ is generally considered small and is therefore omitted.

The combined rotor forces generate Thrust T in the direction of the z-axis of the body. Torque τ_B is made up of torques τ_ϕ, τ_θ, and τ_ψ in the course of the corresponding angles of the body frame.

$$T = \sum_{i=1}^{4} f_i = k\sum_{i=1}^{4} \omega_i^2, \quad T^B = \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix} \tag{2.14}$$

$$\tau_B = \begin{bmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} lk\left(-\omega_2^2 + \omega_4^2\right) \\ lk\left(-\omega_1^2 + \omega_3^2\right) \\ \sum_{i=1}^{4} \tau_{M_i} \end{bmatrix} \tag{2.15}$$

In which l is the distance between the rotor of the quadcopter and its centre of mass. The rolling motion is obtained by raising the velocity of the second rotor and increasing the velocity of the fourth rotor. Similarly, the pitch movement is acquired by reducing the first rotor speed and rising the third rotor speed. Yaw motion is gained by increasing the angular velocities of two opposite rotors and cutting the other two velocities (Luukkonen, 2020).

2.6.1 Newton-Euler Equation

It is assumed that the quadcopter is a rigid body, and thus Newton-Euler equations can be used to describe its dynamics. In the body frame, the force required to accelerate the mass $m\dot{V}_B$ and the centrifugal force $\nu \times (mV_B)$ is equal to the $R^T G$ gravity and the total T_B rotor thrust.

$$m\dot{V}_B + \nu \times (mV_B) = R^T G + T_B \tag{2.16}$$

The centrifugal force is nullified in the inertial frame. So only the gravitational force and the magnitude and direction of the thrust contribute to the quadcopter's acceleration.

$$m\ddot{\xi} = G + RT_B \tag{2.17}$$

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = -g \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{T}{m} \begin{bmatrix} C_\psi S_\theta C_\phi + S_\psi S_\phi \\ S_\psi S_\theta C_\phi - C_\psi S_\phi \\ C_\theta C_\phi \end{bmatrix} \tag{2.18}$$

In the body frame, the external torque τ is equal to the angular acceleration of the inertia $I\dot{\nu}$, the centripetal forces $\nu \times (I\nu)$ and the gyroscopic forces Γ.

$$I\dot{\nu} + \nu \times (I\nu) + \Gamma = \tau \tag{2.19}$$

$$\dot{\nu} = I^{-1} \left(- \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} I_{xx}p \\ I_{yy}q \\ I_{zz}r \end{bmatrix} - I_r \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \omega_\Gamma + \tau \right) \tag{2.20}$$

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} (I_{yy} - I_{zz})\, qr/I_{xx} \\ (I_{zz} - I_{xx})\, pr/I_{yy} \\ (I_{xx} - I_{yy})\, pq/I_{zz} \end{bmatrix} - I_r \begin{bmatrix} q/I_{xx} \\ -p/I_{yy} \\ 0 \end{bmatrix} \omega_\Gamma + \begin{bmatrix} \tau_\phi/I_{xx} \\ \tau_\theta/I_{yy} \\ \tau_\psi/I_{zz} \end{bmatrix} \tag{2.21}$$

in which $\omega_\Gamma = \omega_1 - \omega_2 + \omega_3 - \omega_4$. The angular accelerations in the inertial frame are then attracted from the body frame accelerations with the transformation matrix $\boldsymbol{W}_\eta^{-1}$ and its time derivative

$$
\begin{aligned}
\ddot{\boldsymbol{\eta}} &= \frac{\mathrm{d}}{\mathrm{d}t}\left(\boldsymbol{W}_\eta^{-1}\boldsymbol{\nu}\right) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\boldsymbol{W}_\eta^{-1}\right)\boldsymbol{\nu} + \boldsymbol{W}_\eta^{-1}\dot{\boldsymbol{\nu}} \\
&= \begin{bmatrix} 0 & \dot{\phi}C_\phi T_\theta + \dot{\theta}S_\phi/C_\theta^2 & -\dot{\phi}S_\phi C_\theta + \dot{\theta}C_\phi/C_\theta^2 \\ 0 & -\dot{\phi}S_\phi & -\dot{\phi}C_\phi \\ 0 & \dot{\phi}C_\phi/C_\theta + \dot{\phi}S_\phi T_\theta/C_\theta & -\dot{\phi}S_\phi/C_\theta + \dot{\theta}C_\phi T_\theta/C_\theta \end{bmatrix} \nu + \boldsymbol{W}_\eta^{-1}\dot{\nu}
\end{aligned}
\tag{2.22}
$$

2.6.2 Euler-Lagrange Equation

The Lagrangian $\mathcal{L}$ is the sum of the translational E_{trans} and rotational E_{rot} energies minus potential energy E_{pot}.

$$
\begin{aligned}
\mathcal{L}(\boldsymbol{q}, \dot{\boldsymbol{q}}) &= E_{\text{trans}} + E_{\text{rot}} - E_{\text{pot}} \\
&= (m/2)\dot{\boldsymbol{\xi}}^{\mathrm{T}}\dot{\boldsymbol{\xi}} + (1/2)\boldsymbol{\nu}^{\mathrm{T}}\boldsymbol{I}\boldsymbol{\nu} - mgz
\end{aligned}
\tag{2.23}
$$

the Euler-Lagrange equations with external forces and torques are

$$
\begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{\tau} \end{bmatrix} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial \mathcal{L}}{\partial \dot{\boldsymbol{q}}}\right) - \frac{\partial \mathcal{L}}{\partial \boldsymbol{q}} \tag{2.24}
$$

The linear and angular components are not mutually dependent, and they can be studied separately. The total thrust of the rotors is a linear external force. The Euler-Lagrange linear equations are

$$
\boldsymbol{f} = \boldsymbol{R}\boldsymbol{T}_B = m\ddot{\boldsymbol{\xi}} + mg\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{2.25}
$$

which is equivalent to Equation (10).

The Jacobian matrix $\boldsymbol{J}(\boldsymbol{\eta})$ from ν to $\dot{\eta}$ is

$$
\boldsymbol{J}(\boldsymbol{\eta}) = \boldsymbol{J} = \boldsymbol{W}_\eta^{\mathrm{T}}\boldsymbol{I}\boldsymbol{W}_\eta \tag{2.26}
$$

$$= \begin{bmatrix} I_{xx} & 0 & -I_{xx}S_\theta \\ 0 & I_{yy}C_\phi^2 + I_{zz}S_\phi^2 & (I_{yy} - I_{zz})\, C_\phi S_\phi C_\theta \\ -I_{xx}S_\theta & (I_{yy} - I_{zz})\, C_\phi S_\phi C_\theta & I_{xx}S_\theta^2 + I_{yy}S_\phi^2 C_\theta^2 + I_{zz}C_\phi^2 C_\theta^2 \end{bmatrix} \tag{2.27}$$

Thus, the rotational energy E_{rot} can be expressed in the inertial frame as

$$E_{rot} = (1/2)\nu^{\mathrm{T}} I \nu = (1/2)\ddot{\eta}^{\mathrm{T}} J \ddot{\eta} \tag{2.28}$$

The external angular force is the torques of the rotors. The angular Euler-Lagrange equations are

$$\boldsymbol{\tau} = \boldsymbol{\tau}_B = \boldsymbol{J}\ddot{\boldsymbol{\eta}} + \frac{\mathrm{d}}{\mathrm{d}t}(\boldsymbol{J})\dot{\boldsymbol{\eta}} - \frac{1}{2}\frac{\partial}{\partial \boldsymbol{\eta}}\left(\dot{\boldsymbol{\eta}}^{\mathrm{T}}\boldsymbol{J}\dot{\boldsymbol{\eta}}\right) = J\ddot{\boldsymbol{\eta}} + \boldsymbol{C}(\boldsymbol{\eta}, \dot{\boldsymbol{\eta}})\dot{\boldsymbol{\eta}} \tag{2.29}$$

in which the matrix $\boldsymbol{C}(\boldsymbol{\eta}, \dot{\boldsymbol{\eta}})$ is the Coriolis term, containing the gyroscopic and centripetal terms

The matrix $\boldsymbol{C}(\boldsymbol{\eta}, \dot{\boldsymbol{\eta}})$ has the form, as shown in

$$\boldsymbol{C}(\boldsymbol{\eta}, \dot{\boldsymbol{\eta}}) = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \tag{2.30}$$

$$C_{11} = 0$$

$$C_{12} = (I_{yy} - I_{zz})\left(\dot{\theta} C_\phi S_\phi + \dot{\psi} S_\phi^2 C_\theta\right) + (I_{zz} - I_{yy})\,\dot{\psi} C_\phi^2 C_\theta - I_{xx}\dot{\psi} C_\theta$$

$$C_{13} = (I_{zz} - I_{yy})\,\dot{\psi} C_\phi S_\phi C_\theta^2$$

$$C_{21} = (I_{zz} - I_{yy})\left(\dot{\theta} C_\phi S_\phi + \dot{\psi} S_\phi C_\theta\right) + (I_{yy} - I_{zz})\,\dot{\psi} C_\phi^2 C_\theta + I_{xx}\dot{\psi} C_\theta$$

$$C_{22} = (I_{zz} - I_{yy})\,\dot{\phi} C_\phi S_\phi$$

$$C_{23} = -I_{xx}\dot{\psi}S_\theta C_\theta + I_{yy}\dot{\psi}S_\phi^2 S_\theta C_\theta + I_{zz}\dot{\psi}C_\phi^2 S_\theta C_\theta$$

$$C_{31} = (I_{yy} - I_{zz})\,\dot{\psi}C_\theta^2 S_\phi C_\phi - I_{xx}\dot{\theta}C_\theta$$

$$\begin{aligned} C_{32} = &(I_{zz} - I_{yy})\left(\dot{\theta}C_\phi S_\phi S_\theta + \dot{\phi}S_\phi^2 C_\theta\right) + (I_{yy} - I_{zz})\,\dot{\phi}C_\phi^2 C_\theta \\ &+ I_{xx}\dot{\psi}S_\theta C_\theta - I_{yy}\dot{\psi}S_\phi^2 S_\theta C_\theta - I_{zz}\dot{\psi}C_\phi^2 S_\theta C_\theta \end{aligned}$$

$$C_{33} = (I_{yy} - I_{zz})\,\dot{\phi}C_\phi S_\phi C_\theta^2 - I_{yy}\dot{\theta}S_\phi^2 C_\theta S_\theta - I_{zz}\dot{\theta}C_\phi^2 C_\theta S_\theta + I_{xx}\dot{\theta}C_\theta S_\theta$$

Equation (2.29) leads to the differential equations for the angular accelerations which are equivalent with Equations (2.21) and (2.22)

$$\ddot{\eta} = J^{-1}\left(\tau_B - C(\eta, \dot{\eta})\dot{\eta}\right) \tag{2.31}$$

2.6.3 Aerodynamical Effect

The preceding model is about simplifying complex, dynamic interactions by Including drag force created by the air resistance to implement more practical quadcopter behaviour. This is formulated in Equations (2.18) and (2.21), the matrix of diagonal coefficient associating the linear velocities with force slowing the motion.

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = -g\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{T}{m}\begin{bmatrix} C_\psi S_\theta C_\phi + S_\psi S_\phi \\ S_\psi S_\theta C_\phi - C_\psi S_\phi \\ C_\theta C_\phi \end{bmatrix} - \frac{1}{m}\begin{bmatrix} A_x & 0 & 0 \\ 0 & A_y & 0 \\ 0 & 0 & A_z \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} \tag{2.32}$$

in which A_x, A_y,and A_z are the drag force coefficients for velocities in the corresponding directions of the inertial frame.

The model may incorporate many other aerodynamic effects. Thrust dependence was studied on the angle of attack, blade flapping, and airflow disruptions. The role of aerodynamic effects is complicated, and it is difficult to model the effects. Some of the results may only have a noticeable effect at high velocities.

Thus, these effects are excluded from the model, and the simple model presented is used.

2.7 Impulse Modelling from a Gun Firing

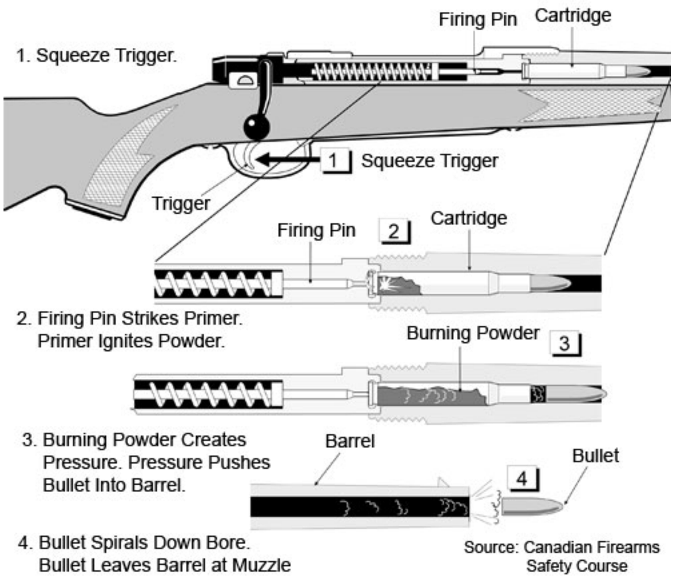

FIGURE 2.8: Gun Firing Model
(*Berapa kecepatan lontar dari sebuah peluru pistol? - Quora*, 2020)

The picture 2.8 is shown on how a gun is fired. After the gun is loaded with a bullet, the shooter can squeeze the trigger. There is a firing pin in the gun, and it will ignite the gun powder inside the gun. The powder creates pressure, and it will push the bullet forward. The bullet has extra spinning for more accurate firing. As the bullet leaves the barrel, there will be recoil. This recoil is the force that this research will use for the gun disturbance.

To measure recoil momentum have to be understood first. Momentum (P) is a measurement of mass in motion. how much mass in how much motion. the equation of momentum is $P = m.v$. m is mass of the object, and v is the velocity of the object. For the gun case, there are two objects in play. The gun itself and the bullets that will be fired. the equation to be used in the gun case is the conservation of momentum which is

$$P_{\text{initial}} = P_{\text{final}} \tag{2.33}$$

the momentum becomes

$$M_{G_i}V_{G_i} + M_{B_i}V_{B_i} = M_{G_f}V_{G_f} + M_{B_f}V_{B_f} \tag{2.34}$$

$$P = MV \tag{2.35}$$

Gun of choice Figure 2.9 in this is P-3A Kal.7.65 mm with a weight of 794 gram and bullet FIgure 2.10 is mu15-tj with an average velocity of 335 m/s and weight of 60 gram. The pistol and the bullet manufactured by PT PINDAD. Combined the pistol and the bullet with the quadcopter combine weight is 3.259 Kg. (*Fiocchi Ammunition | Made By Shooters For Shooters*, n.d.)

FIGURE 2.9: Pistol P3A-1
(*PT. Pindad (Persero) - P-3A Kal. 7.65 mm*, 2020)

FIGURE 2.10: Bullet MU15-TJ1
(*PT. Pindad (Persero) - Kaliber 7.65 x 17 mm*, 2020)

$$3.259_k g(0) + 60_g(0) = 3.259_K g(x) + 60_g(335_{m/s}) \tag{2.36}$$

$$x = -6.16 \text{ m/s} \tag{2.37}$$

$$P = 3259_g * -6.16_{m/s} = -20_{kg.m/s} = -20_{N.s} \tag{2.38}$$

2.8 About Stability and Control

Stability and control of quadcopter is an essential component. The stability characterizes the moment of an object, a quadcopter of when it is flying or hovering, and the controller release the control the quadcopter has to come back to its equilibrium state in this case hovering. The control describes the response to a pilot's actions to induce and maintain equilibrium or execute manoeuvres.

A quadcopter can be considered stable when it is at a hover condition then there is some disturbance from the outside like the wind. The quadcopter will gradually shift to become stable when the disturbance happens. The quadcopter control is when Maintaining equilibrium during phases of ight for which no or gradual changes in ight conditions occur, executing a transition between two states of equilibrium, or manoeuvring. A quadcopter is inherently unstable because it flies and turns only by using its rotor and angle of attack. When quadcopter is in hover condition, it just flies up using the same rotor speed. If somehow the quadcopter is given and angle of attack, it will move on that angle. In outdoor flight, there always be a disturbance, especially from the wind. When wind disturbs the quadcopter to make the quadcopter stay hover, it will need a stability and control technique.

Stability in aviation can be divided into two types, static stability, and dynamic stability. Static stability also divided into three types, positive static stability, neutral static stability, and negative static stability. Positive static stability is when a quadcopter is in hover, and it experiences some disturbance like the wind. The quadcopter will stabilize itself. Neutral static stability is quadcopter at hover condition and is blown by the wind; it follows where the wind blows. Negative static stability is the opposite of positive stability. Meaning when the quadcopter is given a disturbance, not only it goes along with the disturbance it even makes the disturbance bigger.

The dynamic stability also divided into three positive dynamic stability, neutral dynamic stability and negative dynamic stability. The positive dynamic stability is when the quadcopter moving, then take the finger off the controller quadcopter, will gradually come to hover. The neutral dynamic stability is instead of stopping or hovering the quadcopter still moving. In the negative dynamic stability, when the controller takes the finger off the controller, it will move even faster.

Quadcopter inherently lean-to negative stability. It will need some stability and control techniques to make a quadcopter become an armed quadcopter. In this research, we will use the PID control technique to stabilize the quadcopter. Proportional Integrated Derivative Controller (PID) is feedback from a control loop. The measures an error value continuously as the difference between the target setpoint (SP) and a calculated process variable (PV) and applies a correction based on proportional, integral, and derivative terms.

In stability and control, there is a term of step response or system time response. Time response is a time that the control system will take to reach a steady-state value. System time response can be divided into two parts transient response and steady-state response. Transient response varies with time. It has parameters of rising time, which is time that goes from 0 to 90% of the final value, overshoots the maximum time when the system goes above the final value. Settling time is' the time when the system goes from 0 to stay at 2% of the final value and steady-state error which is the error of the system that deviates from the final value. The steady-state response is the response after the system attains steady-state values.

