M Tech
Presentation
on

Design of a Control Algorithm for Recoil Mitigation of a Multi rotor Unmanned Combat Aerial Vehicle

By

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Under the Guidance of

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Motivation

- The Unmanned Combat Ariel Vehicle (UCAV) is gaining more and more popularity in the drone industry, both for military purposes and for drone based games.
- This type of drone will be useful in a variety of applications from shooting zip lines to planting trackers/cameras onto specific surfaces for video/audio surveillance.
- This requires accurate control systems and exact knowledge of the dynamics of the Gun/Projectile Launching Device and the UAV as well.
- So a systematic study of the issues facing such a drone and designing controllers to overcome the issues is required.

Overview

Introduction

- Projectile launching Device(PLD): Any device capable of shooting out an object at a high velocity in a short period of time is considered as a PLD

Unmanned Ariel Vehicle (UAV)

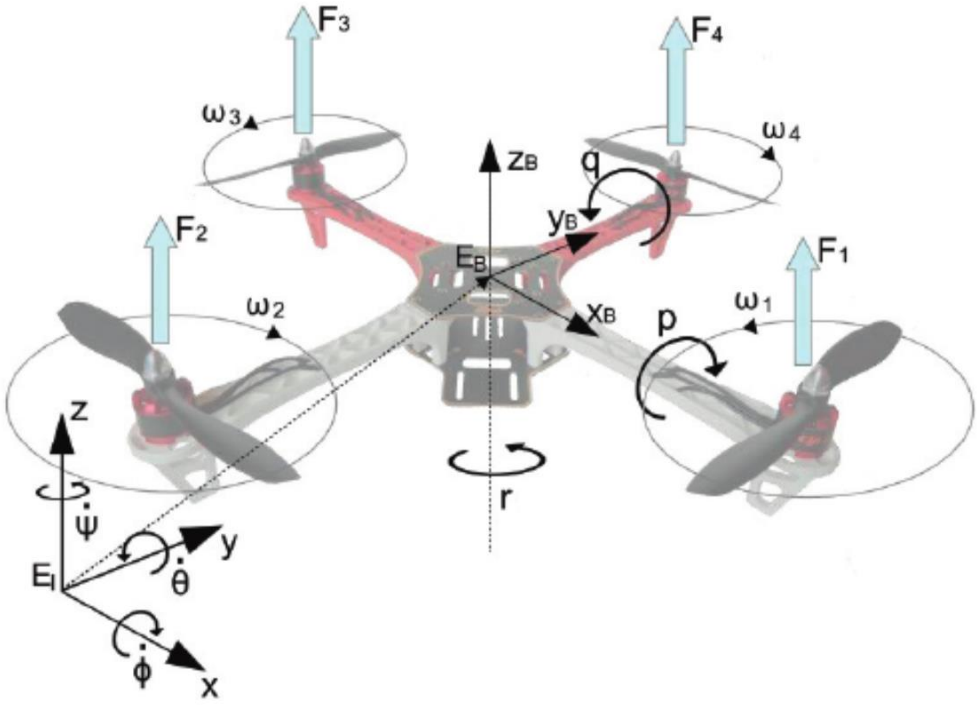
Multi rotor UAV

Fixed Wing UAV

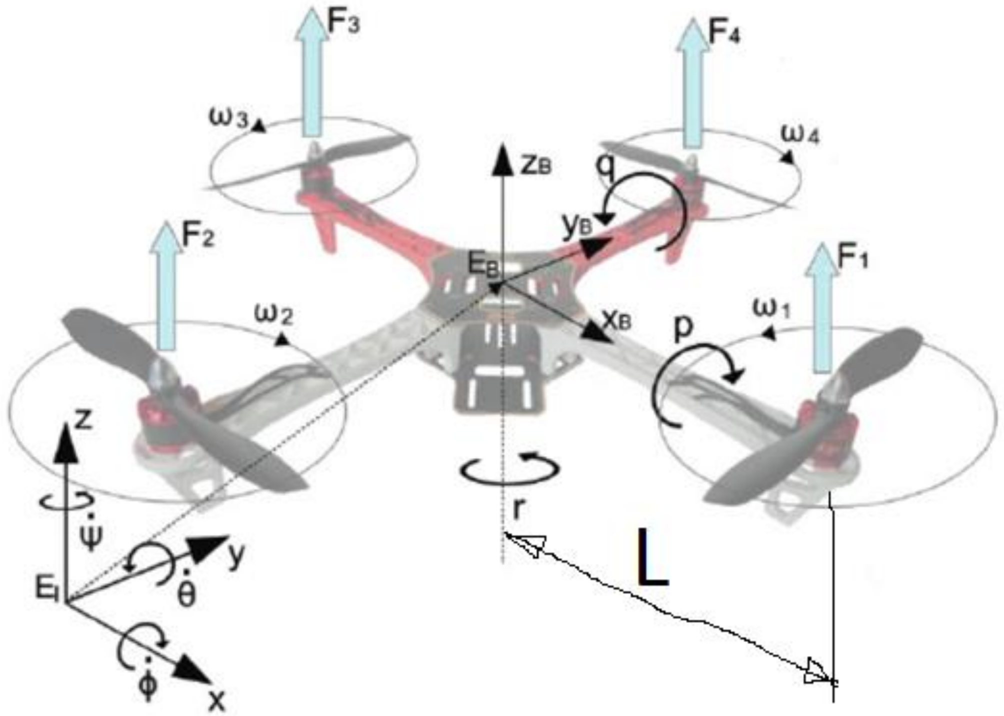
Unmanned Combat Ariel Vehicle (UCAV)

Standard Quadcoptor

- Quadcopters use two pairs of identical propellers
- These use independent variation of the speed of each rotor to achieve control.
- By changing the speed of each rotor it is possible to specifically generate a desired total thrust or turning force.



Equation of motion



Using Newton's Second Law of motion we can say

$$\begin{bmatrix} \ddot{x}_i \\ \ddot{y}_i \\ \ddot{z}_i \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} + \frac{1}{m}(RT_b) + F_D$$

Using Euler's rotation equations in Body frame we can say

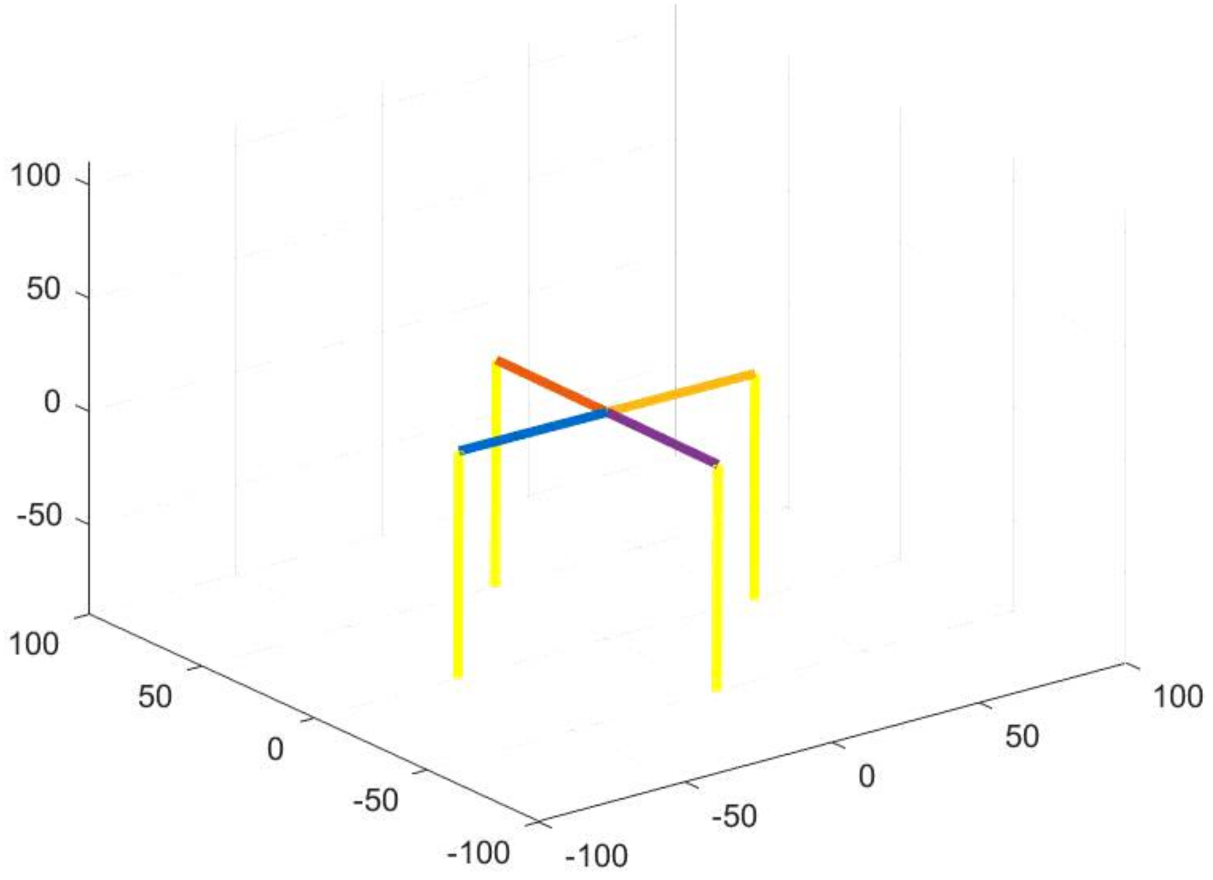
$$\begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{bmatrix} = \begin{bmatrix} {I_x}^{-1} & 0 & 0 \\ 0 & {I_y}^{-1} & 0 \\ 0 & 0 & {I_z}^{-1} \end{bmatrix} \tau_b + \begin{bmatrix} \frac{I_z - I_y}{I_x} \omega_y \omega_z \\ \frac{I_x - I_z}{I_y} \omega_x \omega_z \\ \frac{I_y - I_x}{I_z} \omega_x \omega_y \end{bmatrix}$$

Where I_x, I_y and I_z are the Principal moments of inertia of the Quadcoptor

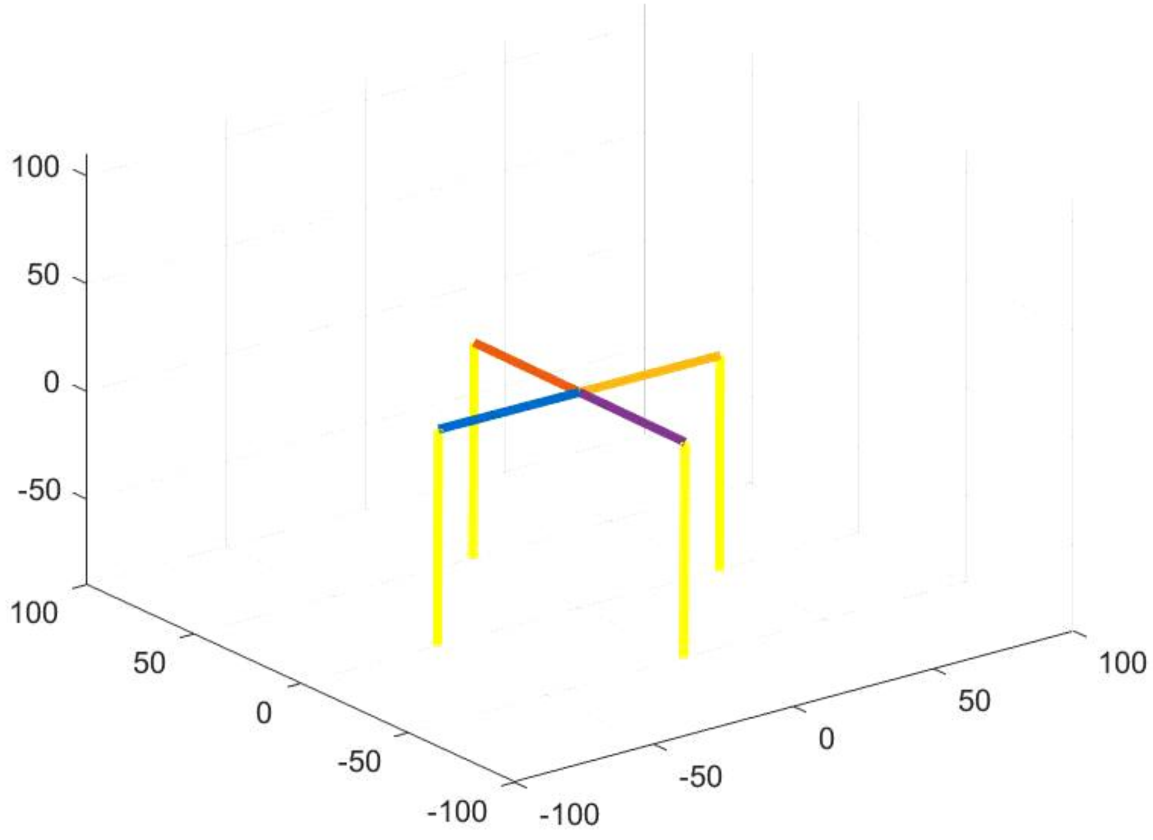
Quadcoptor Simulation

A MATLAB simulator using Euler's method

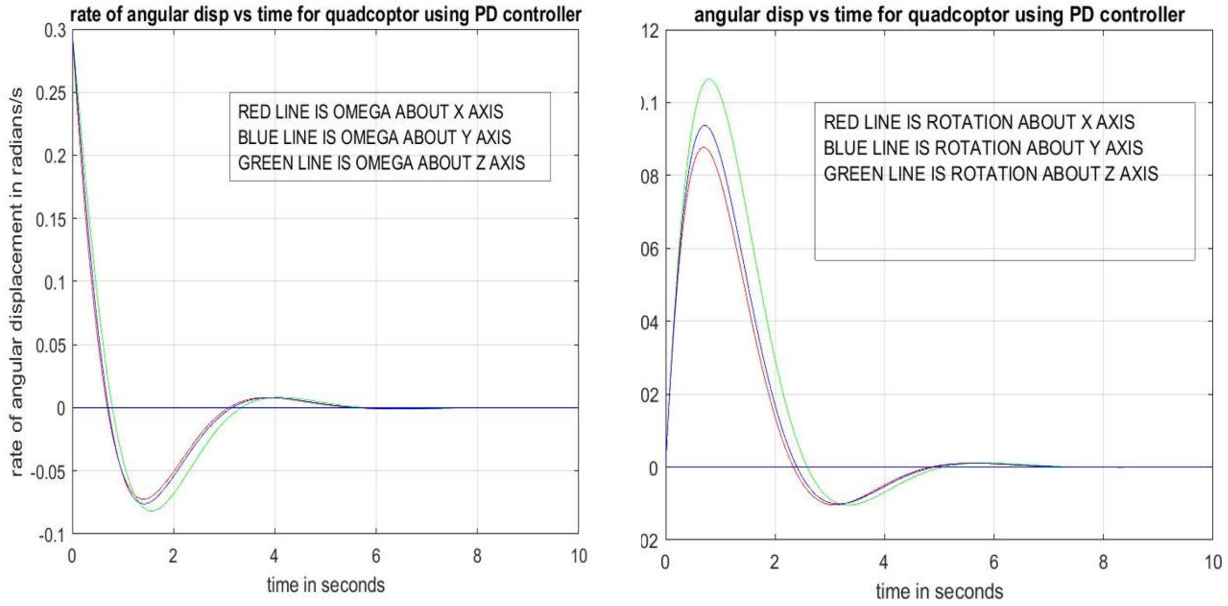
Random initial angular velocities



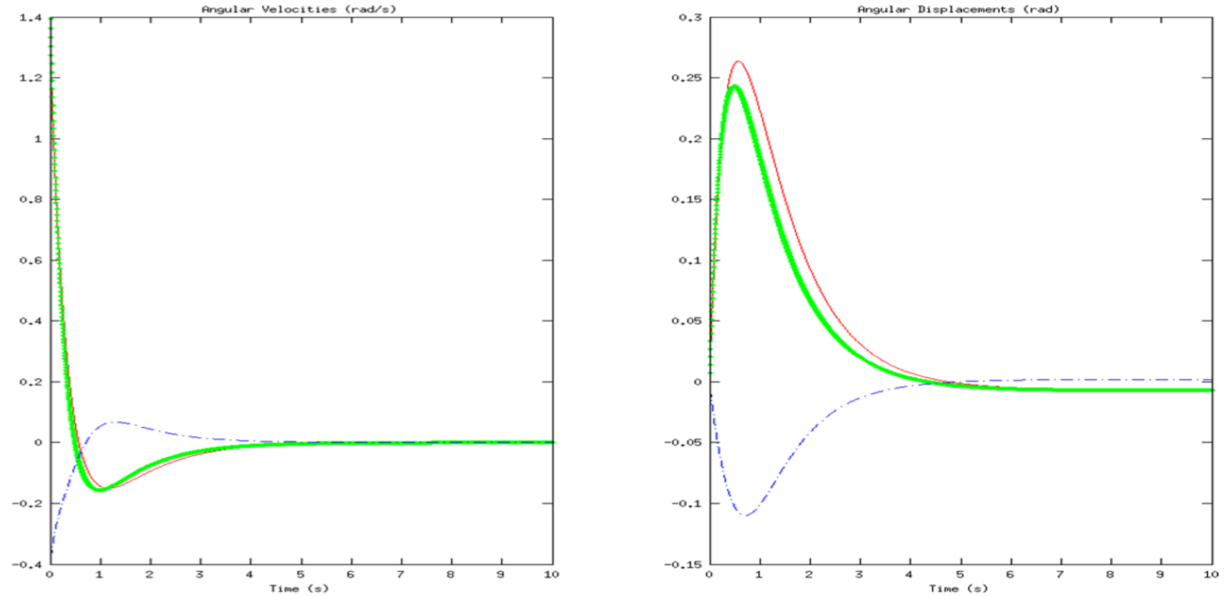
PD Controller Output



Quadcoptor PD Output Plot



Quadcoptor PD output in the reference paper



PLD Parameters

0.32" ASHANI MARK -II Pistol

TECHNICAL SPECIFICATION:-

Caliber	: 0.32"
Barrel length	: 91.44mm
Magazine	: Box type (capacity-08 rounds)
Weight	: 680 grams
Range	: 18.27 meters
Action	: Semi automatic (blow back)
Replacement of magazine	: Quick release mechanism (Push button)
Hammer position	: Exposed
Grip	: Full Wooden/Polymer Grip with GSF metallic logo
Safety	: Four Types
Dimention	: 163 X 111 X 38 (mm)

Impulse on Gun = Mass bullet*Muzzle velocity
= 7.5gms * 300m/s
= 2.25 kgm/s
Taking into account expanding gases ,
Total impulse = 1.5*2.25 = 3.375 kgm/s

Time taken by bullet in barrel =
0.00059285 seconds (Barrel Time)

Max time of flight =
0.06 seconds (Time till impact)

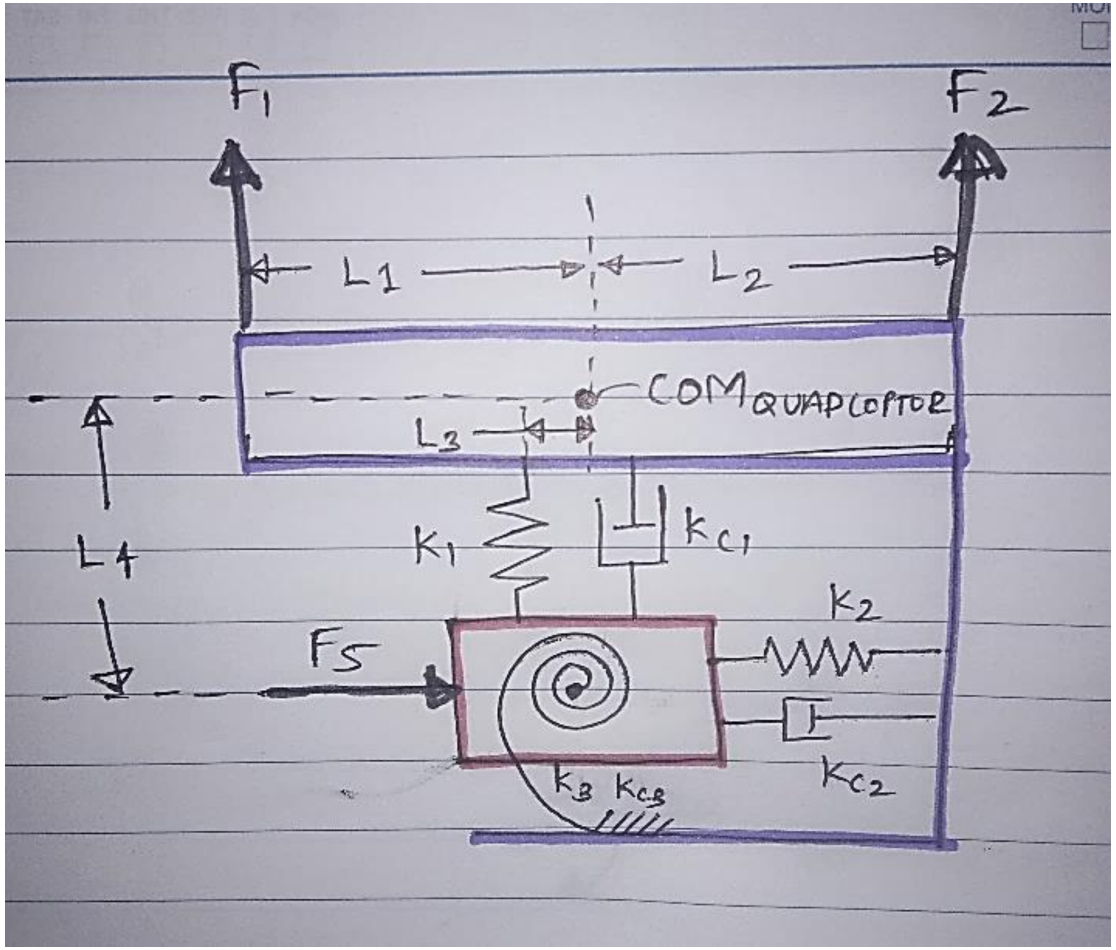
Max drop in height due to projectile motion =
17.658 millimeters

The Bullet leaves the barrel 600 micro seconds after the trigger has been pulled, thus the problem of accuracy and stabilization can be cleanly divided into two

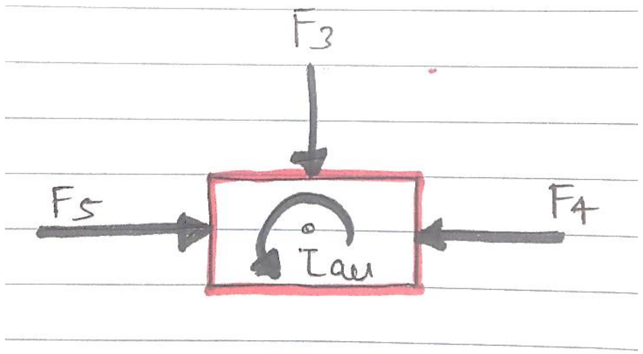
Part 1: Short term effect on the PLD under 0.0006 seconds

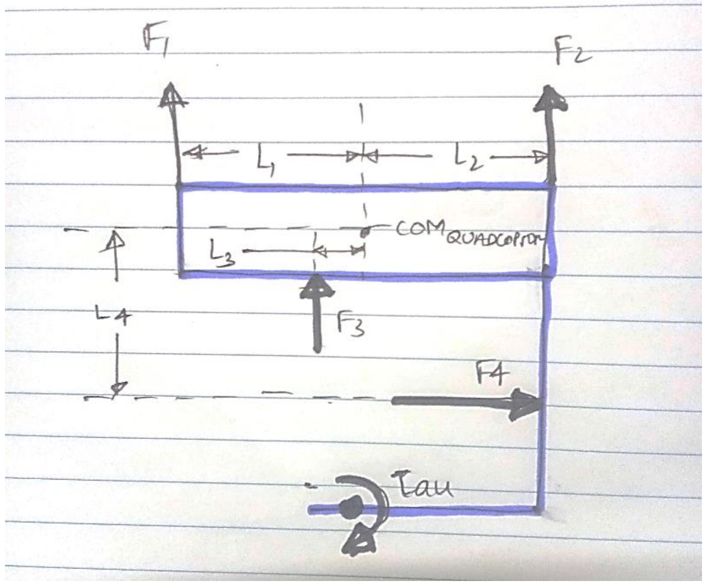
Part 2: Long term effect on the PLD. Time taken for the PLD to stabilize after the shot has been fired so that the next shot may be fired.