By knowing the parameters of the system in transient response, the system can be controlled by using a control technique. By knowing the rising time, the system can be controlled in how fast the object wants to be moved. For example, a quadcopter from 0 to hover can be controlled on how the time it takes. By knowing overshoot, the quadcopter can be controlled on how high is the altitude error. By knowing the settling time, the quadcopter can be controlled on how fast it goes to hover. By knowing the steady-state error, the quadcopter can be controlled, so the error is minimized.Figure 2.11 is a step response system graph(*The 3 Types Of Static And Dynamic Aircraft Stability*, 2020).

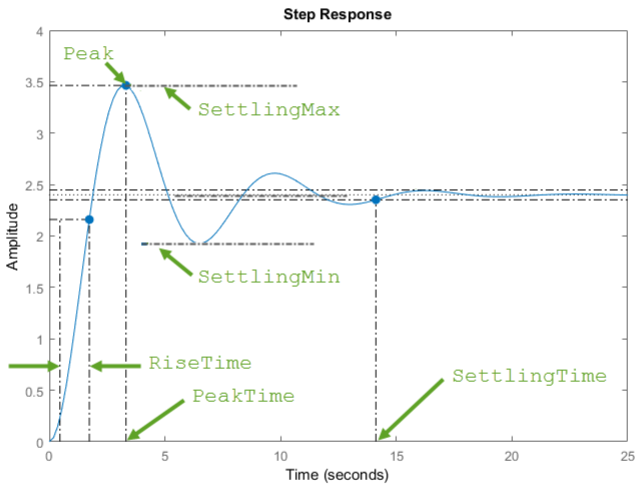

FIGURE 2.11: Step Response

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Overview

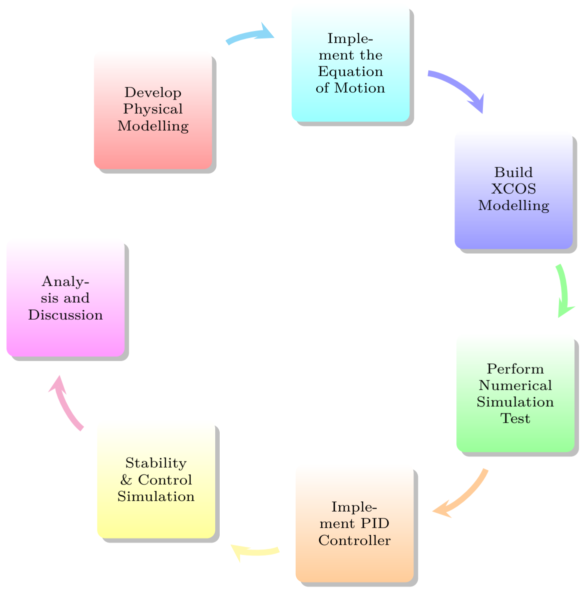

FIGURE 3.1: Chart Overview

3.2 Design and Instrumentation

This research will focus on quadcopter stability and control. initially, the quadcopter is on the hover condition then it will get a disturbance by a gun recoil.

The research will be conducted by a simulation method Scilab. XCOS block in Scilab is used to simulate quadcopter physical modelling and movement then by using PID the quadcopter is controlled.

3.3 Data Analysis

The data analysis for this research will be conducted by simulation. The simulation will be conducted in XCOS Block. XCOS block is a program inside Scilab. XCOS block will be used for data analysis for the following parameter but not limited to:

- Quadcopter in hovering position.
- Quadcopter in motion.
- Recoil of a gun affecting a quadcopter in hover.
- PID control computation for the quadcopter.

Shown in the flow chart 3.1 is the step of progress on this thesis.start of this thesis, the first thing to do is learning the XCOS program in Scilab and creating the introduction and chapter 1. The equation of motion part in this thesis is mainly searching for the best equation of motion for this research. The quadcopter equation of motion can be found using two different equations of motion. The first type using the Newton-Euler equation of motion and the second is the Euler Lagrange equation of motion. The most significant difference from the two-equation is the Newton-Euler equation considers all the forces that affect the quadcopter and the Euler Lagrange consider the quadcopter placement in space in a specific time and the equation integrates the beginning and the end of the quadcopter placement.

The physical modelling of the quadcopter is taken from the model quadcopter that is chosen. The chosen model quadcopter for this thesis is DJI matrice 100. The DJI matrice 100 is chosen because of the payload capacity up to 1kg and the data availability from the internet. The impulse modelling will be using the P-3A Kal. 7.65 mm from PT.Pindad. The chosen gun is because the small gun and calibre so the recoil will not be too bad and the weight with the gun fully loaded will be about 800g. XCOS modelling is needed for virtual modelling. The simulation will take place when the quadcopter is hovering. Then the gun is fired, and the recoil is considered as the disturbance. The analysis part of this thesis is considering what happens to the quadcopter after the gun firing can the quadcopter stabilize itself.

3.4 Physical Modelling

The quadcopter requirement for this research is that it needs to have a payload more than the gun and ammo combined with having the quadcopter flies on the air. An octocopter has been used in similar conditions as an armed drone, so it needs to be a quadcopter. The specification of octocopter also challenging to find because the widespread use of drones is the quadcopter. For physical modelling, the quadcopter needs to have a good template by taking the specification of the quadcopter that has been sold. The quadcopter preferably also have been researched.

The target quadcopter for this thesis is the SONGAR drone by ASISGUARD. The SONGAR drone is a drone introduce in December of 2019. This turkey drone military drone has a width of 145 cm, counting from rotor to rotor. It has a maximum take-off weight of 45 kg. This drone is equipped with a machine gun. It also has a gun stabilization system for when it is firing a weapon the drone remain in stable flight. This drone has a quadcopter configuration with a double rotor on each arm. With this drone in mind and the simplified version will be the armament for the drone instead of machine gun change into a handgun for lighter weight and recoil. Then for convenient purposes, the configuration will be a typical quadcopter which has a single rotor in each on its four arms.

The chosen quadcopter for this research is DJI matrice 100. The DJI matrice 100 is chosen because when the big payload quadcopter is searched the only quadcopter with an almost perfect data is the DJI matrice 100. With the payload up to 1000g, it can carry the weapon and the ammo of chosen. DJI matrice 100 is a drone made by DJI. The quadcopter made with carbon fibre material not only is a lightweight; it is also rigid and robust material. The carbon fibre material can reduce vibration, and it is also a dependable material. Even each of the drone arms has soft absorbing content that almost eliminates feedback.

The DJI has a diagonal wheelbase 650mm. It weighs 2355g with a take-off weight of 3600g. DJI matrice 100 has four propellers with each rotation about 6000RPM. It has a max pitch angle of 35 degrees. It has a max ascent speed of 5 m/s. Max wind resistance of 10m/s. The drone comes with softer landing pads with spring in every arm of the quadcopter. It helps the drone to protects the delicate system component of the quadcopter.

Fig. 3.2 is the physical modelling of a quadcopter that will be used on this thesis. The quadcopter takes the base of DJI Matrice 100 and adds a turret below the quadcopter. The total weight of the quadcopter becomes 3.259 kg. The turret material chosen is a light material and a small-calibre round bullet because of the max take-off weight of the quadcopter.

The 3D modelling is drawn by using Solid Edge software. DJI Matrice 100 3d drawing is from grabcad.com. It is a place where people share a 3D rendering. Using Solid Edge, the drawing is analyzed to fit the specification of DJI matrice 100 then the material is chosen for the drawing. The quadcopter material is mostly carbon fibre. The turret/gun on the quadcopter is made from the beginning of this paper. The turret material is aluminium and titanium, making it strong and light, and the weight for the turret is around 0.9 Kg. The quadcopter weight with the gun overall is about 3.259 Kg.

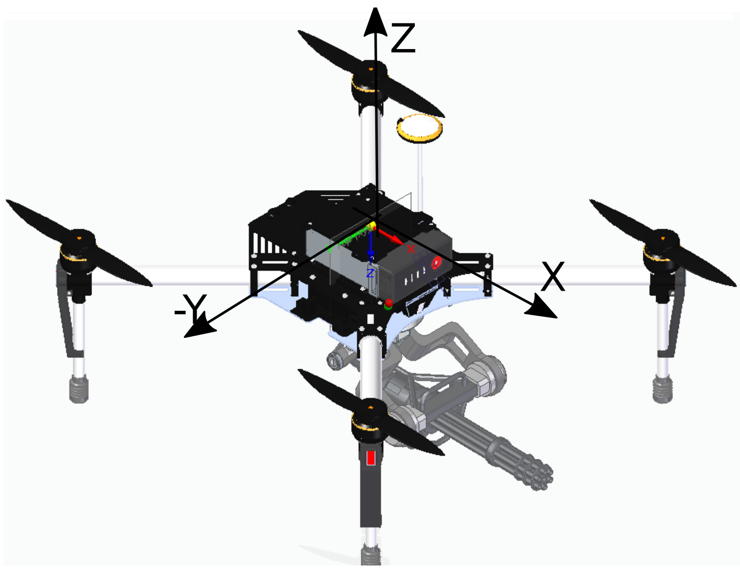

FIGURE 3.2: Isometric View

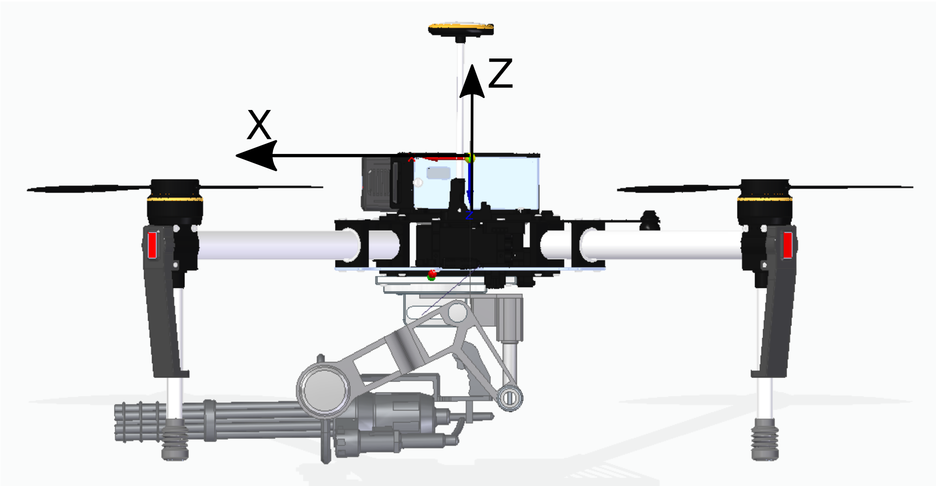

Figure 3.3: Side View

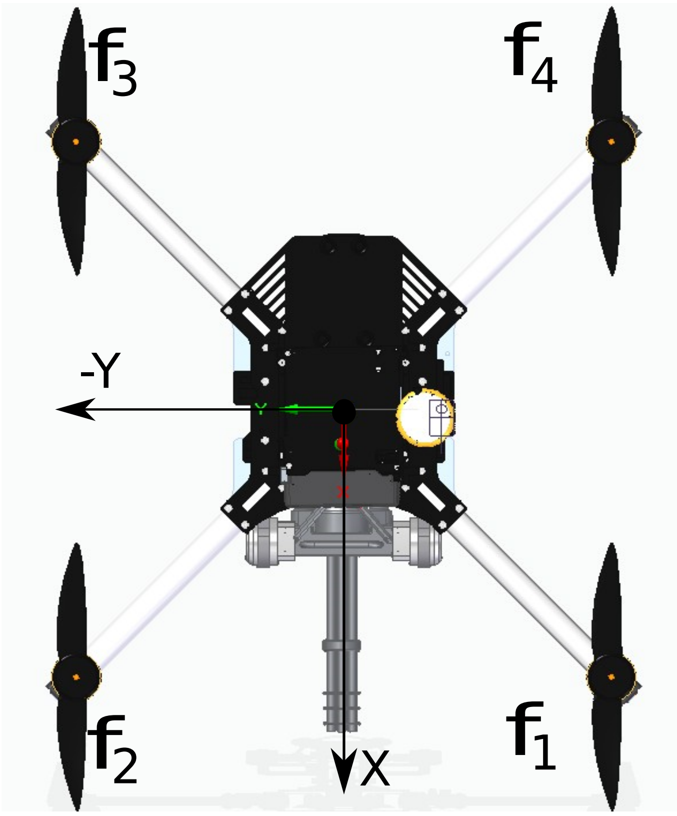

Figure 3.4: Top View

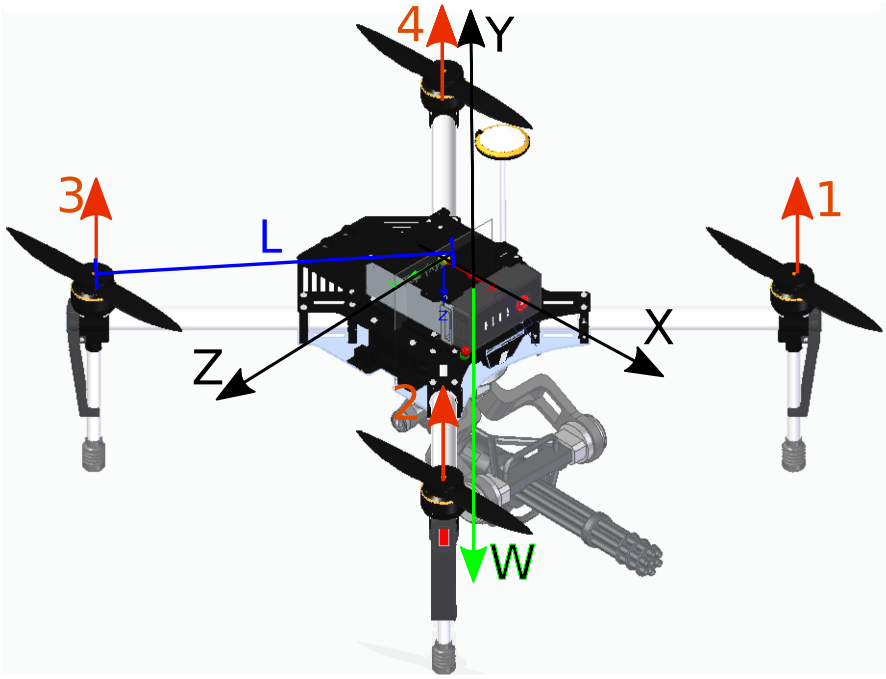

FIGURE 3.5: Free Body Diagram

Table. 3.1 is the inertial moment table of the gun quadcopter drawing. A quadcopter is a rigid body, so it only contains $I_{xx}, I_{yy}, andI_{zz}$ numbers.

	$I_x(\mathrm{kg\,m^2})$	$I_y(\mathrm{kg\,m^2})$	$I_z(\mathrm{kg\,m^2})$
I_x	0.067	0	0
I_y	0	0.077	0
I_z	0	0	0.058

TABLE 3.1: Inertial Moment of Gun Quadcopter

3.5 Mathematical Modelling

The equation of motion on the quadcopter can be researched into two different approaches to the equation. The first equation is the Newton-Euler equation. This equation the most widespread one because it also called classical mechanics. This equation in detail can be found in a blog of Charles Tytler. This equation divides the frame into two: the inertial frame and the body-fixed frame. The velocity of the quadcopter also divided into two linear velocity and angular velocity. Then every force that affects the quadcopter is calculated. The example of forces that affect quadcopter is the thrust of the four propellers and the gravity that affect the quadcopter.

The second equation of motion that is considered to be used in this thesis is the Euler-Lagrange equation. The most significant difference between Euler-Lagrange and the Newton-Euler is that the former does not consider the forces of the quadcopter. The Lagrange the sum of translational energy and rotational energy minus potential energy. This equation link directly to the quadcopter position. The initial position of the quadcopter integrated until the final position of the quadcopter.

3.6 XCOS Model Development

In a simulation using xcos in Scilab, there is one example that similar to the envision of this thesis simulation. In that example, the person does an example of a paper. Although the result of the exercise is different from the answer given by the paper, the xcos modelling exercise can be used as a material for this thesis.

The XCOS simulation can be divided into parts. The first part is for the overall thrust and the thrust for pitch, roll, and yaw motion of the quadcopter. The quadcopter thrust goes in one direction, which is upward, so the quadcopter's total thrust can be obtained by summing all the thrust from the rotors (U1). By using the equation of 2.23, the different torque configuration for pitch (U2), roll (U3), and yaw (U4) can be calculated. The signal builder is for various forces that act on the quadcopter.

the equation for thrust is:

$$T = \sum_{i=1}^{4} f_i = k \sum_{i=1}^{4} \omega_i^2, \quad T^B = \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix} \tag{3.1}$$

the second part is the angular velocity. To get the quadcopter angle (ϕ, θ, ψ) the angular velocity (p, q, r) is needed. the angular velocity equation is

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} (I_{yy} - I_{zz})\, qr/I_{xx} \\ (I_{zz} - I_{xx})\, pr/I_{yy} \\ (I_{xx} - I_{yy})\, pq/I_{zz} \end{bmatrix} - I_r \begin{bmatrix} q/I_{xx} \\ -p/I_{yy} \\ 0 \end{bmatrix} \omega_\Gamma + \begin{bmatrix} \tau_\phi/I_{xx} \\ \tau_\theta/I_{yy} \\ \tau_\psi/I_{zz} \end{bmatrix} \tag{3.2}$$

Using above equation $(\dot{p}, \dot{q}, \dot{r})$ are obtained then integrating the result (p, q, r) can be found.