Model 1 - Six DOF Planar System



Equations of motion





$$m_2\ddot{x}_2 = F_5 cos\phi \; - \; F_4 cos\theta + \; F_3 \sin\theta$$

$$m_2\ddot{y}_2 = -m_2 g + \; F_5 sin\phi \; - \; F_4 sin\theta \; - \; F_3 cos\theta$$

$$I_2\ddot{\phi} = -\,\tau$$

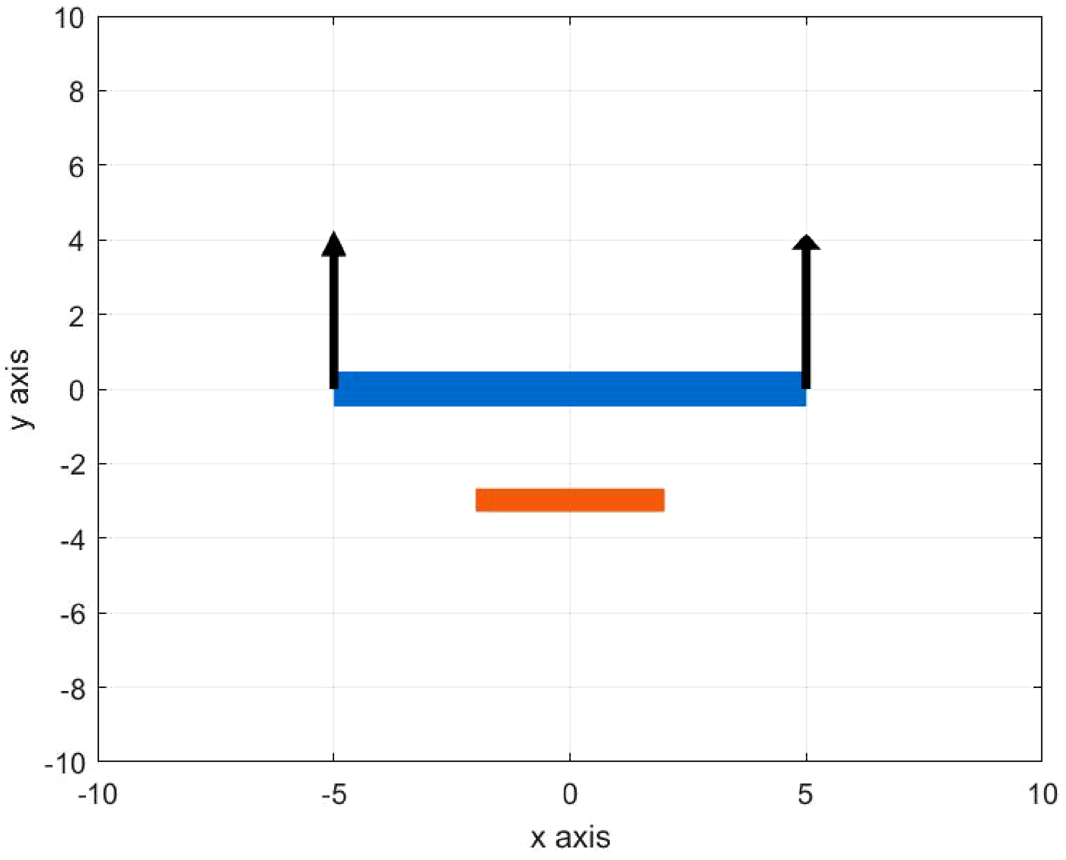
$$m_1\ddot{x}_1 = -(F_1 + F_2 + F_3)\sin\theta + F_4 cos\theta$$

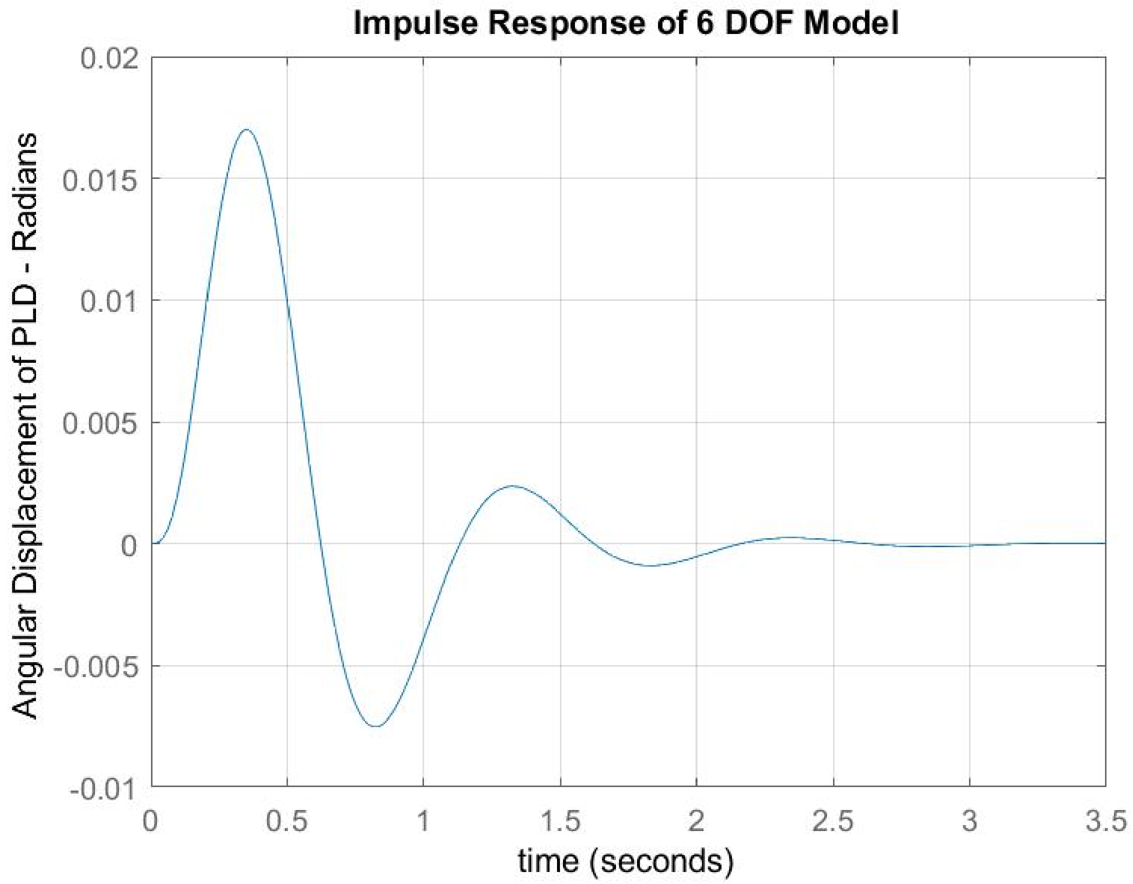
$$m_1\ddot{y}_1 = -m_1 g + \; (F_1 + F_2 + F_3)\cos\theta \; + F_4 sin\theta$$

$$I_1\ddot{\theta} = -F_1L_1 + \; F_2L_2 \; - \; F_3L_3 \; + \; F_4L_4 \; + \; \tau$$

Simulation and Results

The input is an impulse in the x direction to the PLD(orange).

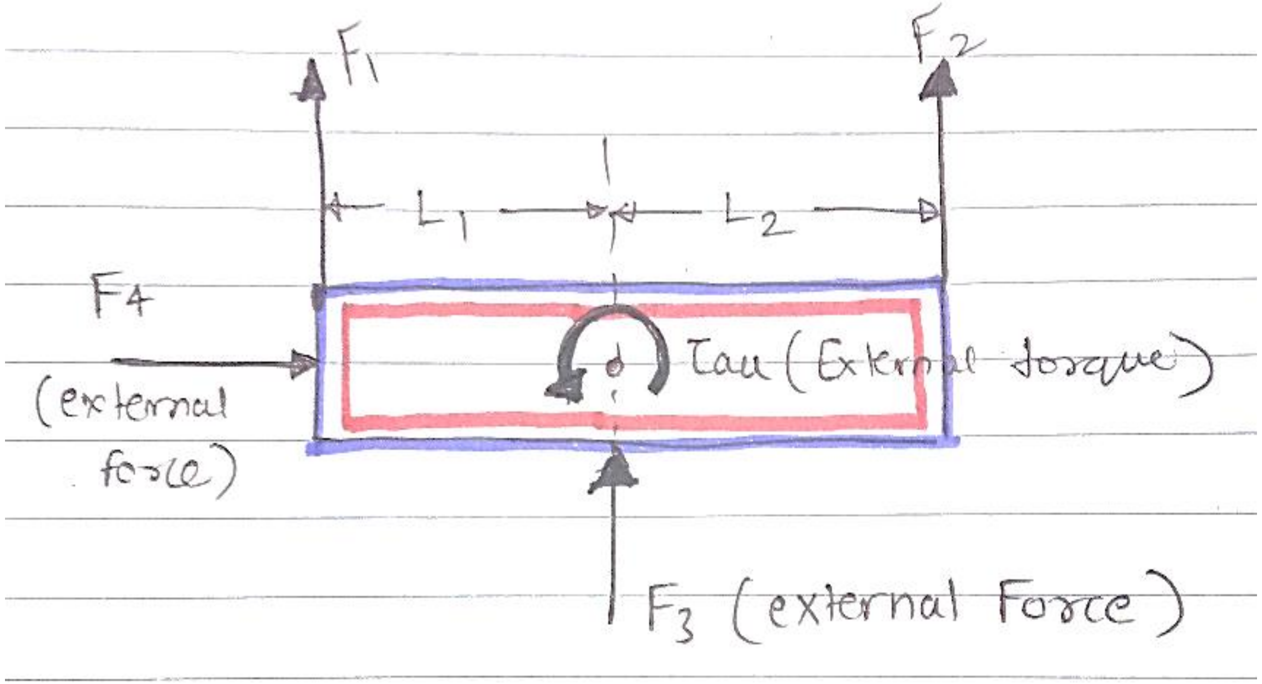




impulse response of the linearized 6 DOF model

At this stage, the no. of design parameters were too large to design an optimal controller

Model 2 – Three DOF Planar System



Equations of motion

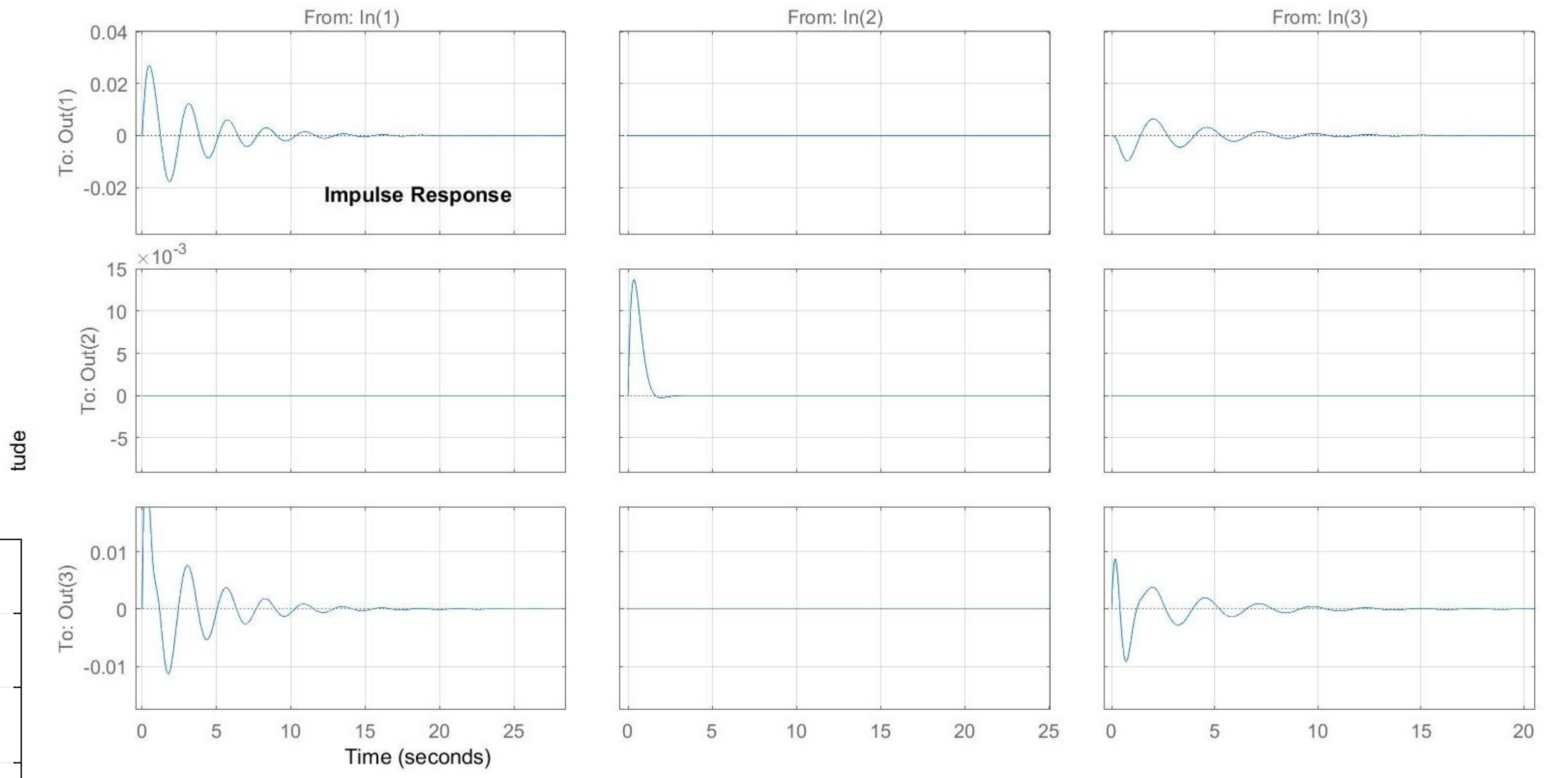
$$m_1\ddot{x}_1 = -(F_1 + F_2 + F_3)\sin\theta + F_4 cos\theta$$

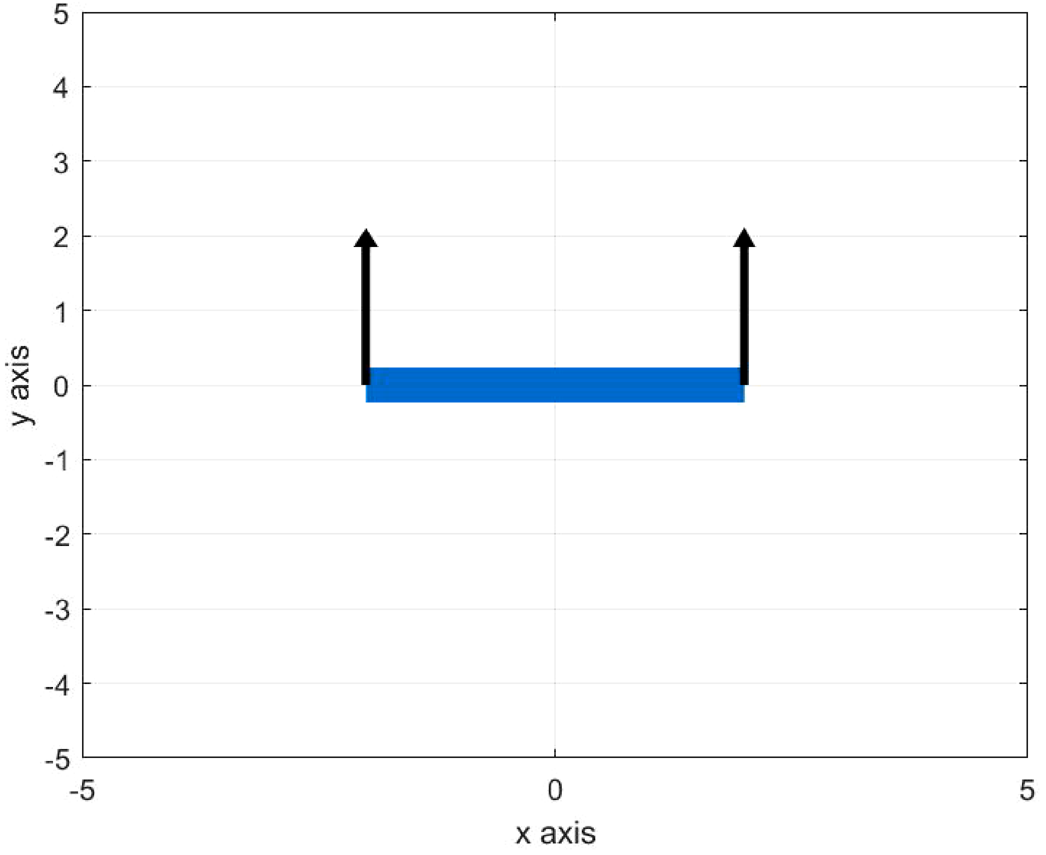
$$m_1\ddot{y}_1 = -m_1 g + (F_1 + F_2 + F_3)\cos\theta + F_4 sin\theta$$

$$I_1\ddot{\theta} = -F_1 L_1 + F_2 L_2 + \tau$$

Simulation and Results

Input 1 is an Impulse along the positive X axis
Input 2 is an impulse along the positive Y axis
Input 3 is an impulsive torque about Z
Output 1 is X displacement
Output 2 is Y displacement
Output 3 is angular displacement

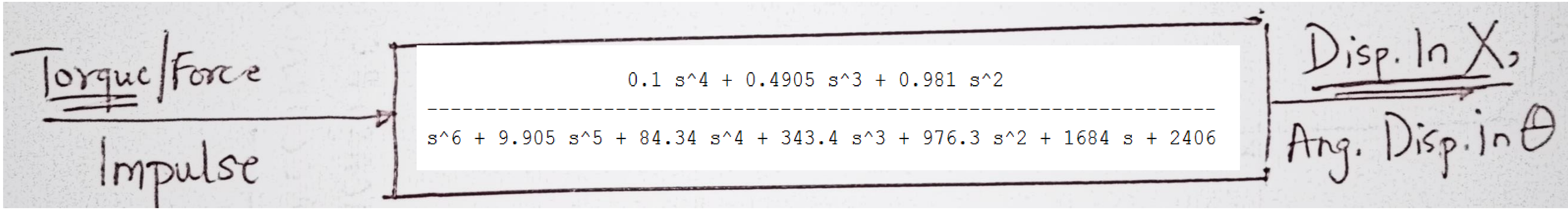




The above graph shows the response of each output to each input impulse for a linearized version of the three DOF model

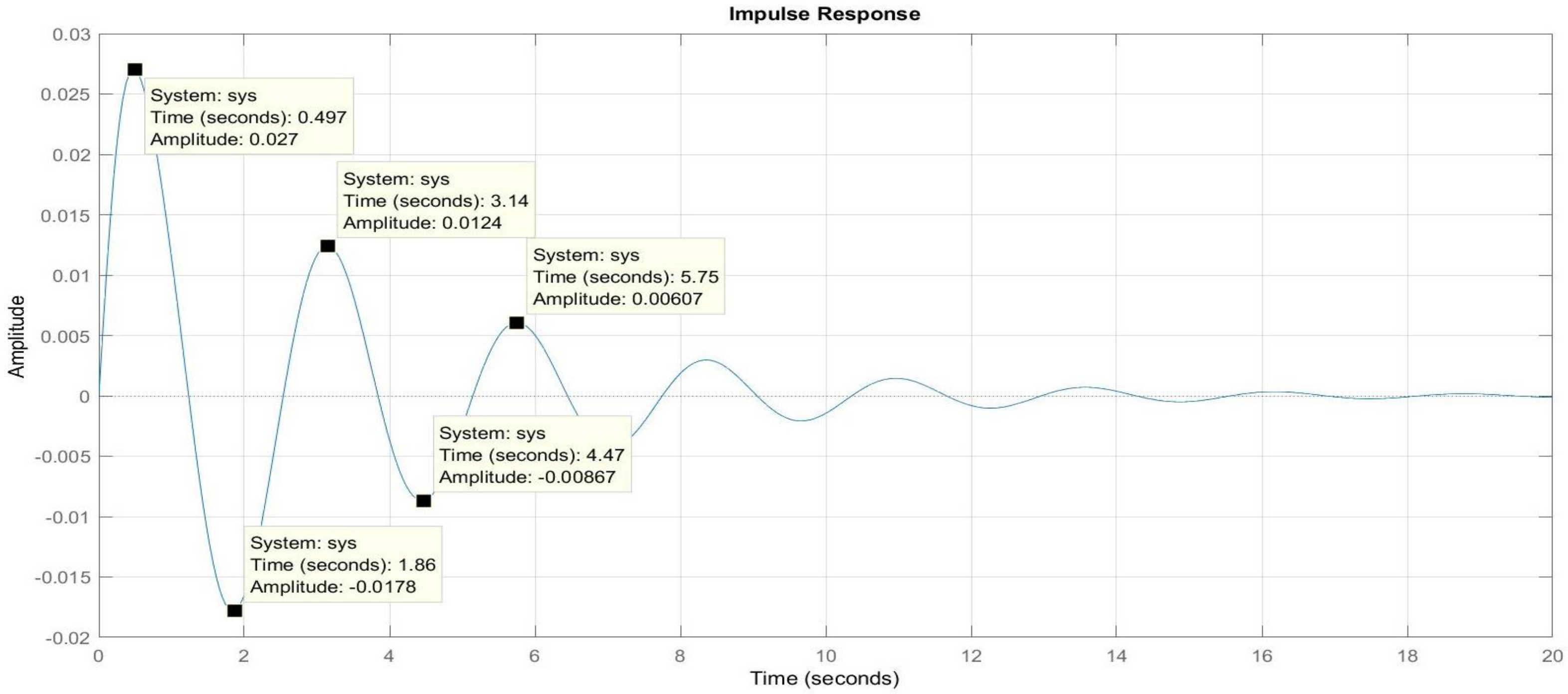
It is observed that the major part of the system response is 2nd order in nature, giving the idea that the Quadcoptor dynamics could be replaced with an analogous spring damper 2nd order system

Methodology for tuning controller gains using spring mass Damper analogy



Using the method of logarithmic decrement and finding the frequency directly through the time period of the response, the 6th order system was approximated by a 2nd order system

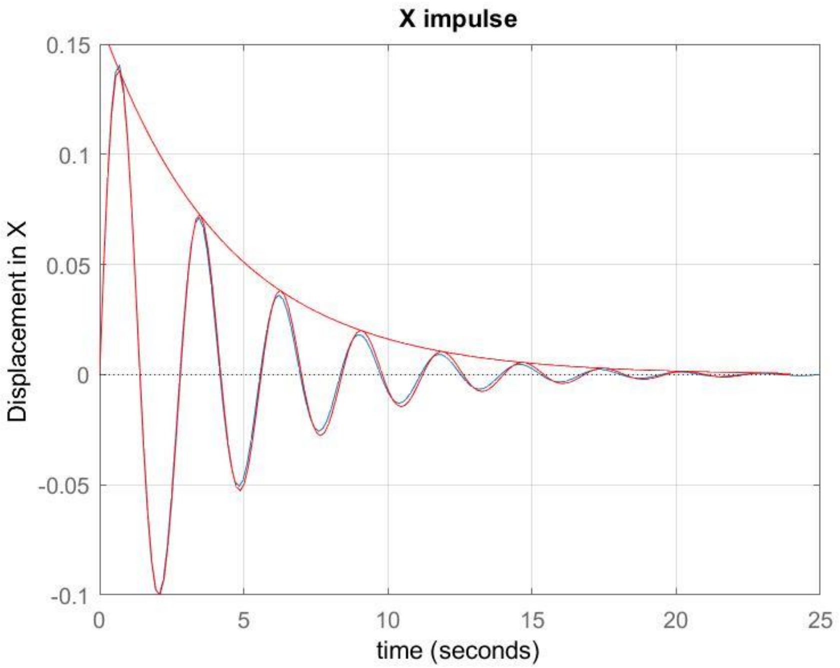
$$\frac{{\omega_n}^2}{s^2 + 2\xi\omega_n s + {\omega_n}^2}$$