The third equation the quadcopter angle (ϕ, θ, ψ). The angle equation is:

$$\begin{aligned} \ddot{\boldsymbol{\eta}} &= \frac{\mathrm{d}}{\mathrm{d}t}\left(\boldsymbol{W}_\eta^{-1}\boldsymbol{\nu}\right) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\boldsymbol{W}_\eta^{-1}\right)\boldsymbol{\nu} + \boldsymbol{W}_\eta^{-1}\dot{\boldsymbol{\nu}} \\ &= \begin{bmatrix} 0 & \dot{\phi}C_\phi T_\theta + \dot{\theta}S_\phi/C_\theta^2 & -\dot{\phi}S_\phi C_\theta + \dot{\theta}C_\phi/C_\theta^2 \\ 0 & -\dot{\phi}S_\phi & -\dot{\phi}C_\phi \\ 0 & \dot{\phi}C_\phi/C_\theta + \dot{\phi}S_\phi T_\theta/C_\theta & -\dot{\phi}S_\phi/C_\theta + \dot{\theta}C_\phi T_\theta/C_\theta \end{bmatrix} \nu + \boldsymbol{W}_\eta^{-1}\dot{\nu} \end{aligned} \tag{3.3}$$

then:

$$\dot{\eta} = W_\eta^{-1}\nu, \quad \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & S_\phi T_\theta & C_\phi T_\theta \\ 0 & C_\phi & -S_\phi \\ 0 & S_\phi/C_\theta & C_\phi/C_\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{3.4}$$

The fourth equation is for the translational (X, Y, Z) motion of the quadcopter. the translational motion can be obtained after the angle have been found. The Translational equation is:

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = -g \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{T}{m} \begin{bmatrix} C_\psi S_\theta C_\phi + S_\psi S_\phi \\ S_\psi S_\theta C_\phi - C_\psi S_\phi \\ C_\theta C_\phi \end{bmatrix} - \frac{1}{m} \begin{bmatrix} A_x & 0 & 0 \\ 0 & A_y & 0 \\ 0 & 0 & A_z \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} \tag{3.5}$$

3.7 Recoil Effect

To analyze the stability and control of quadcopter in this thesis, it needs to have a shock loading given to it. The chosen shock loading for this quadcopter is a gun P3A-1. P3A-1 gun is the smallest variant gun from PT.PINDAD. By selecting a small calibre gun, the impulse from the recoil should not be too big, and the quadcopter can handle it. The calculation of recoil impulse is about $2.2881_{N.s}$ then it gets converted into an impulse graph.

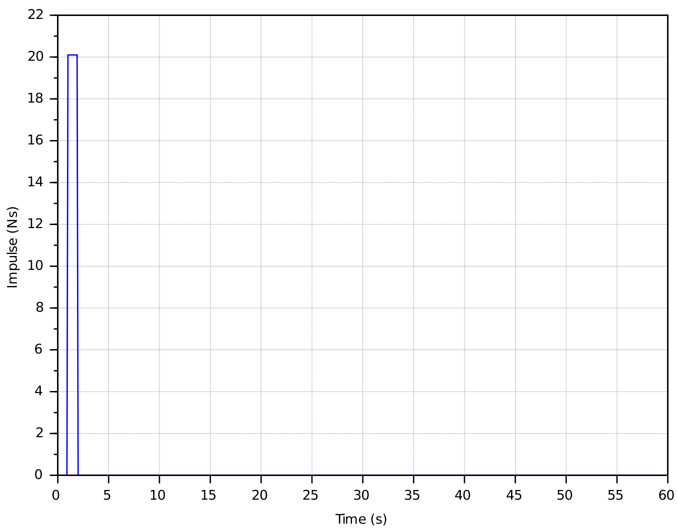

FIGURE 3.6: Impulse Model

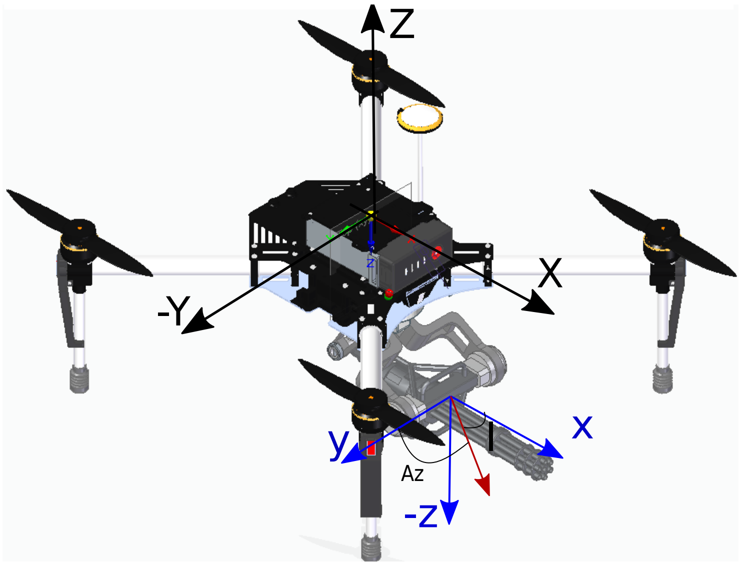

FIGURE 3.7: Gun Angle

Figure 3.7 is a picture of how a gun recoil can affect the quadcopter. The red arrow is the direction of the gun firing. The blue arrow is the axis of the gun. When the gun gave a certain angle, there will be two angles that need to be considered. First is the inclination angle. In Figure 3.7 the inclination angle is the angle between the x-axis and -z-axis because the quadcopter gun directed downward. The azimuth is an angle from x-axis to the y-axis. To calculate it.

$$\Delta V_x = -\Delta V \cos i \cos Az \tag{3.6}$$

$$\Delta V_y = -\Delta V \cos i \sin Az \tag{3.7}$$

$$\Delta V_Z = -\Delta V \sin i \tag{3.8}$$

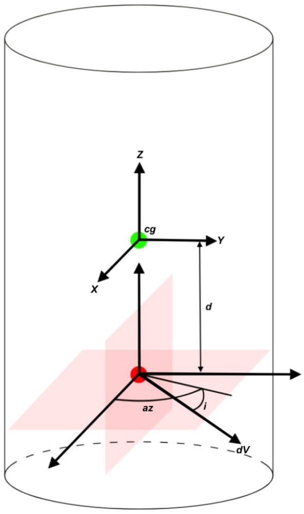

FIGURE 3.8: Free Body of Bullet Velocity and Mass Affecting Quadcopter

From angular momentum conservation:

$$(I_b + I_q)_n \omega_n = I'_{b_n} \omega'_{b_n} + I'_{q_n} \omega'_{q_n} \tag{3.9}$$

by equation 3.9 then $v_b = v_b i$ then q = quadcopter, b = bullet, and n = x,y,z. the assumption was initially the quadcopter is at a hover condition or at an equilibrium state with $\omega = 0$ then the gun was fired.

$$\omega_b = \frac{v'_{b_x}}{d}, \tag{3.10}$$

$$I_b = m_b d^2 \tag{3.11}$$

$$I'_{qn} = I_{yy} \tag{3.12}$$

$$\dot{\theta}_0 = \frac{M_b d^2}{I_{yy}} \frac{\Delta V_x}{d} = \frac{m_b \Delta V_x d}{I_{yy}} \tag{3.13}$$

$$\frac{(0.06)(335)(0.14)}{0.077} = 36.545 rad/s \tag{3.14}$$

By equation 3.13 the pitch moment can be calculated based on angular perturbation due to impulse, and it is equation 3.14. With similar fashion, we can also find the angular momentum perturbation if the angle is varied. For the y-direction, the equation becomes.

$$\dot{\phi}_0 = \frac{m_b \Delta V_y d}{I_{xx}} \tag{3.15}$$

It is the angular momentum in roll motion. While for the z-direction, since the linear momentum in z-direction has no moment, then

$$\dot{\psi}_0 = 0 \tag{3.16}$$

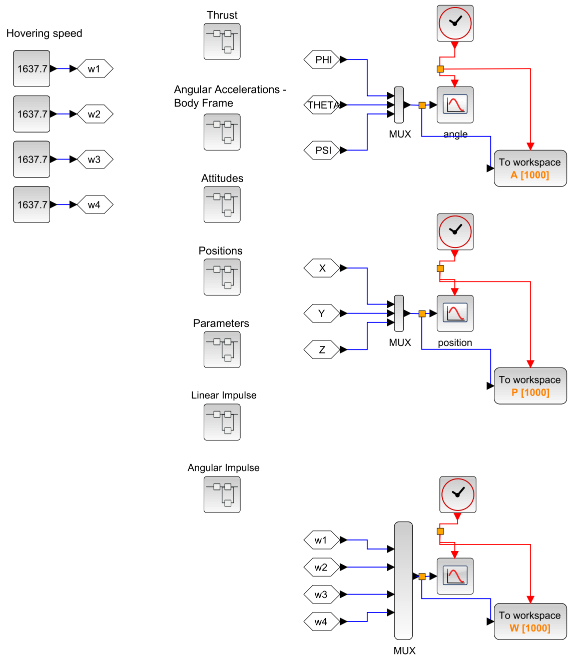

FIGURE 3.9: Overall XCOS before PID

3.8 PID Controller Implementation

The motion of a quadcopter is described by 6 states (dof): translation $\vec{\xi}(x, y, z)$ and rotation $\vec{\eta}(\phi, \theta, \psi)$.

However, only four control inputs are available, from the four rotors ω_i, so if we want to control all the states simultaneously, the control problem becomes underactuated.

Following (Dikmen, Arisoy, & Temeltas, 2009), in this thesis for the quadcopter control, the select controlled states (variables) are, z, ϕ, θ, ψ.

This is a reasonable and of practical choice, to control the attitudes and altitude at the same time.

Hence the PID controller for the quadcopter are:

$$\begin{aligned}
T &= \left(g + K_{z,D}(\dot{z}_d - \dot{z}) + K_{z,P}(z_d - z) + K_{z,I}\int_0^t (z_d - z)\right)\frac{m}{C_\phi C_\theta} \\
\tau_\phi &= \left(K_{\phi,D}(\dot{\phi}_d - \dot{\phi}) + K_{\phi,P}(\phi_d - \phi) + K_{\phi,I}\int_0^t (\phi_d - \phi))\right) I_{xx} \\
\tau_\theta &= \left(K_{\theta,D}(\dot{\theta}_d - \dot{\theta}) + K_{\theta,P}(\theta_d - \theta) + K_{\theta,I}\int_0^t (\theta_d - \theta))\right) I_{yy} \\
\tau_\psi &= \left(K_{\psi,D}(\dot{\psi}_d - \dot{\psi}) + K_{\psi,P}(\psi_d - \psi) + K_{\psi,I}\int_0^t (\psi_d - \psi))\right) I_{zz}
\end{aligned} \tag{3.17}$$

$z_d, \phi_d, \theta_{d,}, \psi_d$ are respectively the altitude and attitudes of the quadcopter at an equilibrium condition.

By using PID the angular velocity of the rotors becomes:

$$\begin{aligned}
\omega_1^2 &= \frac{T}{4k} - \frac{\tau_\theta}{2kl} - \frac{\tau_\psi}{4b} \\
\omega_2^2 &= \frac{T}{4k} - \frac{\tau_\phi}{2kl} + \frac{\tau_\psi}{4b} \\
\omega_3^2 &= \frac{T}{4k} + \frac{\tau_\theta}{2kl} - \frac{\tau_\psi}{4b} \\
\omega_4^2 &= \frac{T}{4k} + \frac{\tau_\phi}{2kl} + \frac{\tau_\psi}{4b}
\end{aligned} \tag{3.18}$$

The XCOS block after PID is implemented:

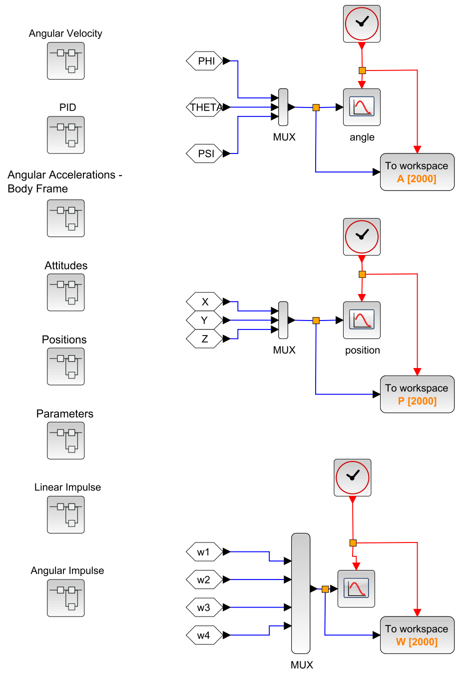

FIGURE 3.10: Overall XCOS after PID

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Up and Down Motions Simulation

Figures 4.1, 4.2, and 4.3 are the graph of quadcopter position the x-position is for the quadcopter movement on the x-axis. It is for forward and backward movement of the quadcopter. The y-position is the same as the x-position, but it is for the leftward and rightward movement of the quadcopter. The z-position is to increase or decrease the altitude of a quadcopter, using four constant blocks for the angular velocity. The hover condition of a quadcopter can be found. In this paper case, the hover condition is 1637.7 (RPM). The increase and decrease of the altitude can be adjusted.

Figure 4.1 is when the quadcopter angular velocity (RPM) cannot lift the quadcopter. For the quadcopter that this thesis research all four of the rotors angular velocity ω is less than 1643 (RPM) or in Figure 4.1 is 1617.7. To make The quadcopter altitude decreasing.

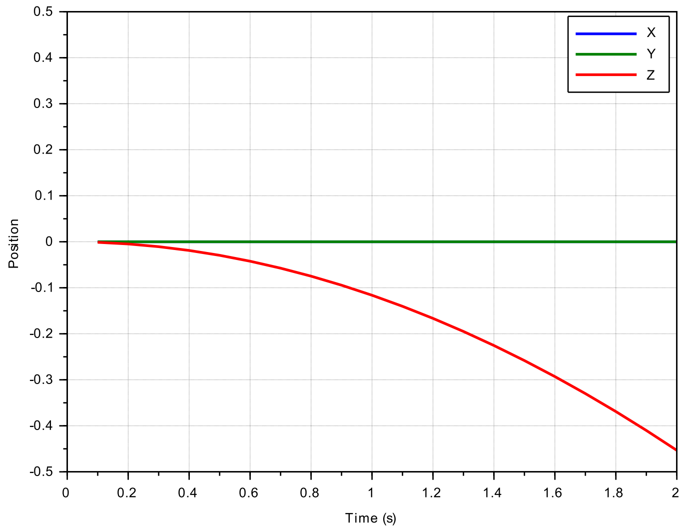

FIGURE 4.1: Z Position-Down Motion

Figure 4.2 is when the quadcopter in hover condition the angular velocity (RPM) generates lift, which is the same as the weight of the quadcopter. In this thesis case, the hover angular velocity for the four rotors is around 1637.7 (RPM) to make the hover altitude at hover.

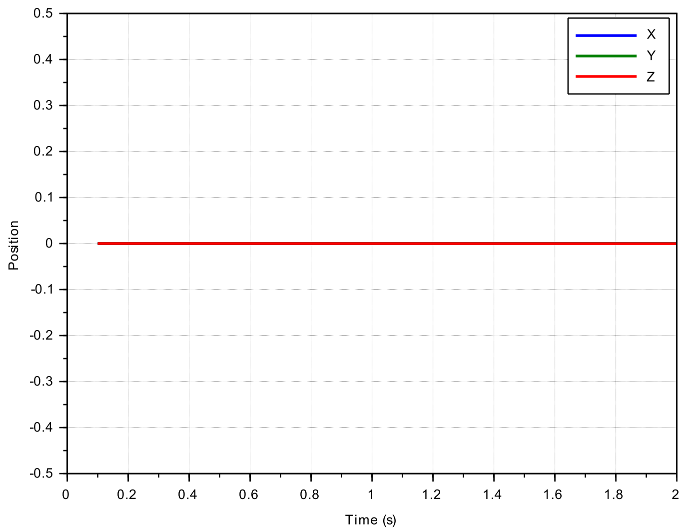

FIGURE 4.2: Z Position Under Equilibrium Condition

Figure 4.3 is when the quadcopter angular velocity (RPM) lifts the quadcopter. When all the four rotors' angular velocity is exceeded 1637.7 (RPM) or in Figure 4.3 is 1657.7, the Z position is going up.

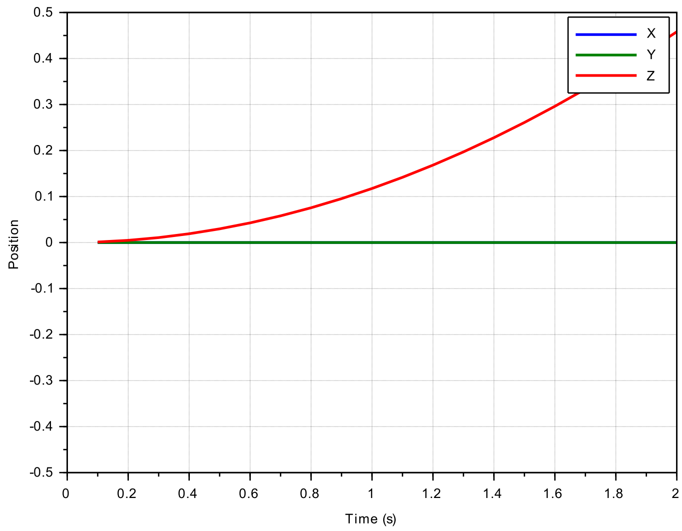

FIGURE 4.3: Z Position-Up Motion

4.2 Attitude Motion Simulation

Before the quadcopter is given the shock loading from a gun, it needs to be tested on whether there is an error in Xcos block programming. The method to search for the error in this paper is to make the quadcopter do Up and Down motion, Roll motion, Pitch motion, and Yaw motion. By making those four motion, the quadcopter movement can be seen.

Figure 4.4 is when a quadcopter is doing roll motion ϕ. By an X-configuration quadcopter, for roll motion, the pair of rotors would be left side rotor 1, and 4 the other couple would be rotor 2, and 3. the blue line represents roll motion. By increasing rotor 1, and 4 decreasing the rotor 2, and 3 the quadcopter roll increase.

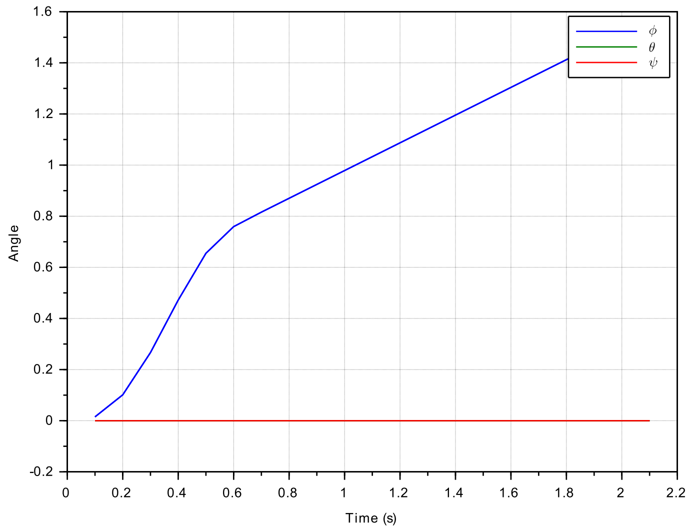

FIGURE 4.4: Quadcopter Pure Roll Angle Simulation

Figure 4.5 is when a quadcopter is doing pitch motion θ. X-configuration quadcopter, for pitch motion the pairs of the rotor would be the front and back of quadcopter. The first, and second rotor for the front and third and fourth rotor for the back rotors. The green line represents the pitch motion. By increasing the third and fourth rotor and decreasing the first and second rotor, the quadcopter would do the pitch motion increasing the green line.

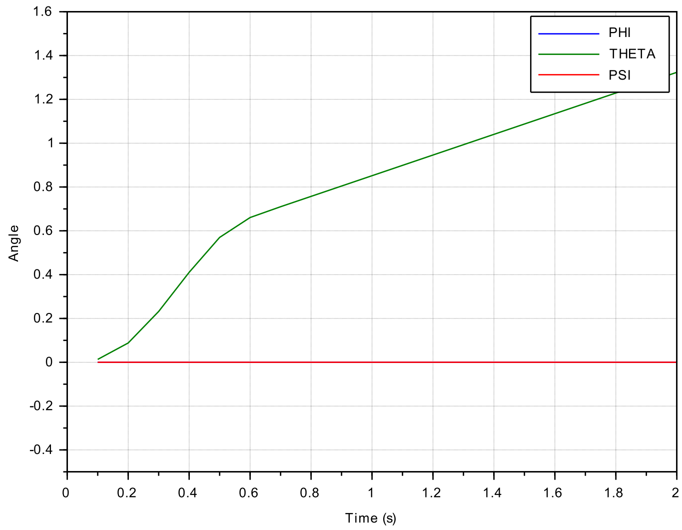

FIGURE 4.5: Quadcopter Pure Pitch Angle Simulation

Figure 4.6 is when a quadcopter is doing yaw motion θ. In general quadcopter have a pair of rotors that spin clockwise and another pair of rotors that spin counter-clockwise. The gyroscopic effect would take place when one pair of rotor rotate slower or faster than the other pair. For quadcopter to yaw, it takes advantage of this phenomenon. The pair of rotors will be 2, and 4 for the clockwise direction and the 1, and 3 rotor is for the counter-clockwise rotation direction. The red line represents yaw motion by increasing the 1, and 3 rotors the yaw motion increase.

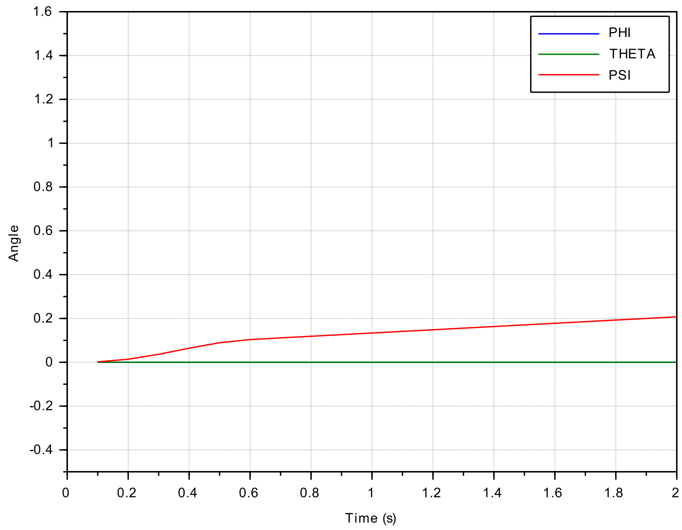

FIGURE 4.6: Quadcopter Pure yaw Angle Simulation

4.3 Quadcopter Motion Simulation Under Pre-programmed Thrust

Figure 4.10 is the angular velocity of the quadcopter when the quadcopter is given motions. The motion carried is simulated in around 2 minutes time frame, and a difference for each movement is about the same around 0.15 minutes. The quadcopter in this paper is presented the X-configuration. Meaning rotor 1 and 2 is at the front rotor 3, and 4 is at the back of the quadcopter. Initially, the quadcopter was in a hover condition with angular velocity 1637.7 (RPM) in all four rotors next the quadcopter is increasing its rotors angular velocity to 1800 (RPM), to increase its altitude. The next motion is the angular velocity for all the rotors is decreased to 1500 (RPM) so the quadcopter decrease in height. Then the quadcopter angular velocity was back to hover condition in 1637.7 (RPM).

Next, the quadcopter is put into roll motion. From hover condition, the first and fourth rotor angular velocity was increased to 1687.7 (RPM) and decrease the second and third angular velocity rotor to 1592.7 (RPM). The difference in angular velocity was not too big because if the roll angle is too big, the quadcopter can be upside down and fall. The difference in small numbers also makes controlling the quadcopter easier because the rolling motion will not be too fast. By two different angular velocity, the quadcopter will create a roll motion. For the quadcopter to move in the y-direction, the four rotors will need to be at the same speed of 1637.7 (RPM). For the quadcopter, motion is back at hover condition. The movement is reverse. The first and fourth rotor angular velocity was decreased to 1592.7 (RPM) and increased the second and third angular velocity rotor to 1687.7 (RPM). Then next by making all four angular velocities at 1637.7 (RPM), the quadcopter was back to hovering.

Then, similar to the roll motion, a pitch motion is created by increasing the third and fourth rotors' velocity to 1687.7 (RPM) and decreasing the velocity of the first and second rotors to 1592.7 (RPM). In the pitch case, the angular velocity difference also needs to be small because the pitch and roll motion is similar. For the quadcopter to move in the x-direction, the four rotors will need to be at the same speed of 1637.7 (RPM). The motion is stopped by reducing the velocity of the third and fourth rotors to 1592.7 (RPM) and increasing the velocity of the first and second rotors to 1687.7 (RPM). Then next by making all four angular velocities at 1637.7 (RPM), the quadcopter was back hovering.

Finally, the quadcopter makes the yaw motion. The quadcopter has a pair of counter-clockwise rotation motor for first and third movements and a couple of the clockwise rotor of second and fourth rotors, by increasing the velocities of the first and the third rotors to 1687.7 (RPM) and decreasing the velocities of the second and the fourth rotors to 1592.7 (RPM). The small difference in yam motion is for easier control. Because of the gyroscopic effect, the quadcopter can yaw fast. The yaw motion is stopped by equalizing the four rotors angular velocity to 1637.7 (RPM). For the quadcopter to be back on the initial configuration, it needs to decrease the angular velocities of the first and third rotors to 1592.7 (RPM) and increase the second and fourth rotors' velocities 1687.7 (RPM). Then equalize all the four rotors angular velocities to 1637.7 (RPM).

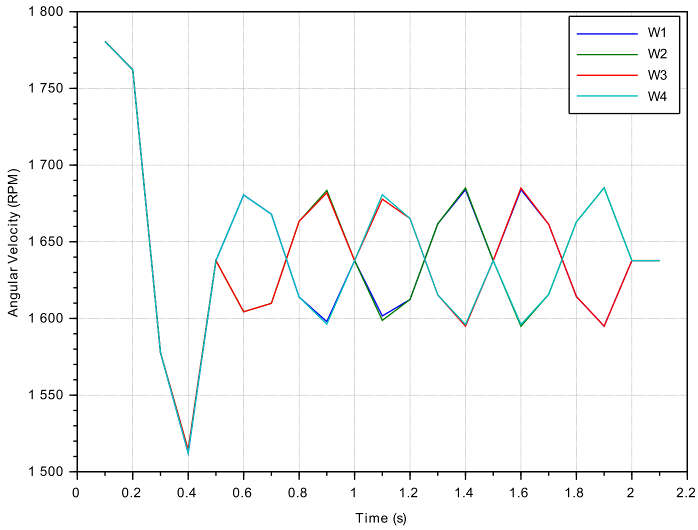

FIGURE 4.7: Angular Velocity Quadcopter Under Preprogrammed Thrust Continous Motion

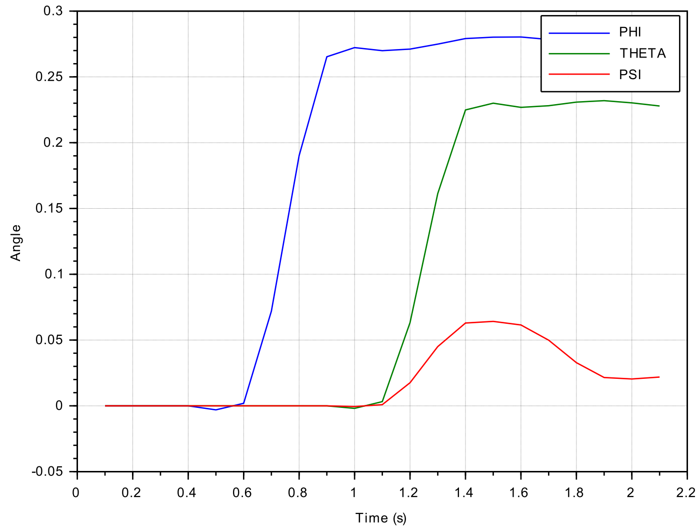

FIGURE 4.8: Attitude of Quadcopter Under Preprogrammed Thrust Continous Motion

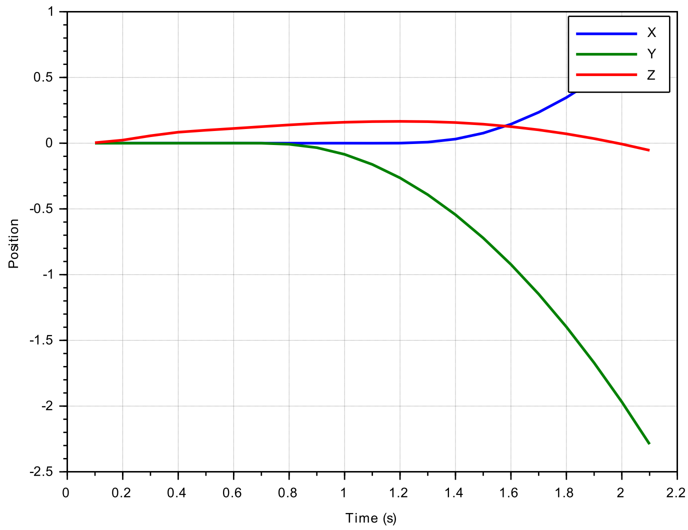

FIGURE 4.9: Position of Quadcopter Under Preprogrammed Thrust Continous Motion

Figure 4.11 and 4.9 is a graph for angle and position of the quadcopter by using Figure 4.10 as the angular velocity of quadcopter rotors. In Figure 4.11, it can be seen that initially, the quadcopter at hover, the angle was zero. Then in 0.6 minutes, the phi angle was increased. The Phi angle is for roll motion. In 0.8 minute, the angle was stopped increasing and becomes stable. In around 1 minute, the theta angle began to rise. Theta angle is for pitch motion. The same for roll motion, it stabilizes in about 1.4 minutes. The next psi angle begins to increase in around 1.3 minutes, and the yaw angle stabilizes in about 1.9 minutes.

Figure 4.9 shows that the z-position is almost stable throughout the quadcopter motion. For the Y-position, it changes around 0.8 minutes. It is nearly the same time as the roll angle, and the X-position change around 1 minute almost the same as the change in theta angle because the quadcopter movement for forward, backward, leftward, and rightward is dependant on its angle of attack. When the quadcopter wants to move translationally except for increasing and decreasing altitude, it needs to change its angle first.

4.4 Motion Simulation Under Linear Impulse Only

For the first simulation, the quadcopter is given shock loading on x-position, y-position, and z-position. The first assumption, the quadcopter is at a hover condition. Then the gun is fired by the quadcopter. The gun angle would be changed in x-position, y-position, and z-position depending on the simulation. The second assumption, the quadcopter is assumed to be stable in attitude position so the quadcopter will not roll, pitch, or yaw.

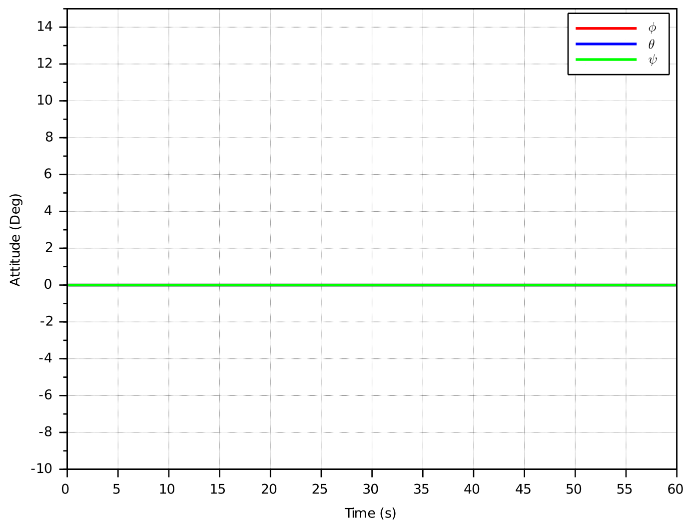

FIGURE 4.10: Quadcopter's Attitude Under X-Axis Impulse

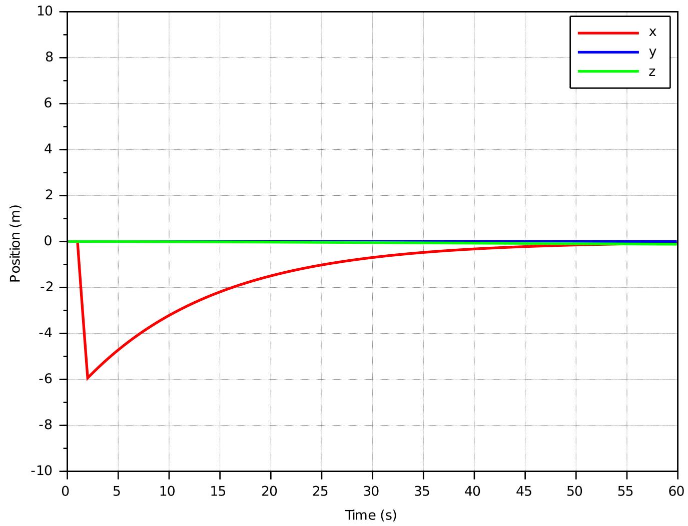

FIGURE 4.11: Quadcopter's Position Under X-Axis Impulse

Figure 4.10 and 4.11 are the attitudes and the position of the quadcopter when the gun is directed at x-direction. in the attitude graph, the quadcopter is stable because of the assumption that it won't pitch. In the position graph, there is a force that affects the X-position of the quadcopter. The gun on this x-direction simulation was directed to the front of the quadcopter. In the positive x-direction, when the gun is fired, then the recoil of the gun makes the quadcopter move opposite to the gun firing direction, which is to the back. It is why the x-position in the graph is negative.

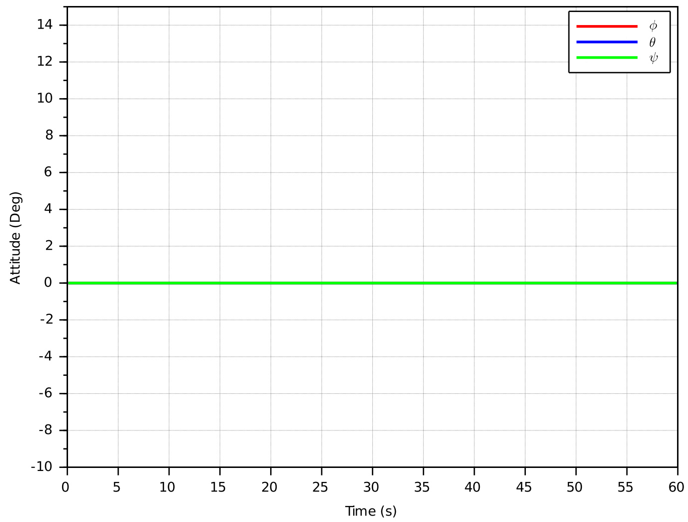

FIGURE 4.12: Quadcopter's Attitude Under Y-Axis Impulse

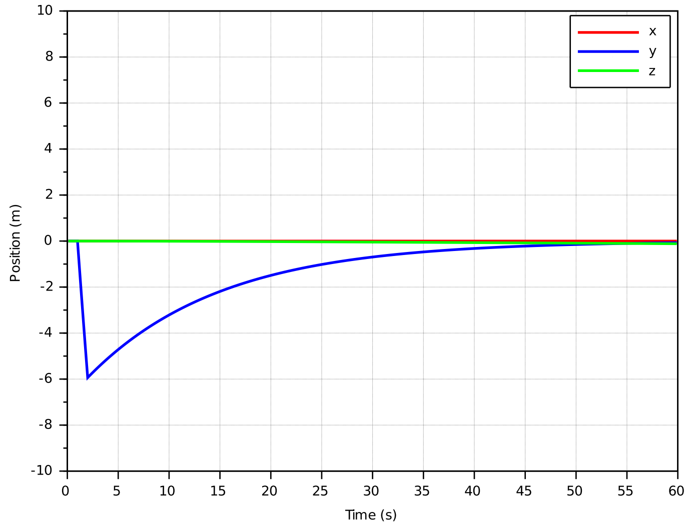

FIGURE 4.13: Quadcopter's Position Under Y-Axis Impulse

Figure 4.12 and 4.13 are the attitudes and the position of the quadcopter when the gun is directed at y-direction. in the y-direction simulation result is the same as the x-direction simulation result. The attitude graph shows no change because the quadcopter cannot roll. Then the gun in y-direction simulation directed at the right side of the quadcopter. When the gun is fired, the recoil makes the quadcopter move left hence the negative y-direction force in a position graph.