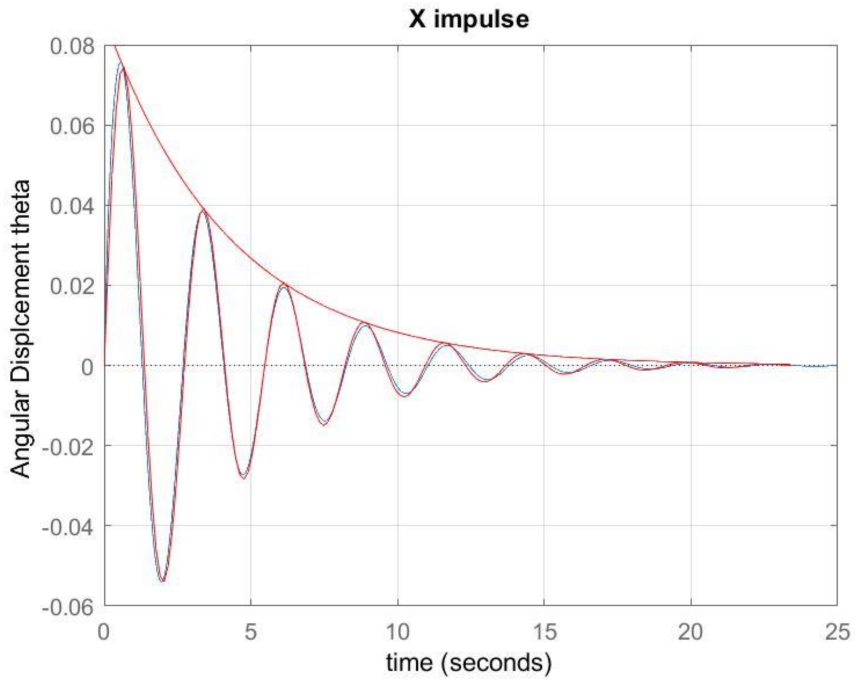


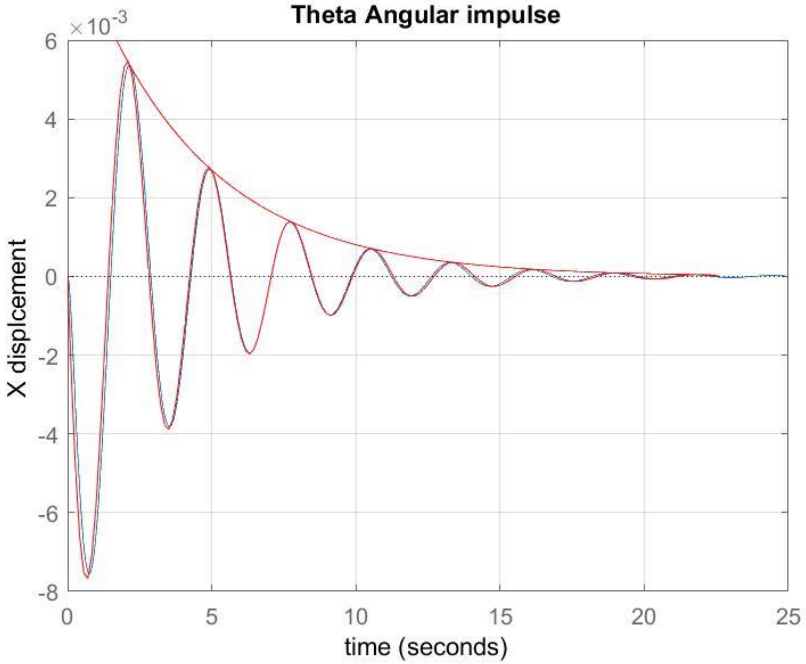
Fitted Response

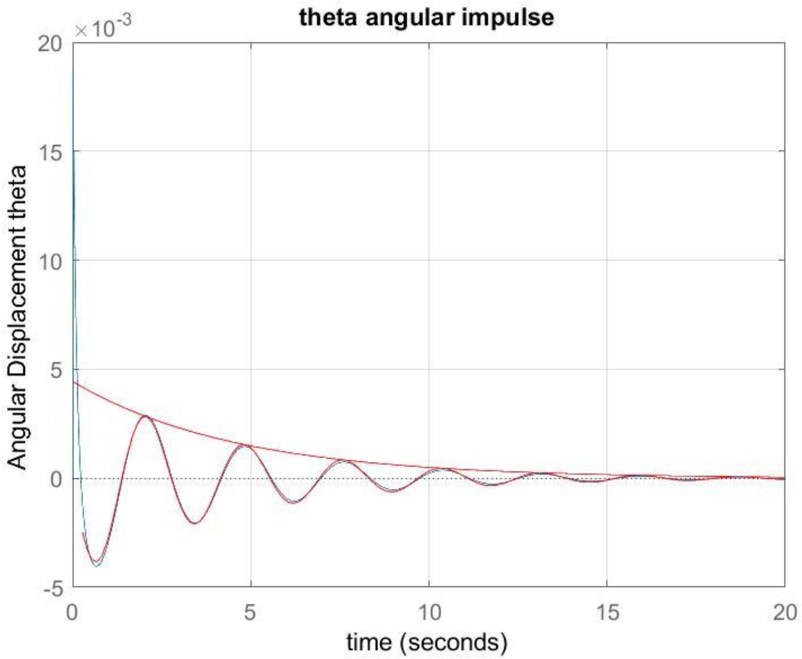
The magnitude of the angular displacement at the moment when the bullet just leaves the barrel is 0.00857 radians which translates into a displacement of 154 mm in accuracy.

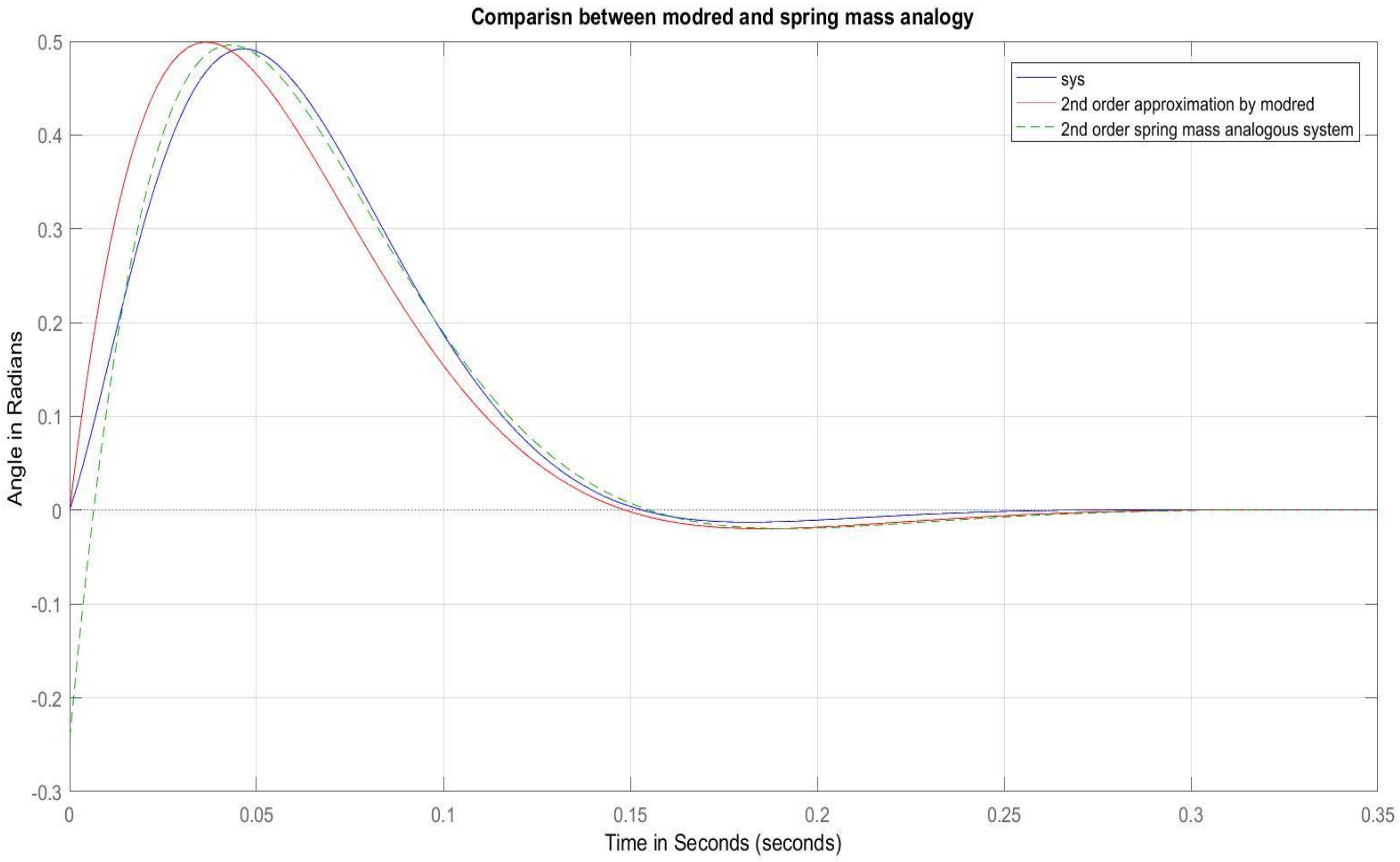
And for an impulse of 3.375 the corresponding angular displacement is 1.65 degrees