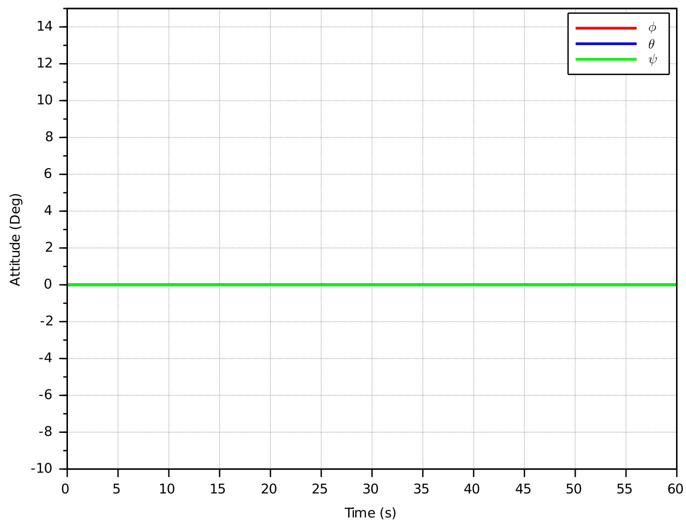

FIGURE 4.14: Quadcopter's Attitude Under Z-Axis Impulse

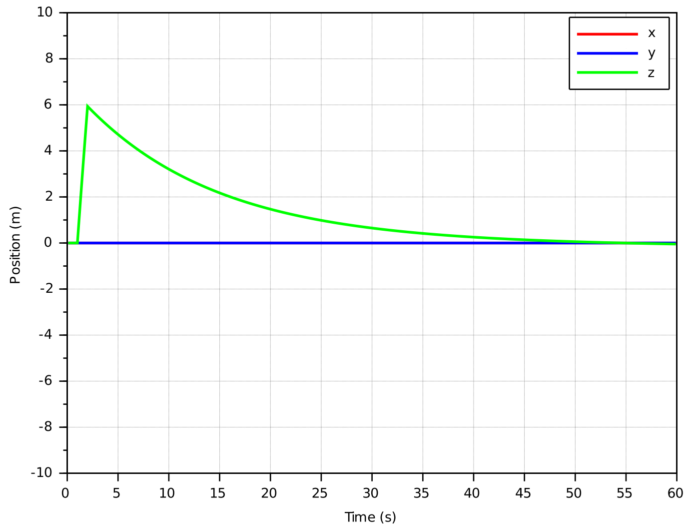

FIGURE 4.15: Quadcopter's Position Under Z-Axis Impulse

Figure 4.14 and 4.15 are the attitudes and the position of the quadcopter when the gun is directed at z-direction. Result of simulation on the z-direction is a little bit different from the x-direction and the y-direction. The attitude graph is still the same, but the position shows a different result from the other two simulations. The gun on z-position simulation was directed directly down. When the gun is fired down, which is a negative z-direction, the recoil of the quadcopter will move up which the positive z-direction.

4.5 Gun Firing Simulation

4.5.1 Simulation Test: Quadcopter Without Active Control

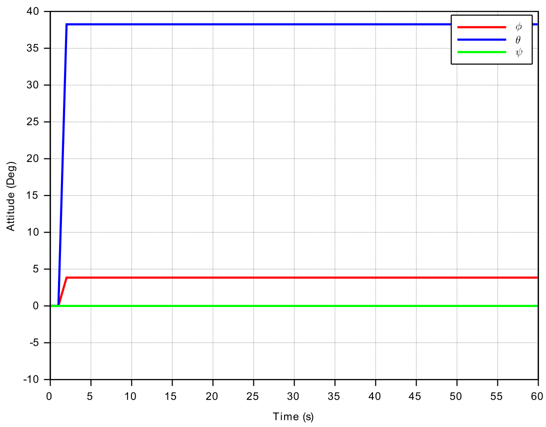

FIGURE 4.16: Quadcopter's Attitude Under Linear (5 degree inclination and azimuth) and Its Angular Impulse

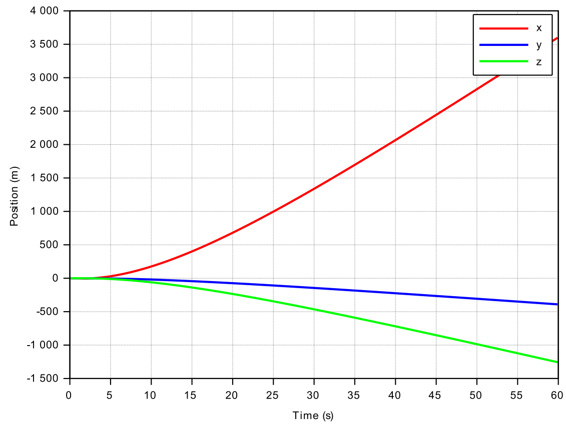

FIGURE 4.17: Quadcopter's Position Under Linear (5 degree inclination and azimuth) and Its Angular Impulses

Figure 4.14 and 4.15 are the attitudes and the position of the quadcopter when it does not have any active controlling. The gun directed at a 5-degree inclination and 5-degree azimuth. There are not any control techniques for this simulation. The position graph for x-position and y-position move because the angle does not return to the initial position.

4.5.2 Simulation Test: Quadcopter With Untuned PID Control

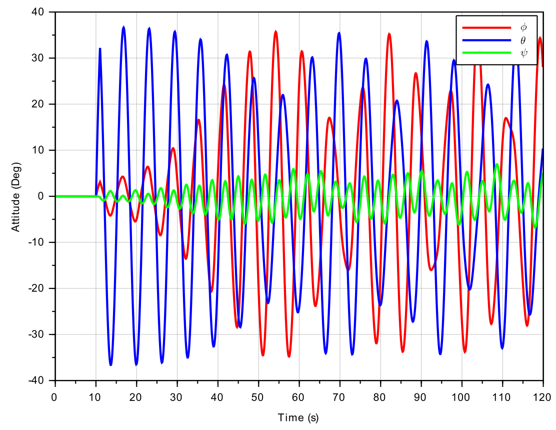

FIGURE 4.18: Quadcopter's Attitude Under Linear (5 degree inclination and azimuth) and Its Angular Impulse with untuned PID

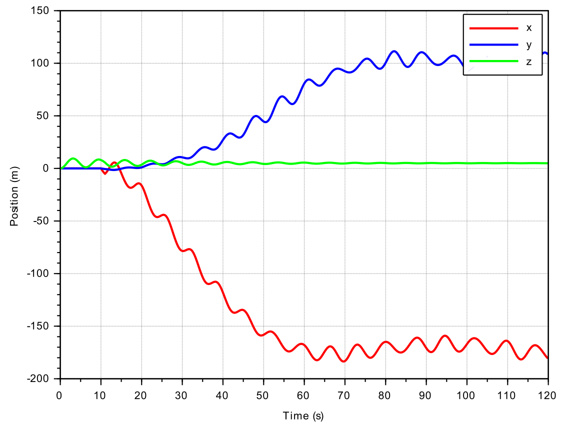

FIGURE 4.19: Quadcopter's Position Under Linear (5 degree inclination and azimuth) and Its Angular Impulses with untuned PID

Figure 4.14 and 4.15 were the attitudes and the position of the quadcopter when it fired 5-degree inclination and 5-degree azimuth when the PID has not been tuned. The P in the PID is 1 for the Z, ϕ, θ, and ψ.

4.6 Stabilization with PD Controller

First, a simple PD tuning is conducted. By using manually tune trial and error. Four variables are controlled by PID Z, ϕ, θ, and ψ because of that, there is eight coefficient that needed to be controlled.

Coefficients	Z	ϕ	θ	ψ
K_P	1	1	1	1
K_I	0	0	0	0
K_D	1	1	1	1

TABLE 4.1: PD Controller

The scenario for this testing is the quadcopter rise to 5m in 5 seconds. Then in the 10 seconds, the gun is fired, and the recoil happens.

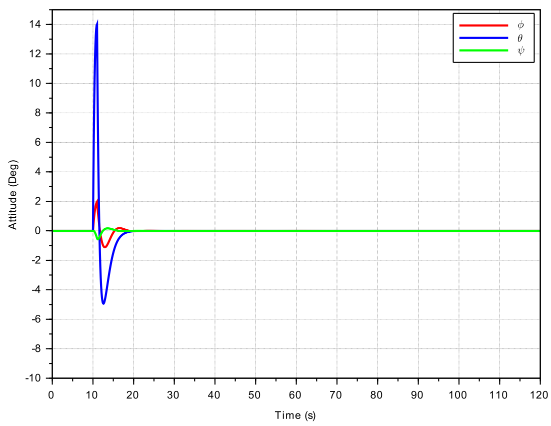

FIGURE 4.20: PD Control: Quadcopter's Attitude

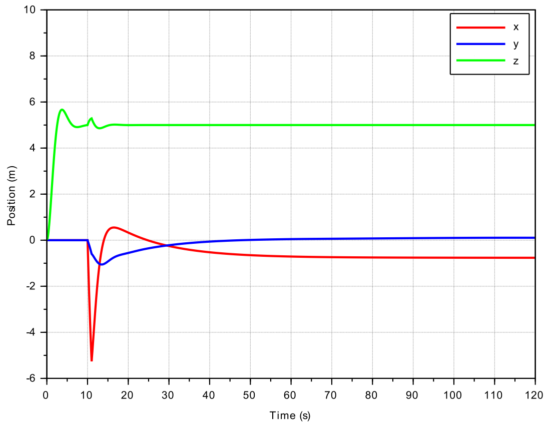

FIGURE 4.21: PD Control: Quadcopter's Position

TABLE 4.2: The PD Control Performance: Positions

Parameter	X	Y	Z
Rise Time (s)	4	30	5
Settling Time (s)	50	30	5
Steady State Error (m)	-1	0	0

TABLE 4.3: The PD Control Performance: Attitudes

Parameter	ϕ	θ	ψ
Rise Time (s)	5	2	8
Settling Time (s)	8	7	10
Steady State Error (m)	0	0	0

Using PD control, the longest settling time is 50 seconds for x-position, so the quadcopter needs 50 seconds after recoil happens to be back to stable, and in x-position, it also has a steady-state error of -1. It means the quadcopter move to the back at 1 meter and stabilized there.

4.7 Stabilization With PID Ziegler Nichol's Method

To use Ziegler Nichol's method, the P coefficient is needed to be added until the graph becomes a critically stable wave. The ϕ gets a critically stable wave at three coefficients, and the θ gets a critically stable wave at two coefficients. For Z and ψ value, the Ziegler Nichols cannot be used because we have tried from 1 coefficient to 10 coefficient for their P-value, but it does not get to critically stable and goes back to stabilize itself slowly.

Coefficients	Z	ϕ	θ	ψ
K_P	1	1.8	1.2	1
K_I	0	1.0909	0.1646	0
K_D	1	0.7425	5.25	1

Table 4.4: PID Controller With Ziegler-Nichol's Tuning Method

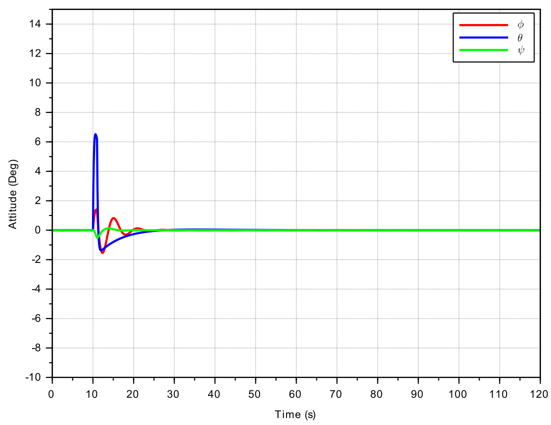

Figure 4.22: Ziegler Nichol's: Quadcopter's Attitude

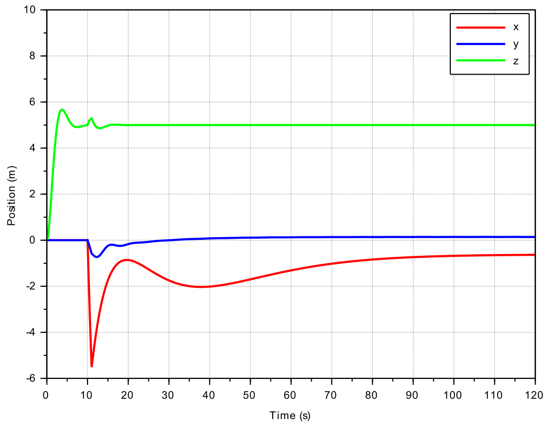

FIGURE 4.23: Ziegler Nichol's: Quadcopter's Position

TABLE 4.5: The PID Control Performance: Positions

Parameter	X	Y	Z
Rise Time (s)	8	50	2
Settling Time (s)	90	50	8
Steady State Error (m)	-1	0.2	0

TABLE 4.6: The PID Control Performance: Attitudes

Parameter	ϕ	θ	ψ
Rise Time (s)	2	2	2
Settling Time (s)	13	15	6
Steady State Error (m)	0	0	0

Using Ziegler Nichol's PID control, the longest settling time is still x-position, and it has a longer settling time than the PD control in 90 seconds. the steady-state error for x-position is still -1. The y-position using Ziegler Nichol's has a steady-state error of -0.2.

4.8 Stabilization With PID Ziegler Nichol's Method + Manual Tuning

The following PID stabilization method is combining the Ziegler Nichol's method and the PD manual tuning.

Coefficients	Z	ϕ	θ	ψ
K_P	1	1.8	1.2	1
K_I	0	1.0909	0.1646	0
K_D	1	10	10	1

TABLE 4.7: PID Controller with Ziegler-Nichol's + Manual tuning method

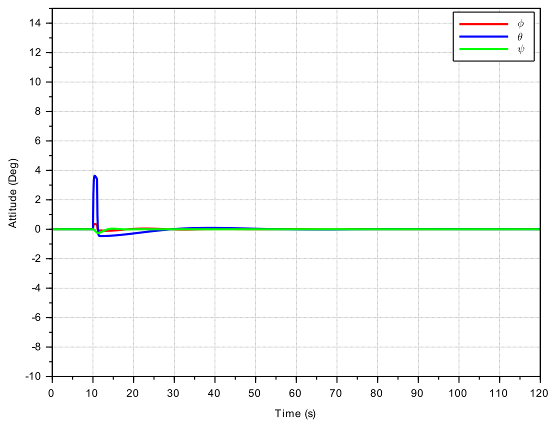

FIGURE 4.24: Ziegler Nichol's + Manual: Quadcopter's Attitude

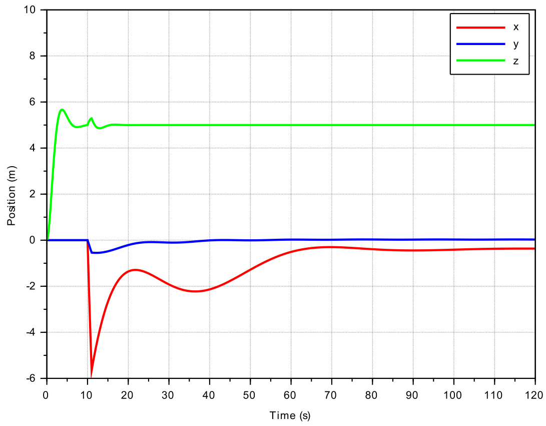

FIGURE 4.25: Ziegler Nichol's + Manual: Quadcopter's Position

TABLE 4.8: The PID Control Performance: Positions

Parameter	X	Y	Z
Rise Time (s)	50	30	5
Settling Time (s)	90	30	5
Steady State Error (m)	-0.3	0	0

TABLE 4.9: The PID Control Performance: Attitudes

Parameter	ϕ	θ	ψ
Rise Time (s)	30	20	5
Settling Time (s)	30	40	8
Steady State Error (m)	0	0	0

Using the Ziegler Nichol's + manual tuning has the least steady-state error even for x-position. The error is just -0.3; it is the closest to the initial condition before the gun is fired.

4.9 Stabilization With PID Ziegler Nichol's Method + Manual Tuning with $i = 25°$, and $i = 45°$

By using Using the Ziegler Nichol's + manual tuning, the angle inclination of the gun is turning to 25 degrees and 45 degrees.