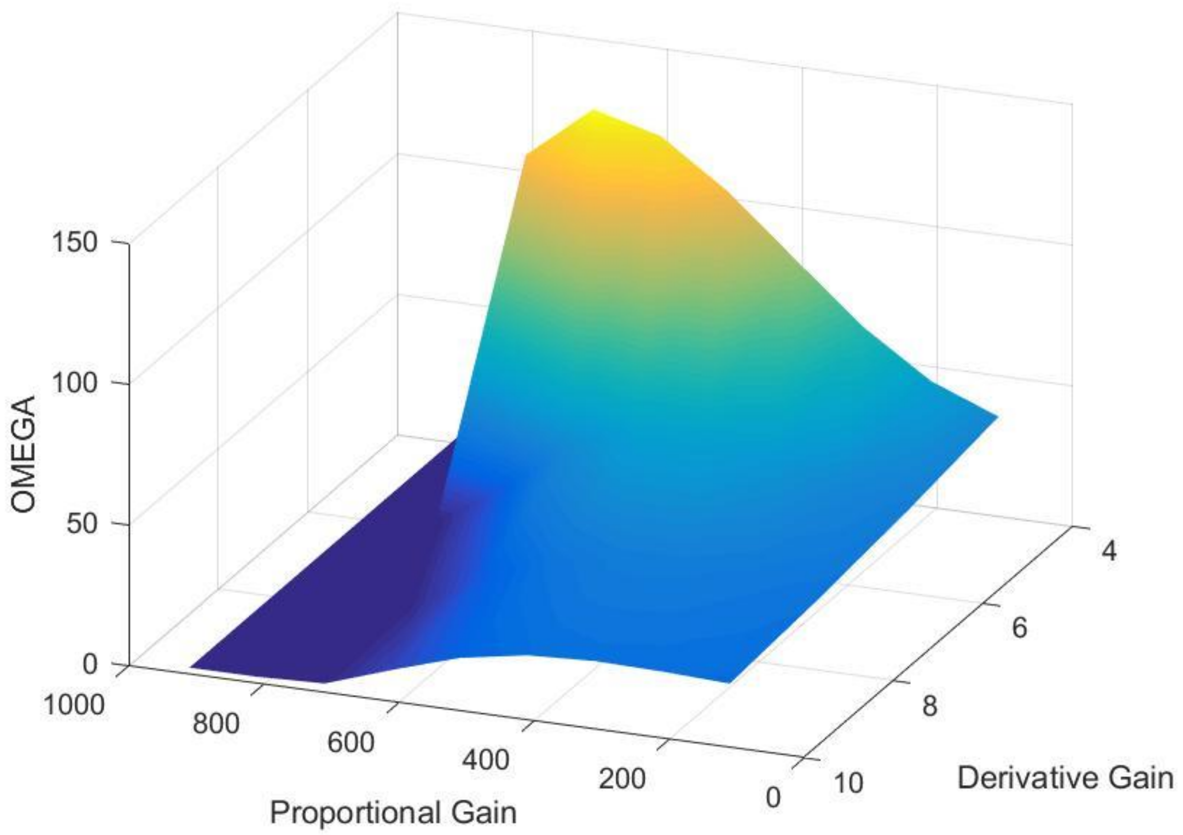


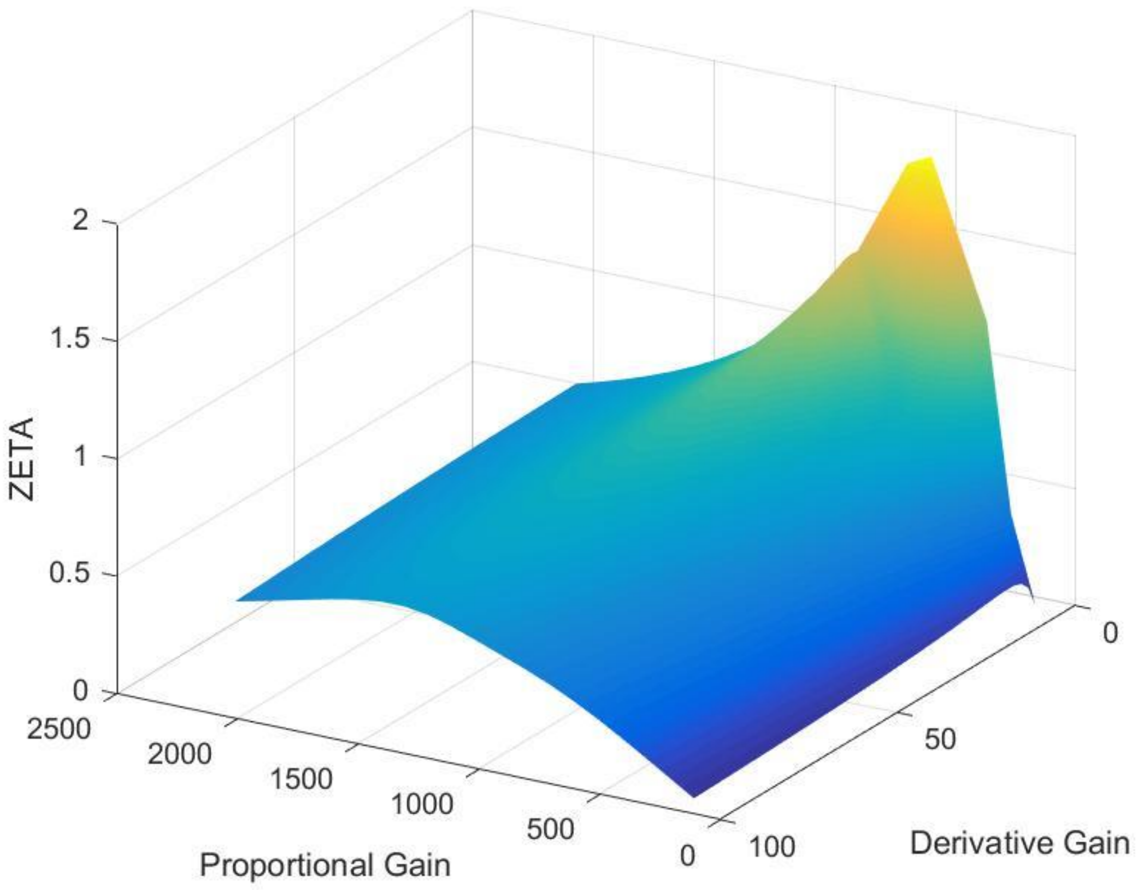





Comparisn between modred and spring mass analogy
sys
2nd order approximation by modred
2nd order spring mass analogous system
Angle in Radians
Time in Seconds (seconds)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

Variation of Damping factor Zeta and Frequency Omega with Proportional and Derivative Gains





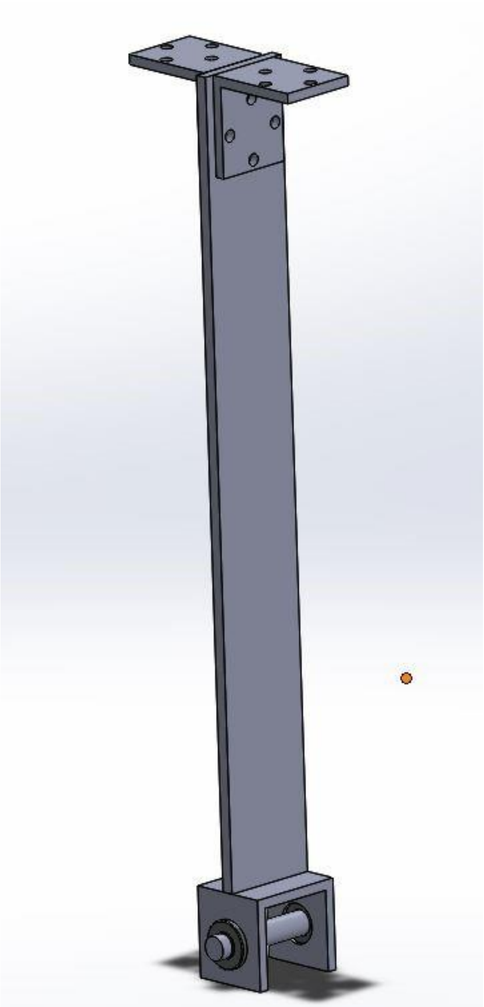
Experimental Setup

The experimental setups considered were as follows–

1. Full Quadcoptor with PLD
2. Full Quadcoptor with a small impulse causing device (to check Quadcoptor stability, etc.)
3. 2D Equivalent of a Quadcoptor with a PLD (to check both accuracy/precision and Quadcoptor behaviour)

Out of the three possible setups, due to time limitations, the third option was selected to be built.

Experimental Setup ideas and manufacturing – 2DOF Model – Linear Motion Generation

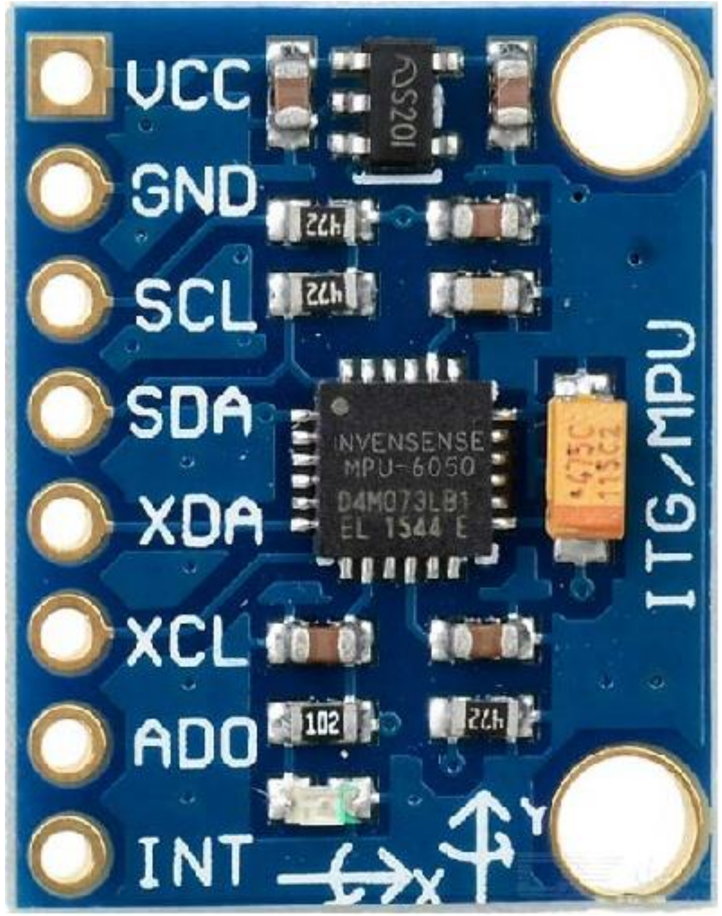


Gun Selection

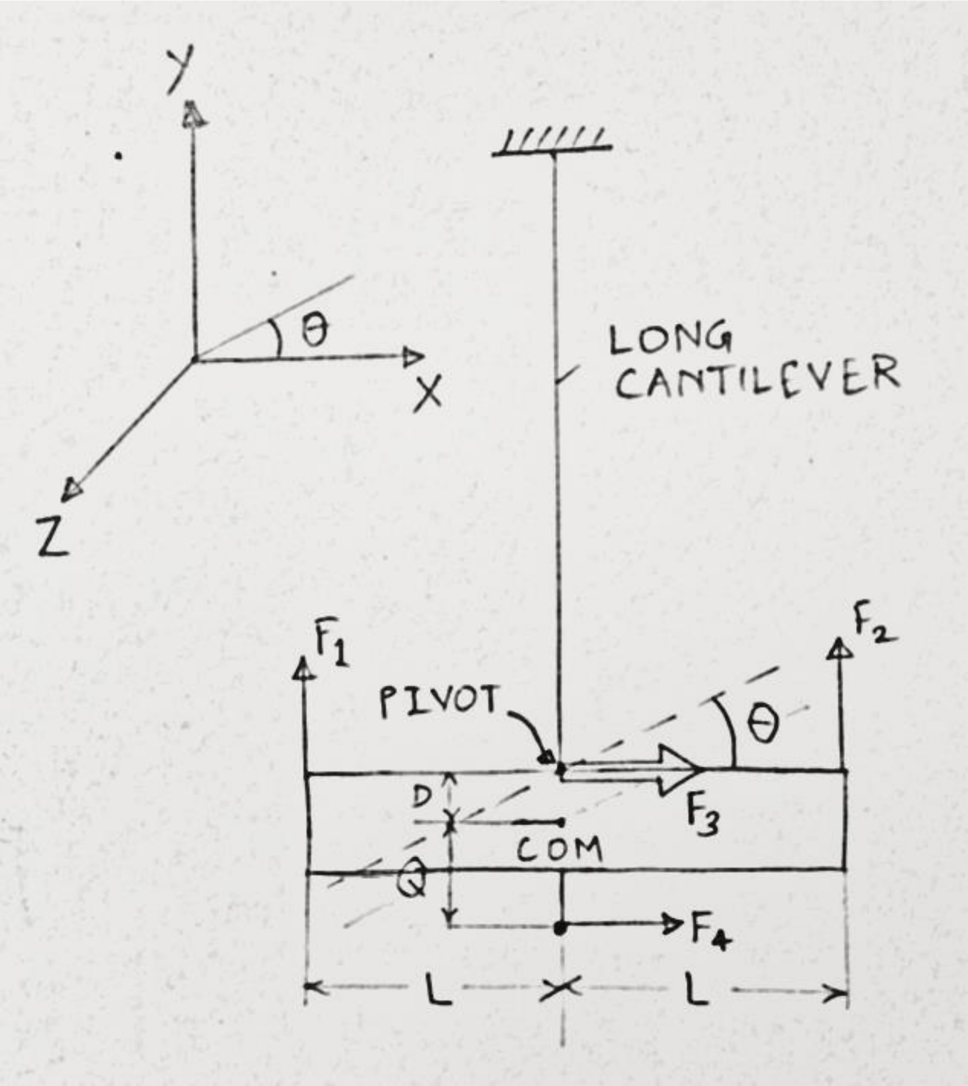
Quadcoptor Size selection and mounting

Full Setup

Sensors and Data Extraction



Mathematical Model



The Equations of the Motion are

$$\ddot{x} = \frac{1}{M}\left[F_3 + F_4 - (F_1 + F_2)sin\theta\right]$$

$$\ddot{\theta} = \frac{1}{M}\left[-F_3D + F_4Q - (F_1 - F_2)L - MgDsin\theta\right]$$

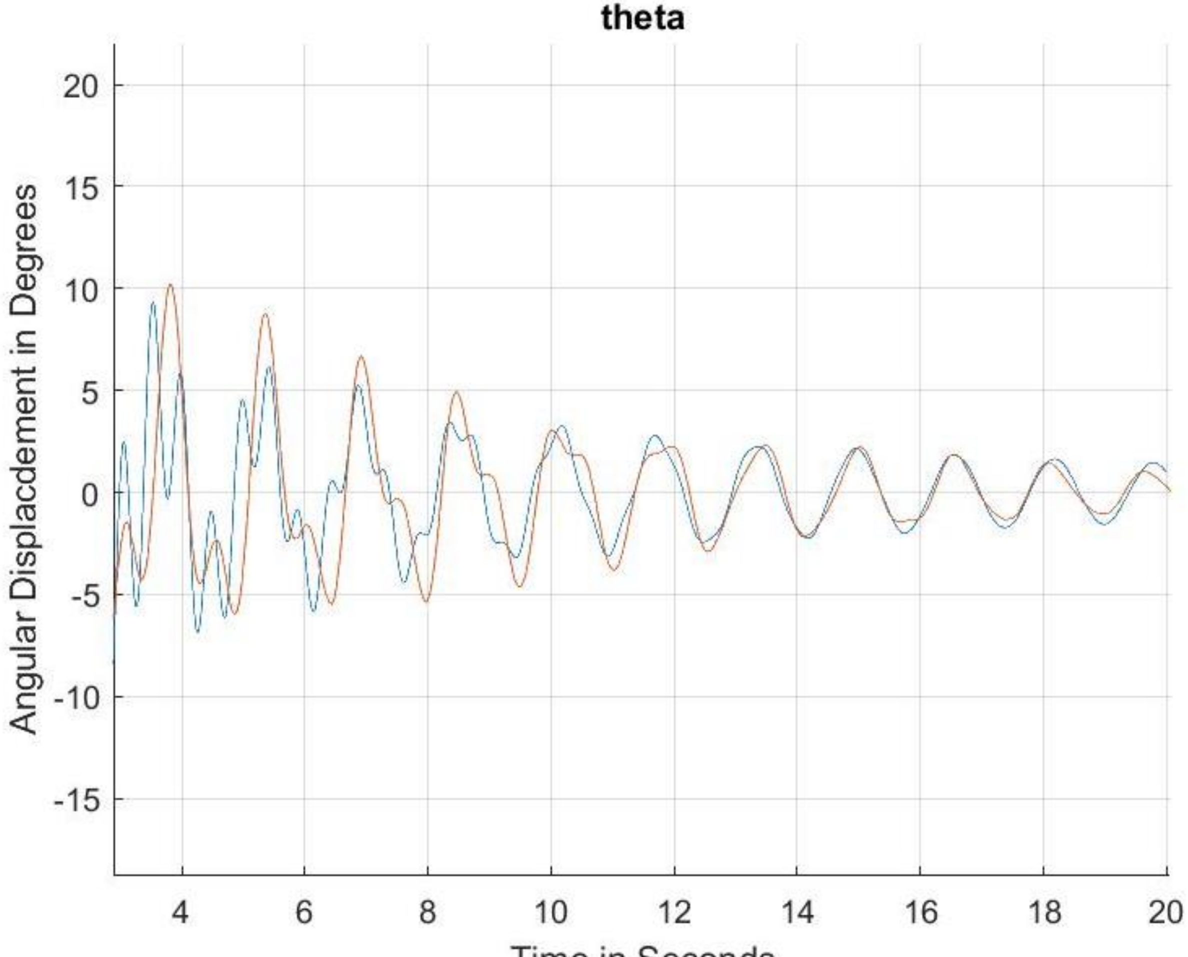
Assuming a Long Cantilever, the motion in y direction is negligible

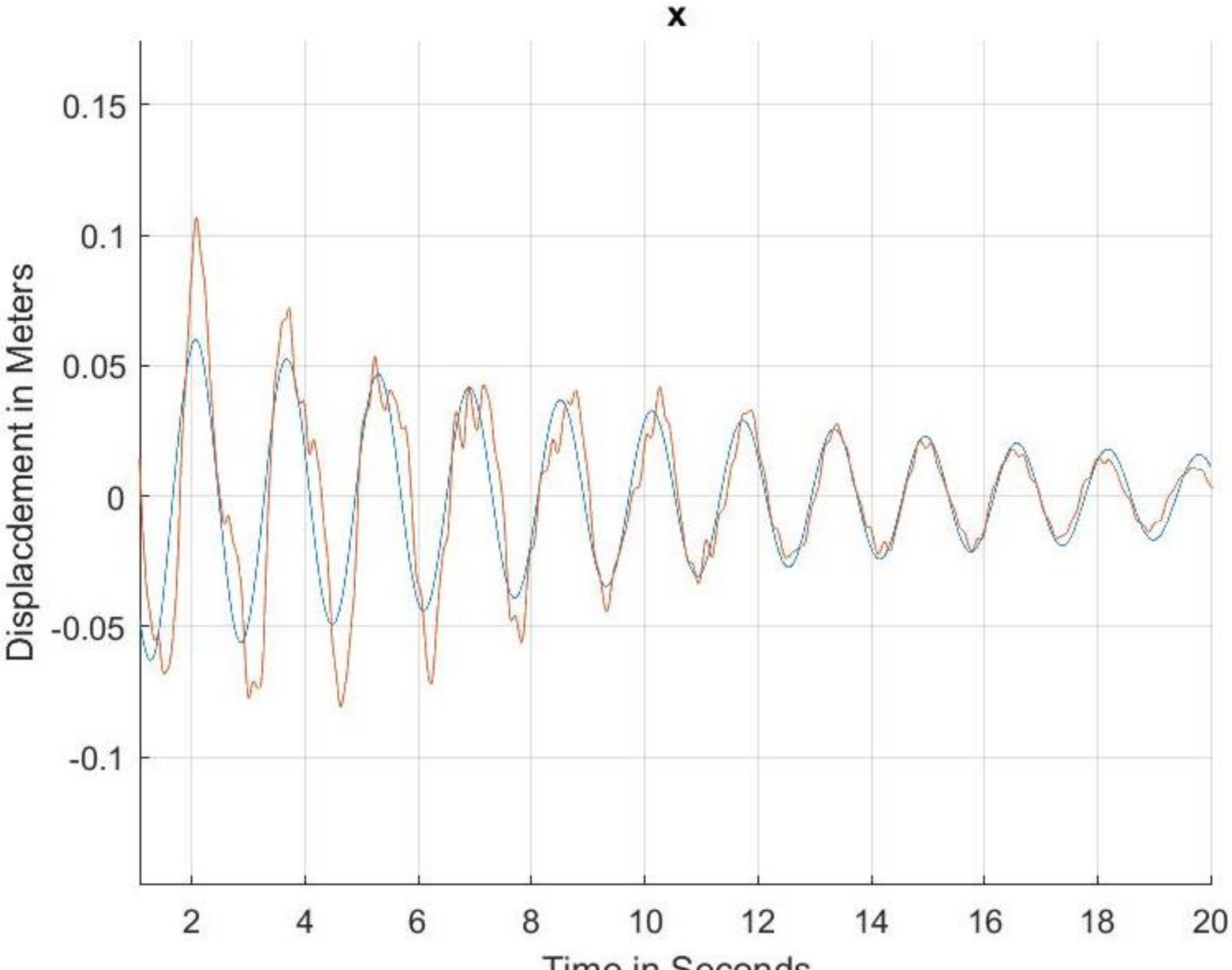
$$\ddot{y} = 0$$

For a small displacement, the force of the cantilever can be given by

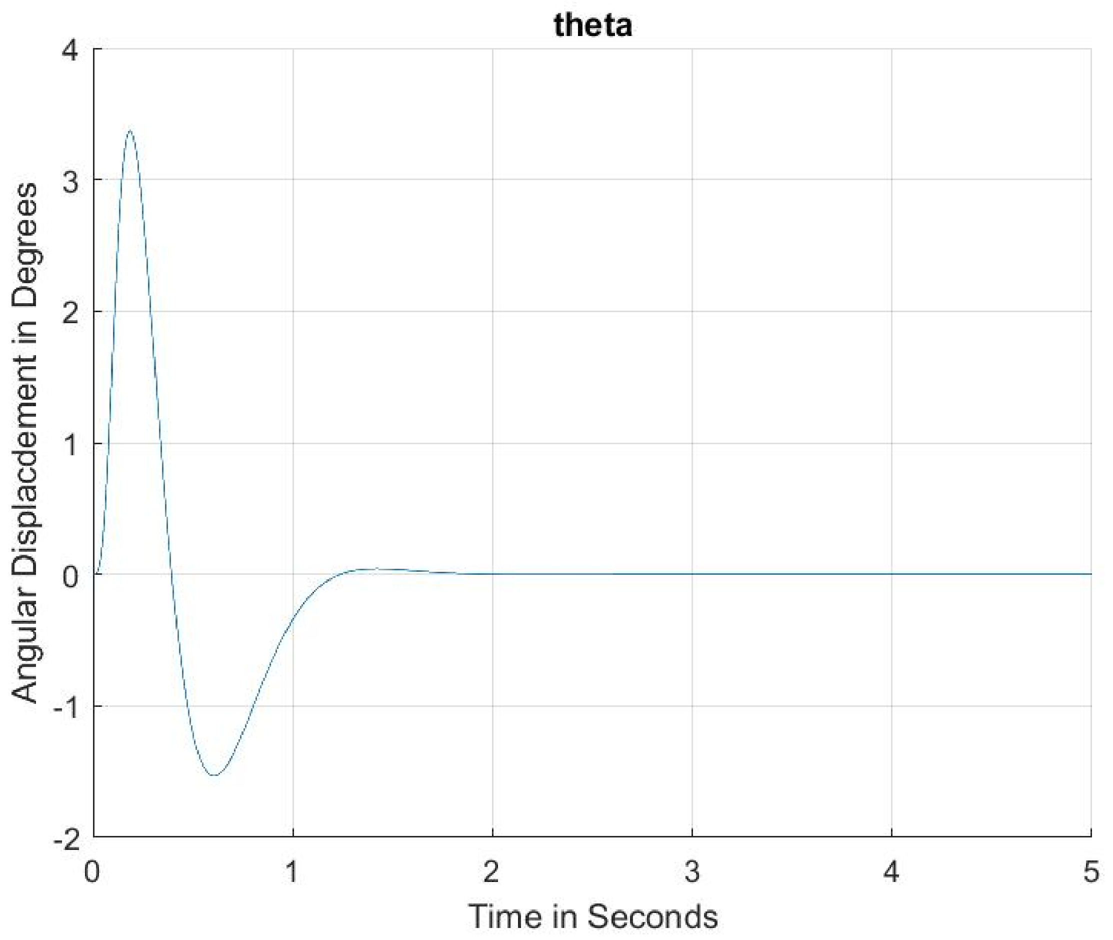
$$F_3 = -kx$$

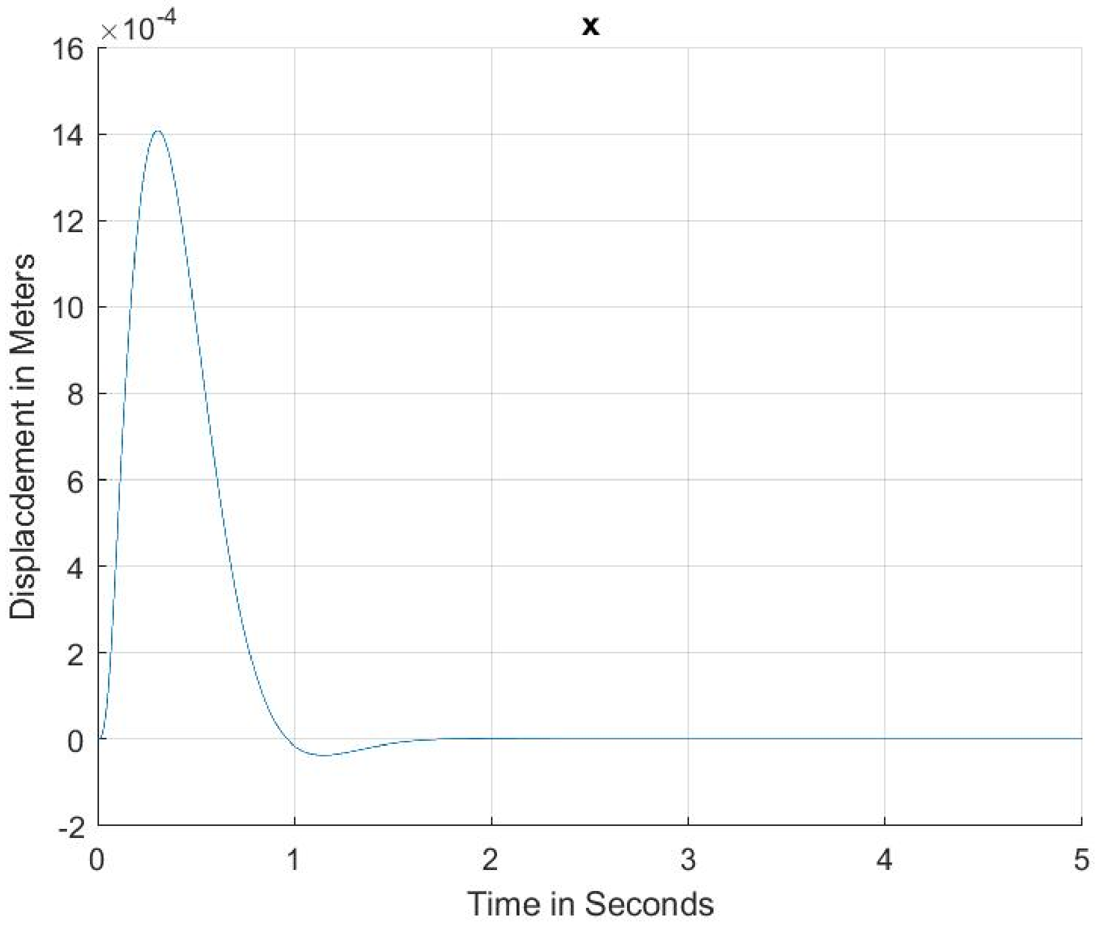
Mathematical Model Validation with actual setup