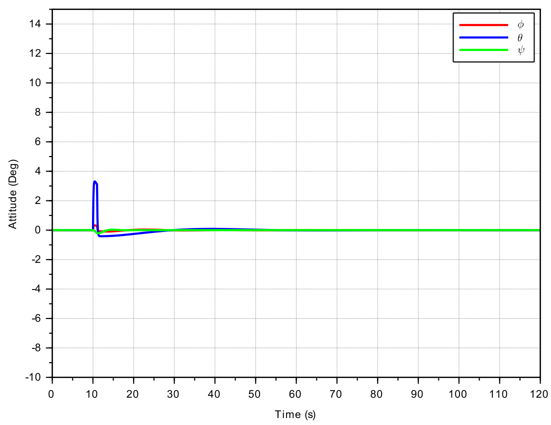

FIGURE 4.26: $i = 25°$ and $az = 5°$ Gun Angles Firing: Quadcopter's Attitude

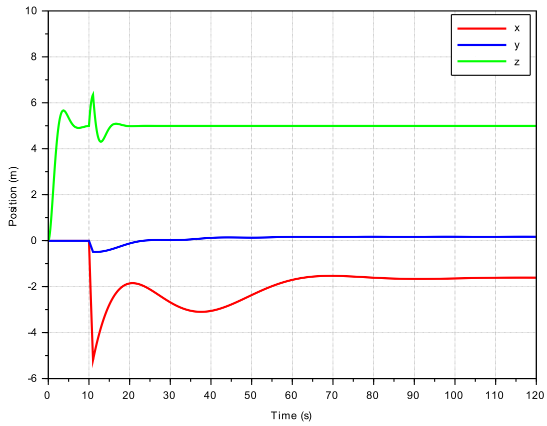

FIGURE 4.27: $i = 25°$ and $az = 5°$ Gun Angles Firing: Quadcopter's Position

TABLE 4.10: The PID Control Performance: Positions

Parameter	X	Y	Z
Rise Time (s)	11	30	2
Settling Time (s)	80	30	10
Steady State Error (m)	-1.8	0.2	0

TABLE 4.11: The PID Control Performance: Attitudes

Parameter	ϕ	θ	ψ
Rise Time (s)	2	2	4
Settling Time (s)	15	40	8
Steady State Error (m)	0	0	0

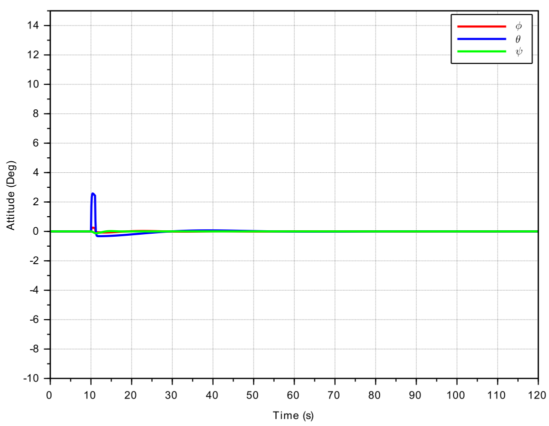

FIGURE 4.28: $i = 45°$ and $az = 5°$ Gun Angles Firing: Quadcopter's Attitude

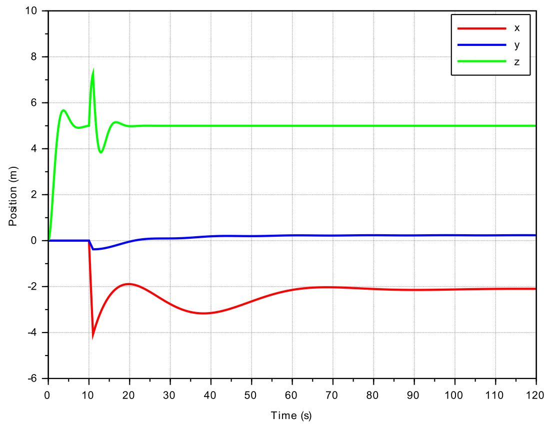

FIGURE 4.29: $i = 45°$ and $az = 5°$ Gun Angles Firing: Quadcopter's Position

TABLE 4.12: The PID Control Performance: Positions

Parameter	X	Y	Z
Rise Time (s)	8	40	3
Settling Time (s)	80	50	10
Steady State Error (m)	-2.1	0.2	0

TABLE 4.13: The PID Control Performance: Attitudes

Parameter	ϕ	θ	ψ
Rise Time (s)	2	2	4
Settling Time (s)	40	2	8
Steady State Error (m)	0	0	0

By increasing the inclination angle, the quadcopter x position steady-state error becomes bigger. The rise time and settling time do not change much with increasing inclination angle.

4.10 Stabilization With PID Ziegler Nichol's Method + Manual Tuning with $az = 25°$, and $az = 45°$

next by using Using the Ziegler Nichol's + manual tuning, the angle Azimuth of the gun is turning to 25 degrees and 45 degrees.

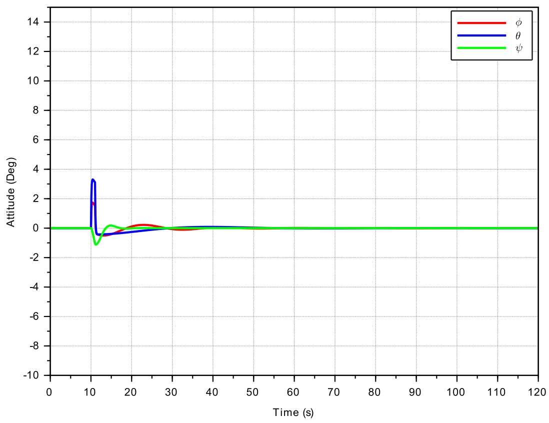

FIGURE 4.30: $i = 5°$, and $az = 25°$ Gun Angles Firing: Quadcopter's Attitude

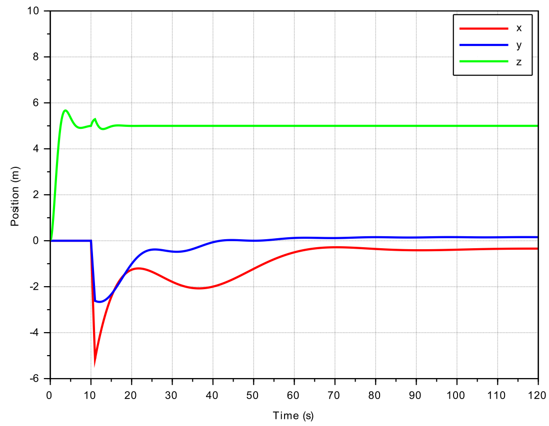

FIGURE 4.31: $i = 5°$, and $az = 25°$ Gun Angles Firing: Quadcopter's Position

TABLE 4.14: The PID Control Performance: Positions

Parameter	X	Y	Z
Rise Time (s)	50	40	2
Settling Time (s)	80	40	8
Steady State Error (m)	-0.3	0.2	0

TABLE 4.15: The PID Control Performance: Attitudes

Parameter	ϕ	θ	ψ
Rise Time (s)	2	2	4
Settling Time (s)	30	40	8
Steady State Error (m)	0	0	0

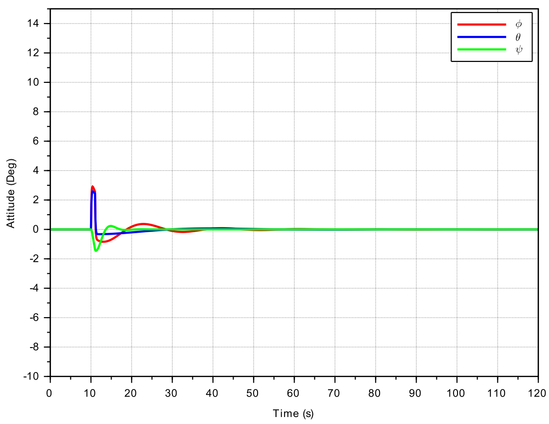

FIGURE 4.32: $i = 5°$, and $az = 45°$ Gun Angles Firing: Quadcopter's Attitude

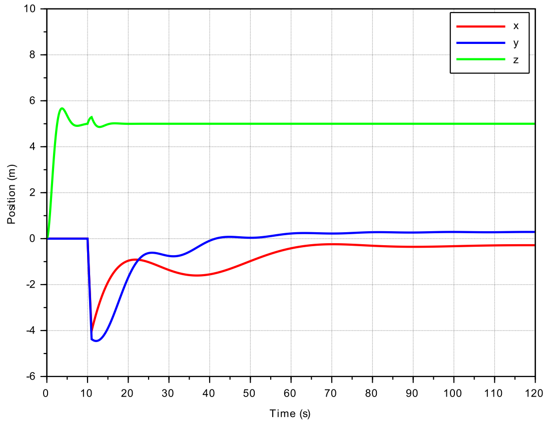

FIGURE 4.33: $i = 5°$, and $az = 45°$ Gun Angles Firing: Quadcopter's Position

TABLE 4.16: The PID Control Performance: Positions

Parameter	X	Y	Z
Rise Time (s)	40	40	2
Settling Time (s)	80	40	4
Steady State Error (m)	-0.3	0.3	0

TABLE 4.17: The PID Control Performance: Attitudes

Parameter	ϕ	θ	ψ
Rise Time (s)	8	2	4
Settling Time (s)	43	40	8
Steady State Error (m)	0	0	0

With azimuth increase, the y position steady-state error increased. The rise time and settling time do not change much from the increasing azimuth angle.

CHAPTER 5
SUMMARY, CONCLUSION, RECOMMENDATION

5.1 Summary

In this thesis, stability and control of a combat quadcopter (quadcopter mounted with a gun) were preliminarily analyzed. The combat quadcopter was based on DJI Phantom 2 Vision and Pistol P-3A Kal.7.65. The particular focus of this thesis was about the stability of the combat quadcopter under gun-shock loading, which is approached as a single impulse. Moreover, implementing PID control using the nonlinear dynamics was also attempted and reported. This thesis assumed that the structure was rigid, and the action point of the gun was at the z-directional axis; hence the angular momentum due to the impulse in yaw directions were ignored. PID control using three different methods is implemented. The PD control using manual tuning or trial and error method, PID control using the Ziegler Nichols method, and PID control using the Ziegler Nichols method with manual tuning. The best rise time and settling time was achieved by PD control using manual tuning, but the best steady-state error is achieved by Ziegler Nichols method with manual tuning, and it is the closest to the initial position.

5.2 Conclusion

From this thesis, one may conclude that

- In this preliminary thesis analysis of stability and control of a quadcopter under gun-shock loading has been reported.

- The physical model was created and build upon DJI Matrice 100 and Pistol P3A-1.
- The gun-shock loading was modelled as momentum perturbation in linear and angular motions.
- Three types of PID Controller has been implemented: PD, PID With Ziegler-Nichol's Method, and PID With Ziegler-Nichol's Method + Manual Tuning.
- It was found that the best rise time was achieved by using the PD manual tuning method. Even though the Ziegler-Nichols's tuning for the attitudes (ϕ, θ, and ψ) was better, but it doubled the amount for X and Y positions.
- The best settling time was also resulted by the PD method, and the two implemented Ziegler Nichol's gave double the time to settle.
- The best steady-state error was produced by using the combination of the Ziegler Nichol's method and some manual tuning; it had an error of -0.3 instead of 1 for the x-position – the closest to the initial condition after the gun fired.
- It was found that by increasing the inclination angle, the x position steady-state error is increased.
- It was found that by increasing the azimuth angle, the y position steady-state error is increased.

5.3 Recommendation

From this thesis, there are several recommendations to be made:

- Iterate the physical model to use larger and more powerful quadcopter; in this thesis, the base model was very light and lacked in power; hence, selecting types of guns to mount became limited.
- To study the effect of consecutive series of impulses that can emulate mounting an automatic gun on a quadcopter.

- To investigate how the distance between the *cg* and the gun action-point and mass reduction influence the combat quadcopter's stability.
- As this study attempted to implement PID Control to the nonlinear dynamics, it is essential to investigate the stability and control of the combat quadcopter under the linearized dynamics.
- Perform control optimization that makes the armed quadcopter more agile and stable.
- Investigate the limit of the PID controller when the shooting's angles are varied.
- To include additional control input (gimbal/additional rotors).
- To investigate the effect of structural asymmetric mass distribution.

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Appendices

Appendix A: Xcos Block

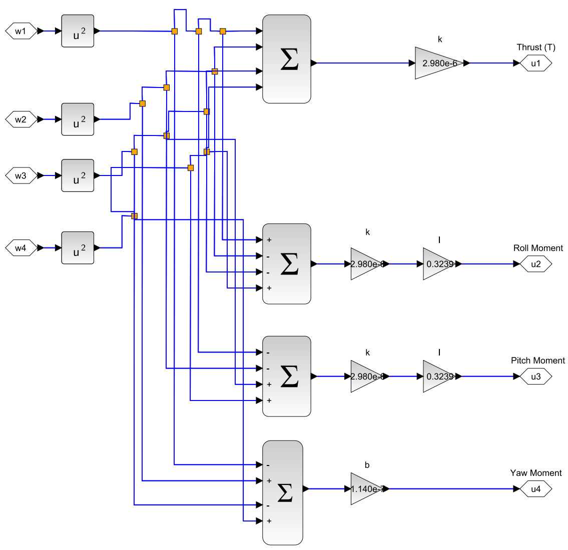

FIGURE 1: Thrust and Torque Model

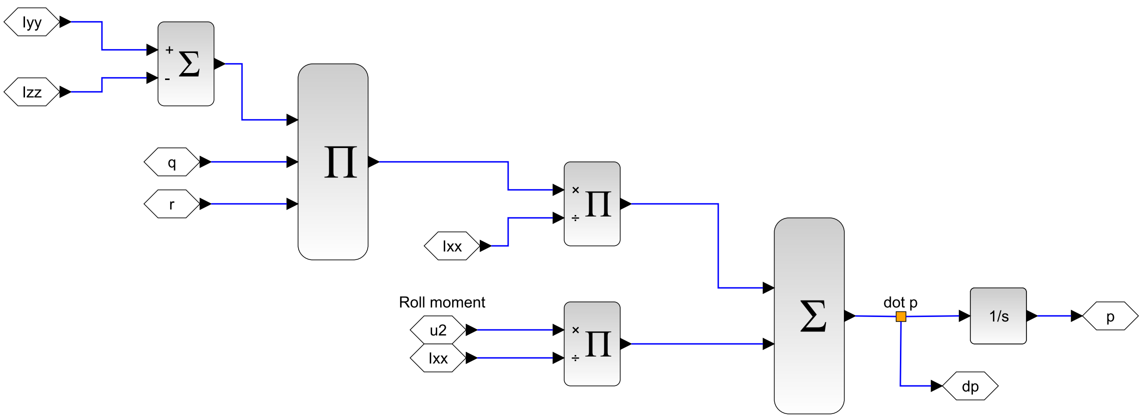

FIGURE 2: Angular Velocity P XCOS Model

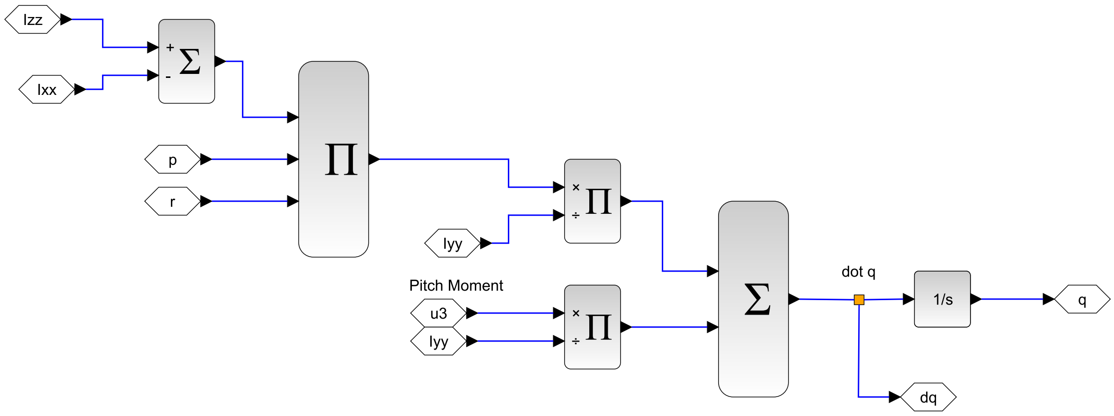

Figure 3: Angular Velocity Q XCOS Model

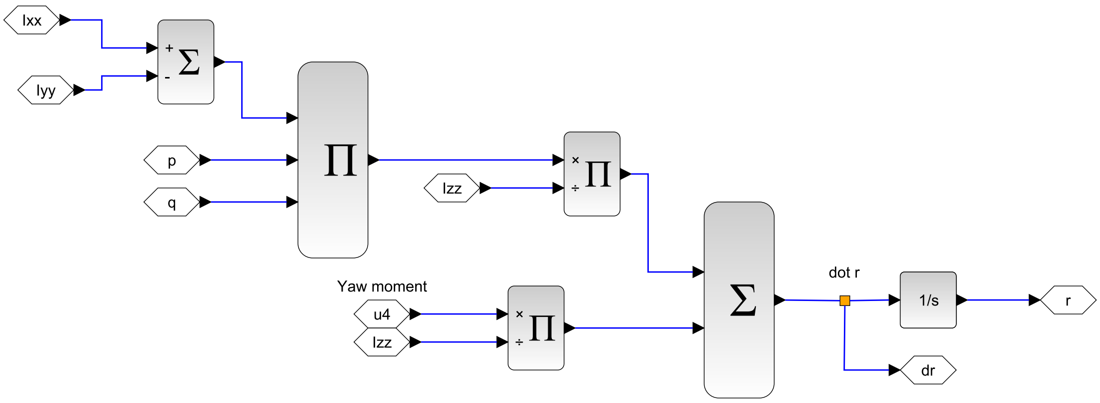

Figure 4: Angular Velocity R XCOS Model

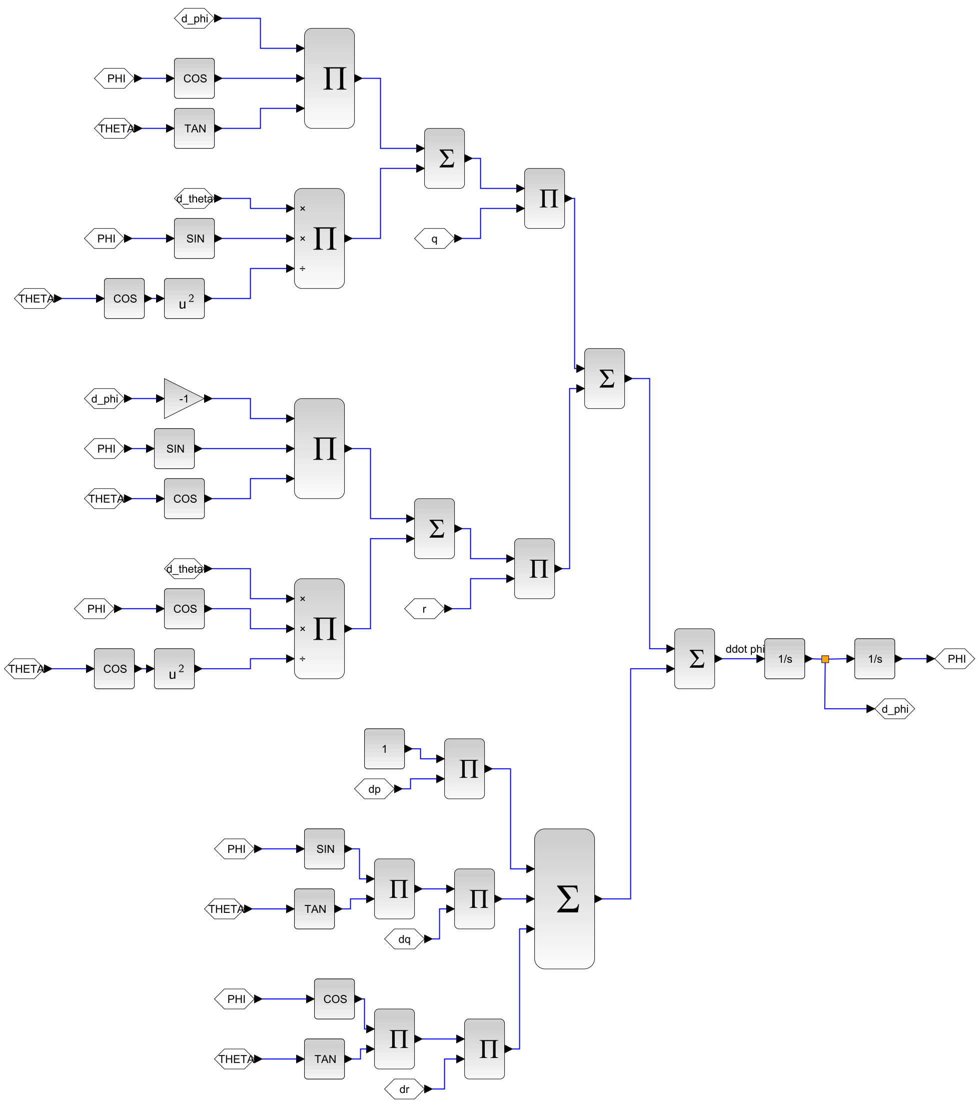

FIGURE 5: Angle ϕ XCOS Model Before Impulse Considered

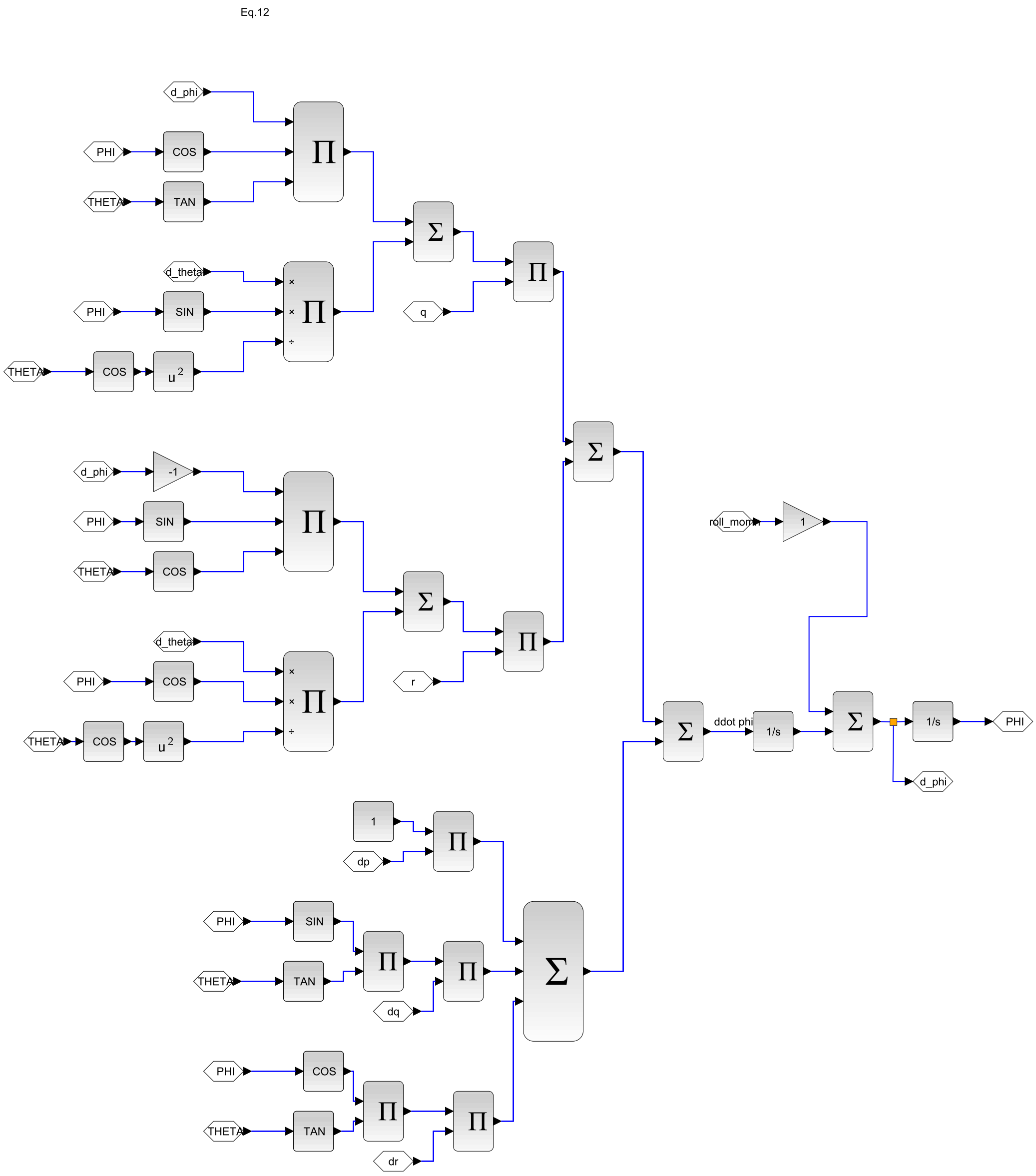

FIGURE 6: Angle ϕ XCOS Model

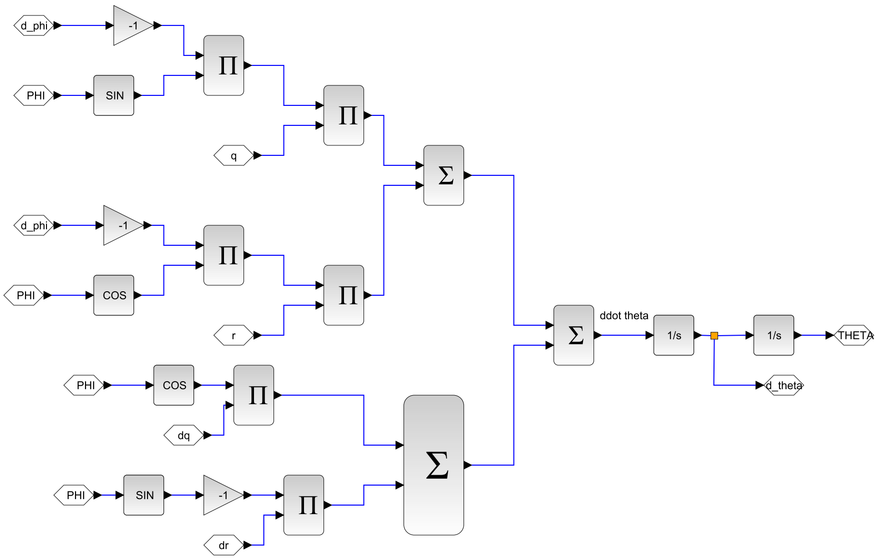

Figure 7: Angle θ XCOS Model Before Impulse Considered

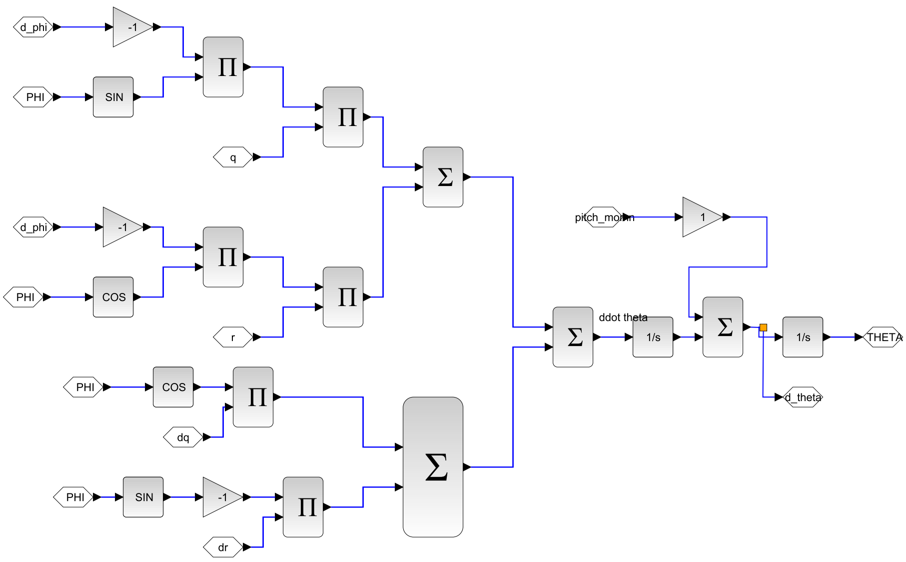

Figure 8: Angle θ XCOS Model

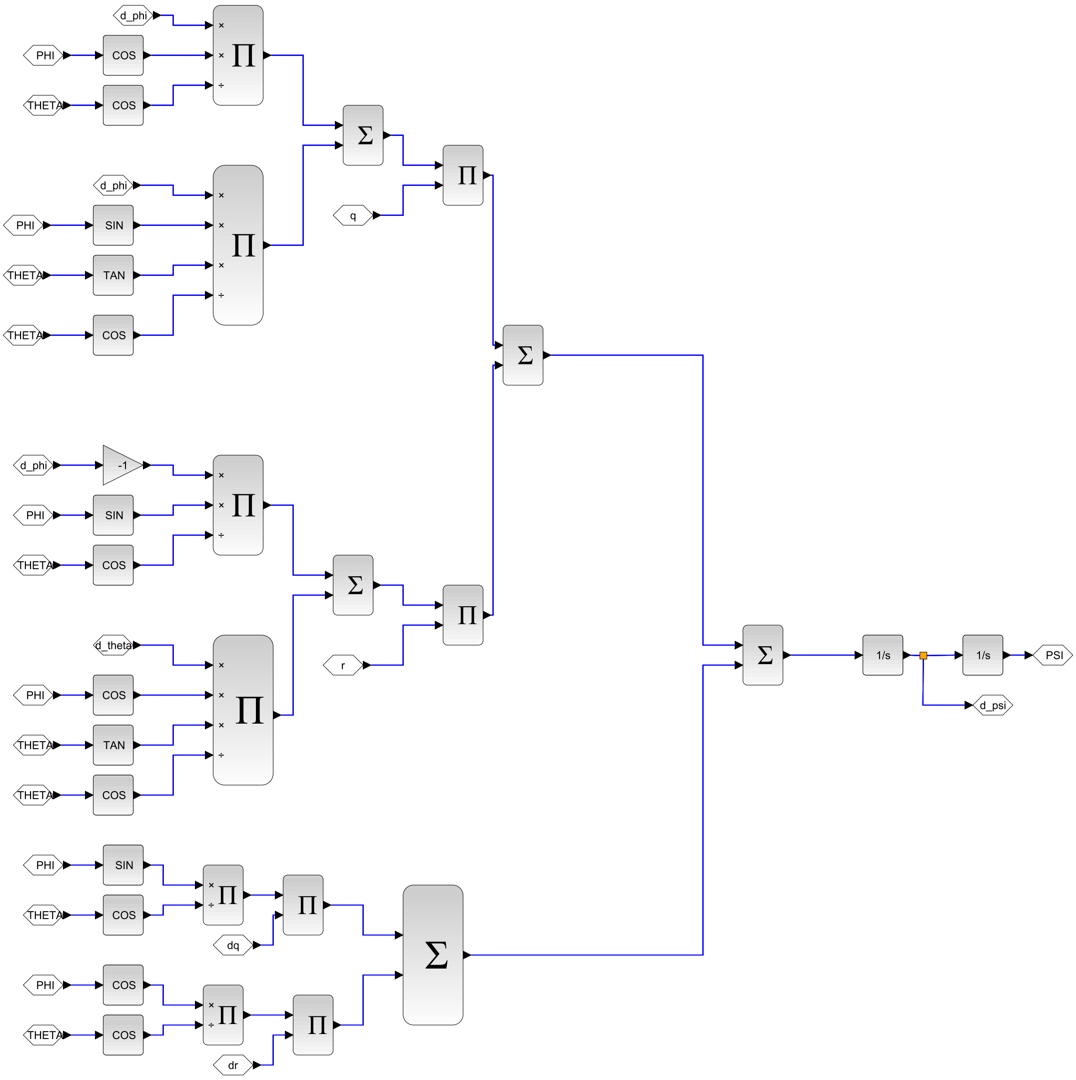

FIGURE 9: Angle ψ XCOS Model

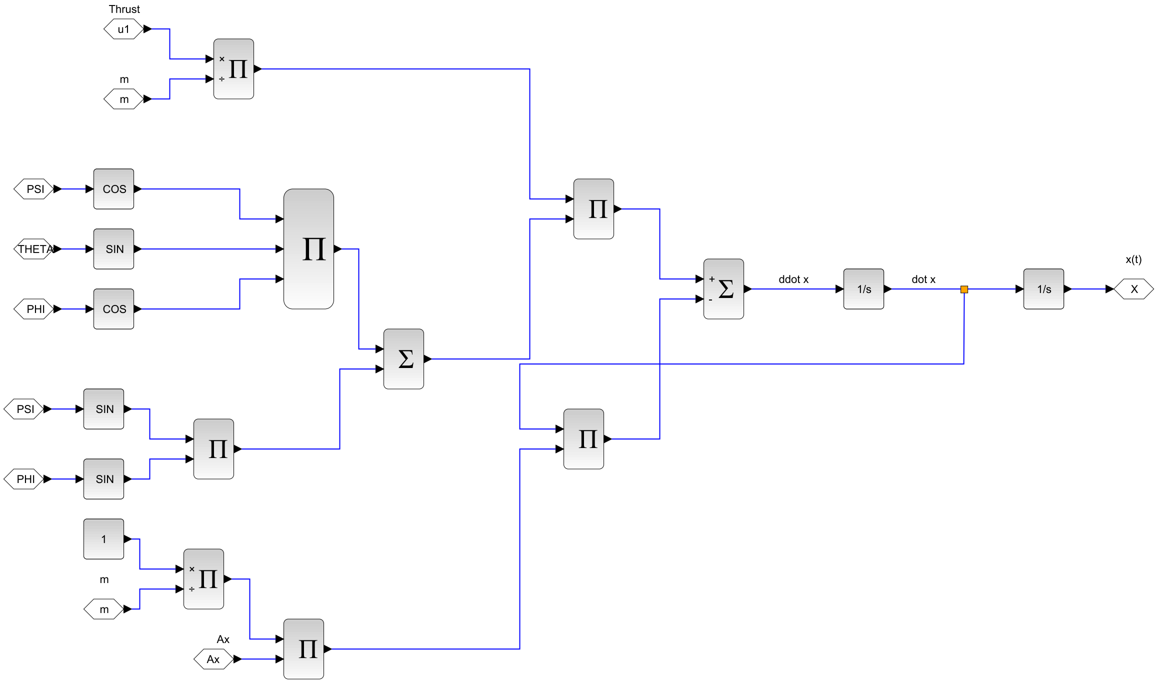

FIGURE 10: X Translational Model Before Impulse Considered

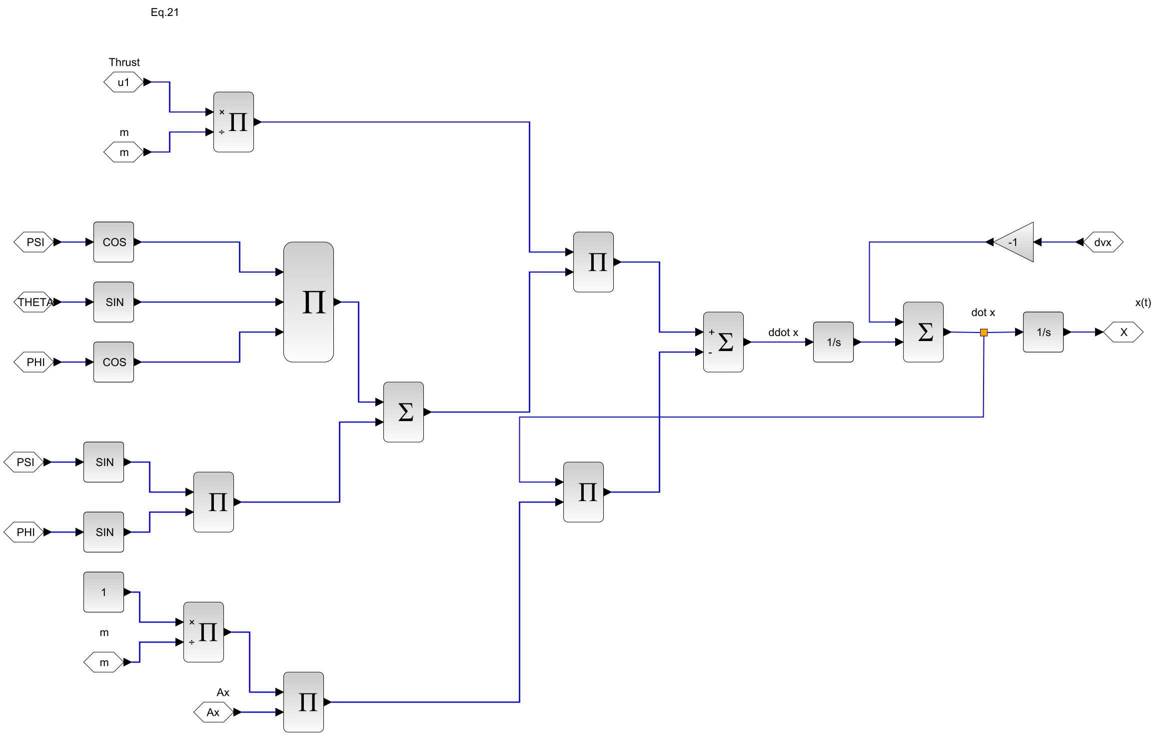

FIGURE 11: X Translational Model

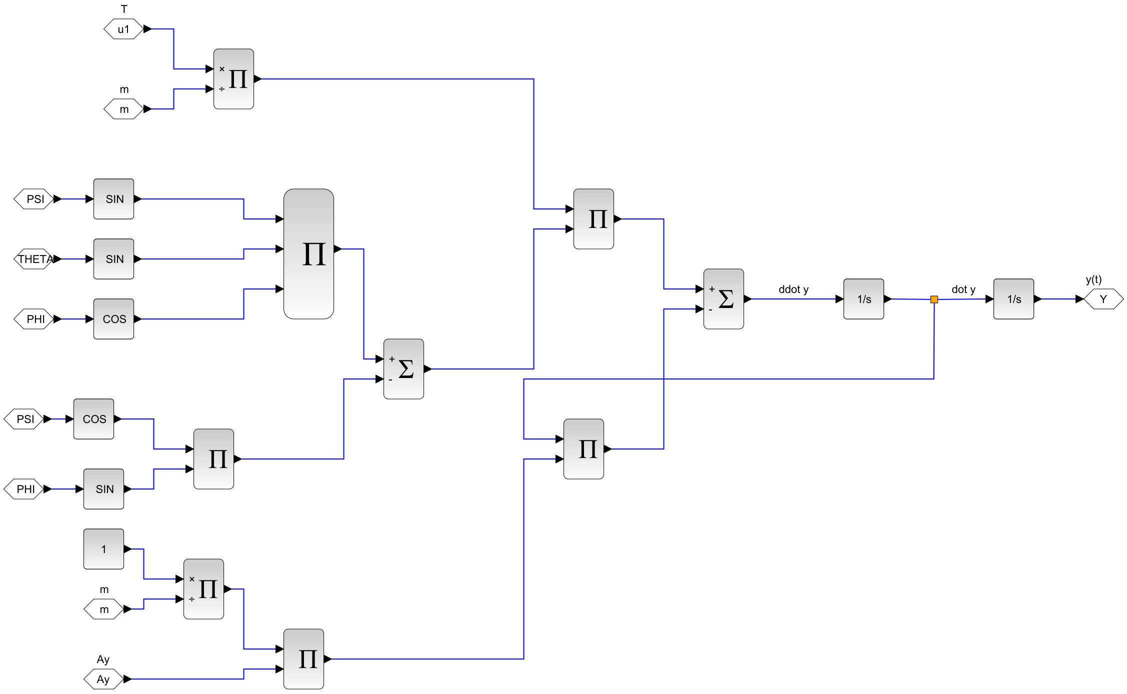

FIGURE 12: Y Translational Model Before Impulse Considered

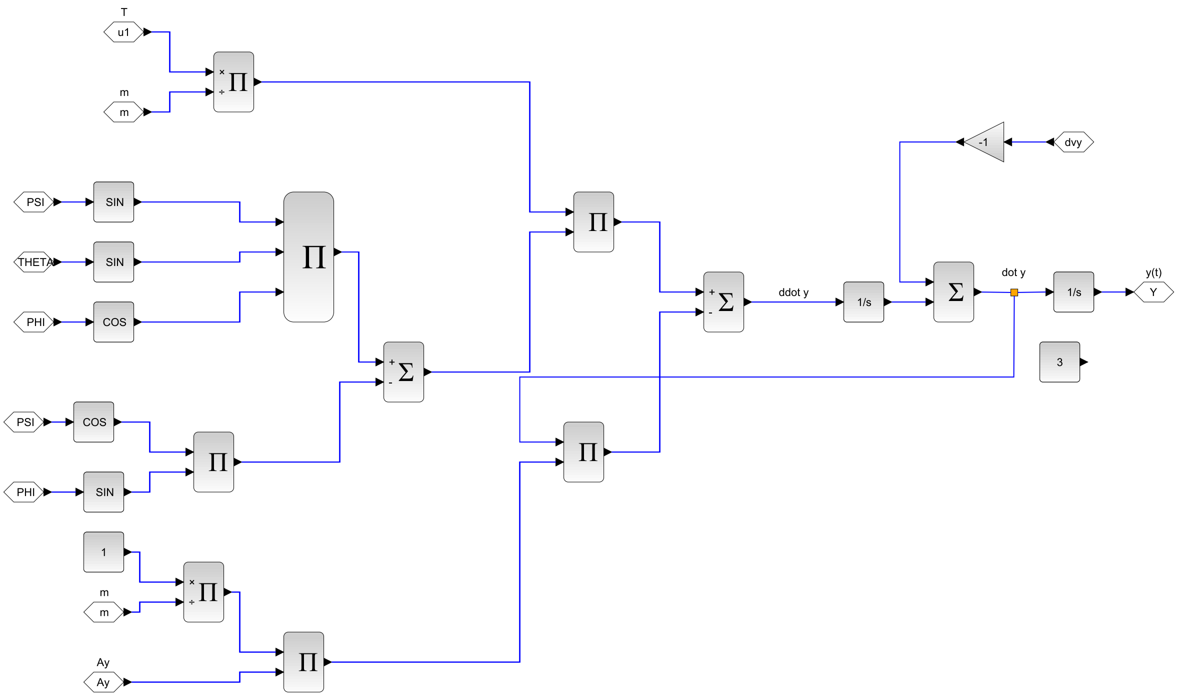

FIGURE 13: Y Translational Model

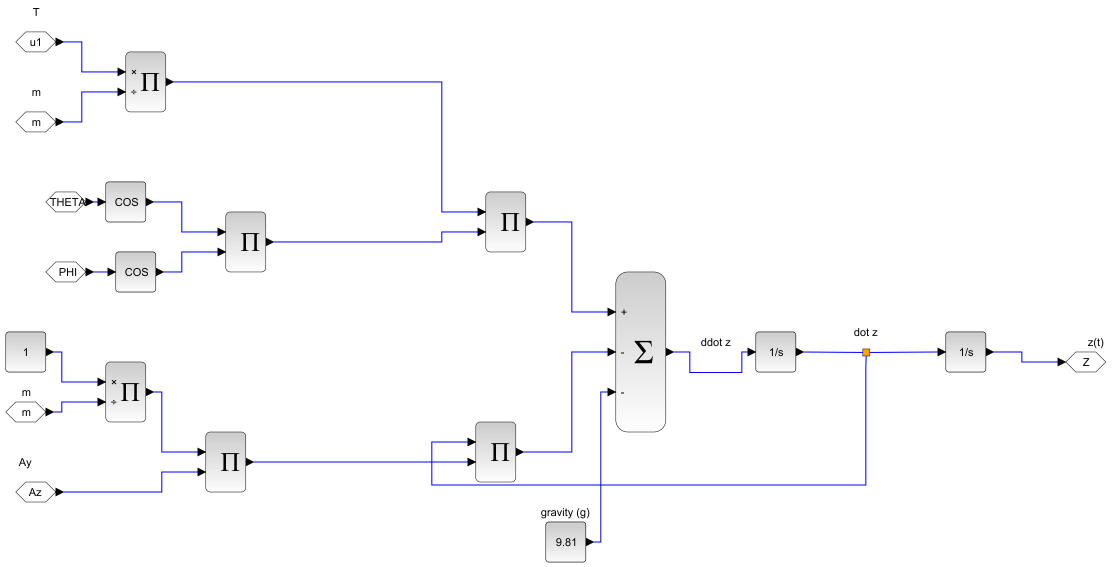

FIGURE 14: Z Translational Model Before Impulse Considered

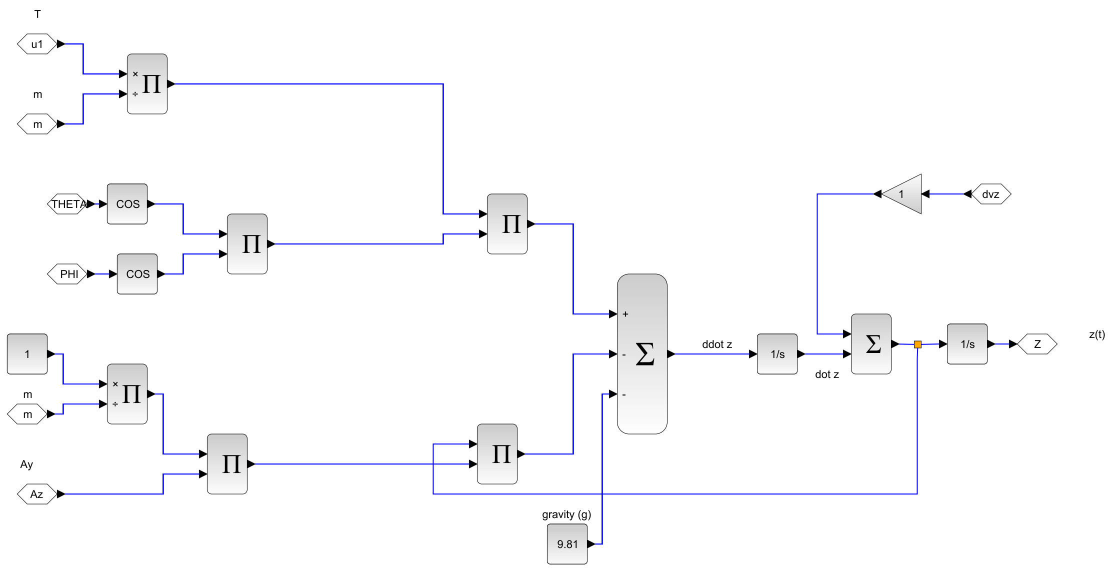

FIGURE 15: Z Translational Model

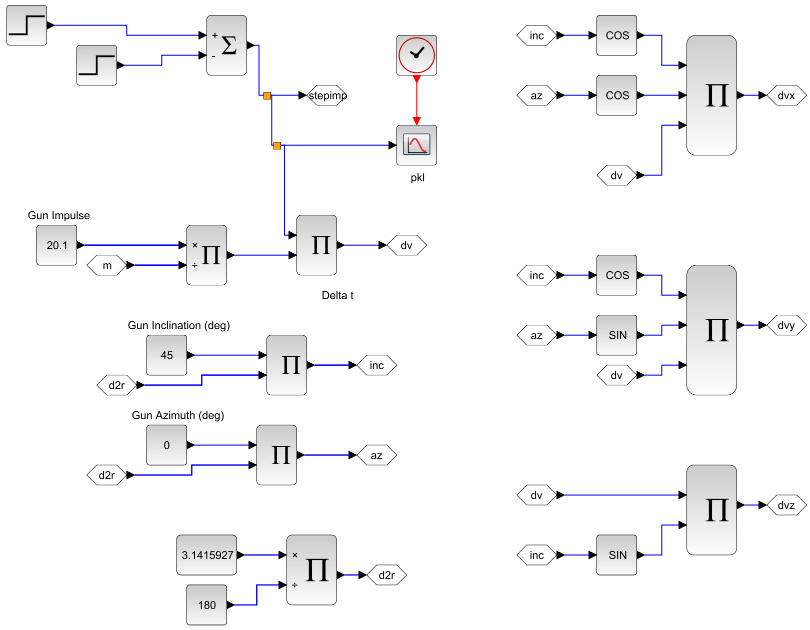

FIGURE 16: The Linear Impulse XCOS Model

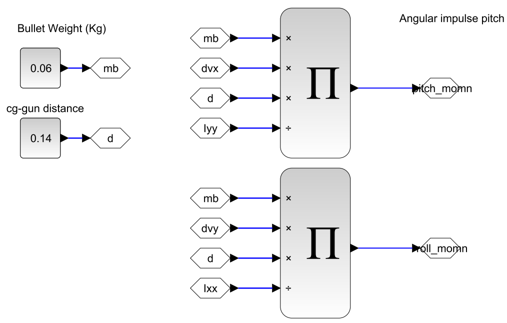

FIGURE 17: The Angular Impulse XCOS Model

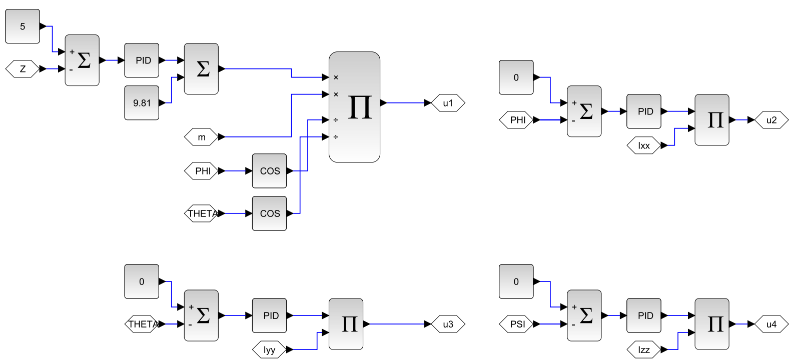

FIGURE 18: PID Placement

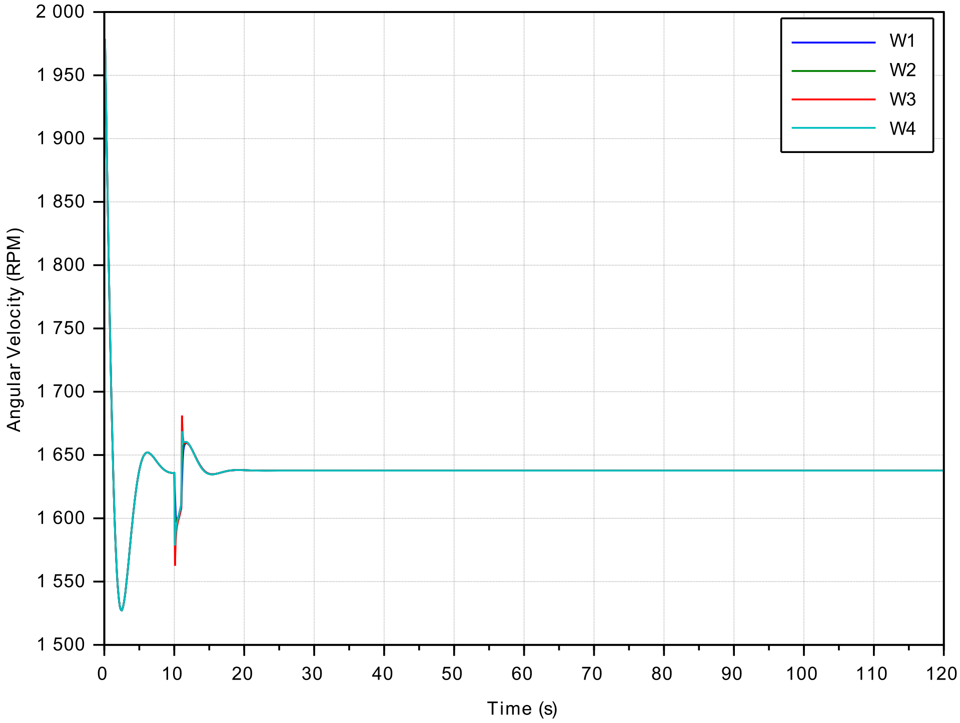

FIGURE 20: Quadcopter's Angular Velocity

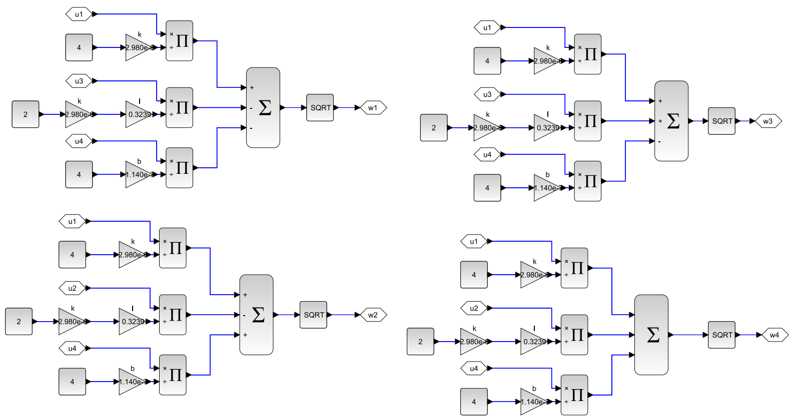

FIGURE 19: Angular Velocity Control after PID

Appendix B: Scinotes For Graph

```
//Position
ts_p = P.time;
xis = P.values;
xs = xis(:, 1)
ys = xis(:, 2)
zs = xis(:, 3)

//Attitude
ts_a = A.time;
etas = A.values;
todeg = 180 / %pi;
phis = etas(:, 1) * todeg;
thetas = etas(:, 2) * todeg;
psis = etas(:, 3) * todeg;

// Plot position
scf(0);
ax=gca(),// gat the handle on the current axes
// Ajust the limit of the axes accordingly
ax.data_bounds= [0, 0; 60, 10]; // [xmin, ymin; xmax, ymax]

plot(ts_p, xs, 'r', 'LineWidth',2);
plot(ts_p, ys, 'b', 'LineWidth',2);
plot(ts_p, zs, 'g', 'LineWidth',2);
hl=legend(['x';'y';'z']);

filename='4chopter_position.pdf';
```

```
xlabel("Time (s)");
ylabel("Position (m)");
xgrid(0, 0.2, 9);
xs2pdf(0, filename);



// Plot Attitude
scf(1);
ax=gca(),// gat the handle on the current axes
// Ajust the limit of the axes accordingly
ax.data_bounds= [0, -10; 15, 15]; // [xmin, ymin; xmax, ymax]
plot(ts_a, phis, 'r', 'LineWidth',2);
plot(ts_a, thetas, 'b', 'LineWidth',2);
plot(ts_a, psis, 'g', 'LineWidth',2);
hl=legend(['$\phi$';'$\theta$';'$\psi$']);
filename='4chopter_attitude.pdf';
xlabel("Time (s)");
ylabel("Attitude (Deg)");
xgrid(0, 0.2, 9);
xs2pdf(1, filename);


// Plot 3D Trajectory
scf(2)
filename='4chopter_trajectory.pdf';
param3d(xs, ys, zs);
a = gca();
a.isoview = 'on';
xlabel("x (m)");
ylabel("y (m)");
zlabel("z (m)");
xgrid(0, 0.2, 9);
```

```
xs2pdf(2, filename);
```

Curriculum Vitae

	Basic Information
Name	Jordy Amar Zikri
Place of Birth	Jakarta, Indonesia
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Address	Jalan Penggilingan baru 1 no 45 RT 09 RW 04 kelurahan dukuh, Kramat Jati, Jakarta
Year	**Education**
2015 - present	International University Liaison Indonesia (IULI)
2011 - 2014	Semesta Bilingual Boarding School (High School)
2008 - 2011	Pribadi Bilingual Boarding School (Middle School)
2002 - 2008	Dukuh 09 (Elementary School)
Year	**Courses**
2018	Festo Training Pneumatics and Hydraulics
Year	**Seminars & Workshops**
2017	Elevator & Angle of Attack (AOA)
Year	**Work Experiences**
2018	Garuda Maintenance Facility (GMF)
2017	Sriwijaya Air