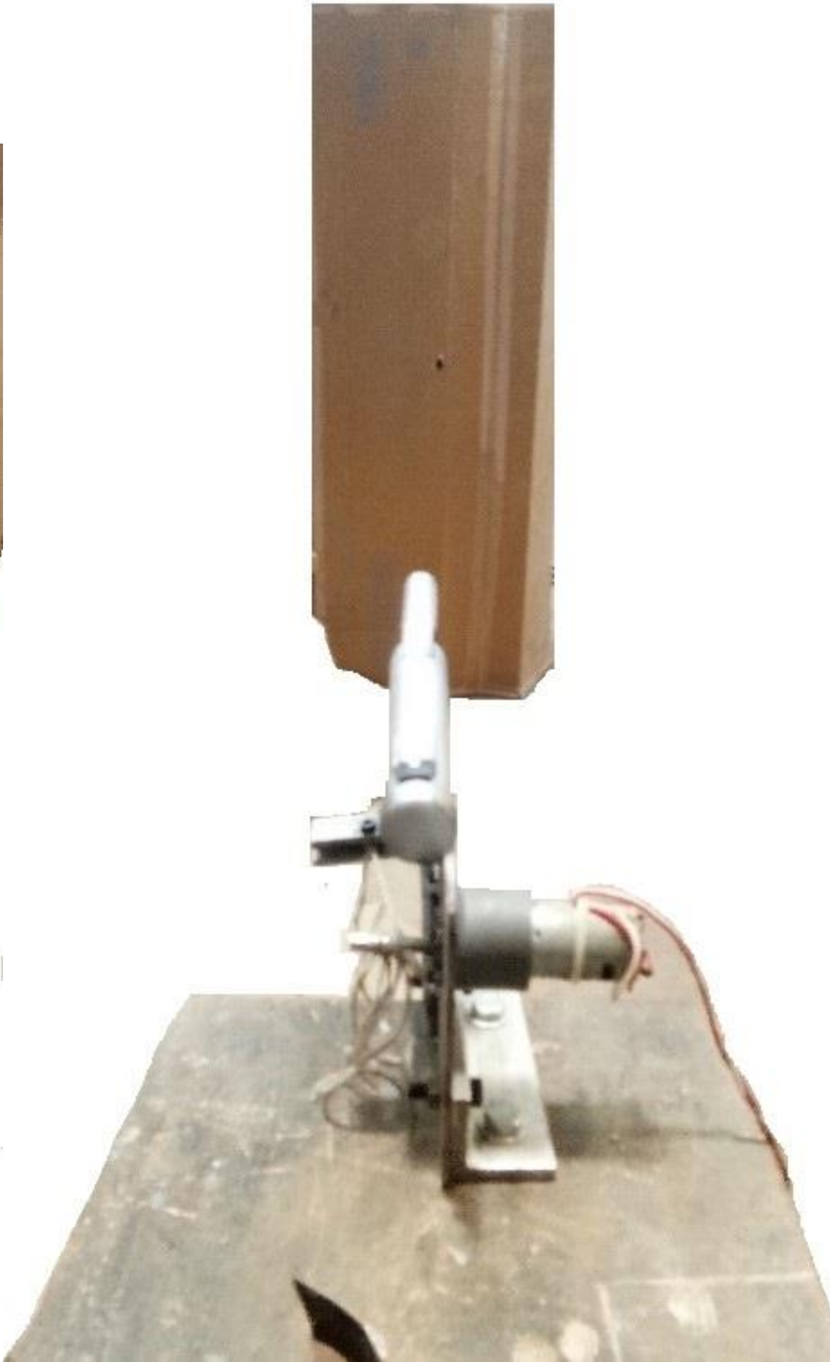


Behaviour at calculated gains





Benchmarking Setup



Shot Pattern

After 10 Shots

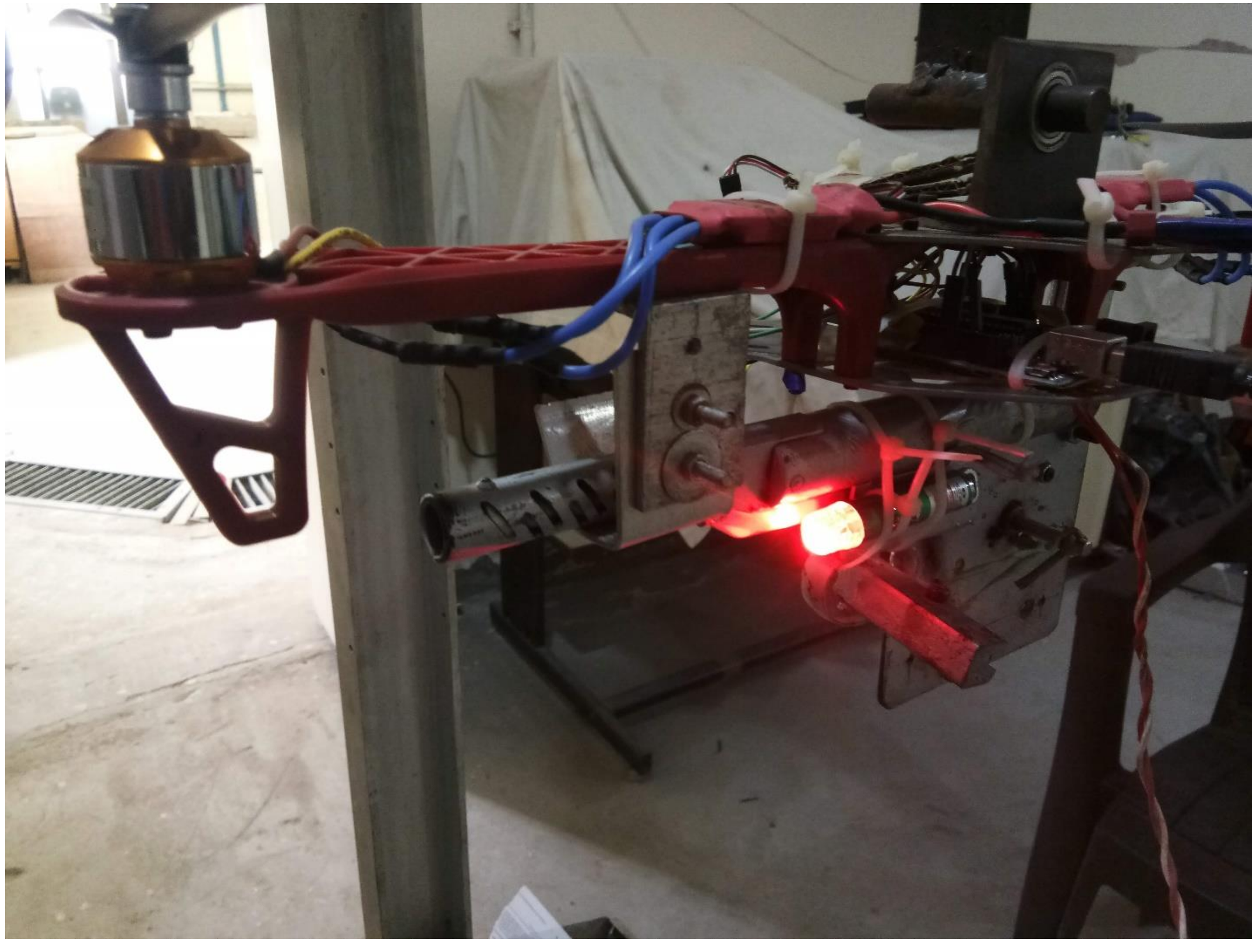
After 20 Shots

After 30 Shots

After 40 Shots

After 50 Shots

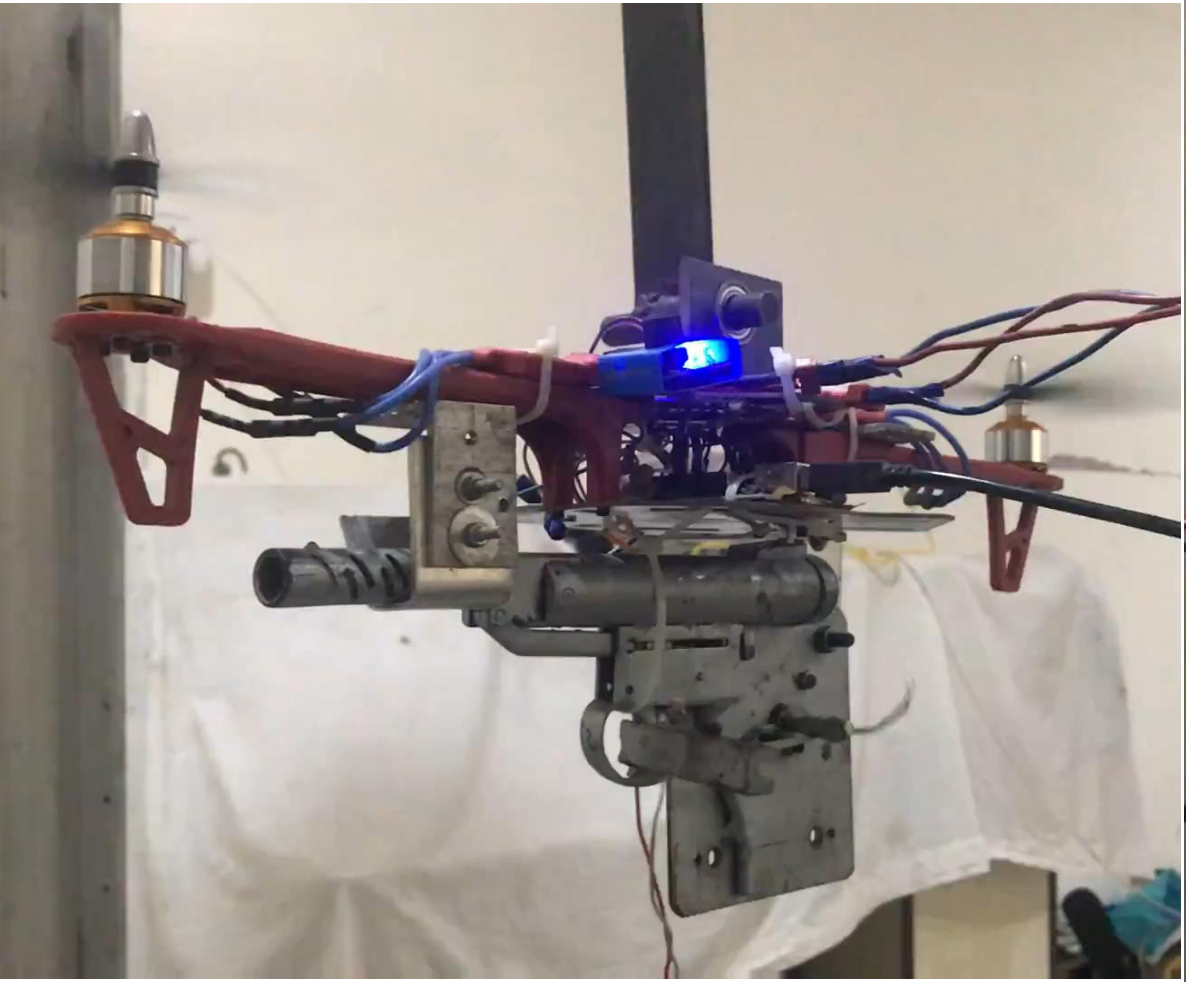
Laser for true aim of the gun

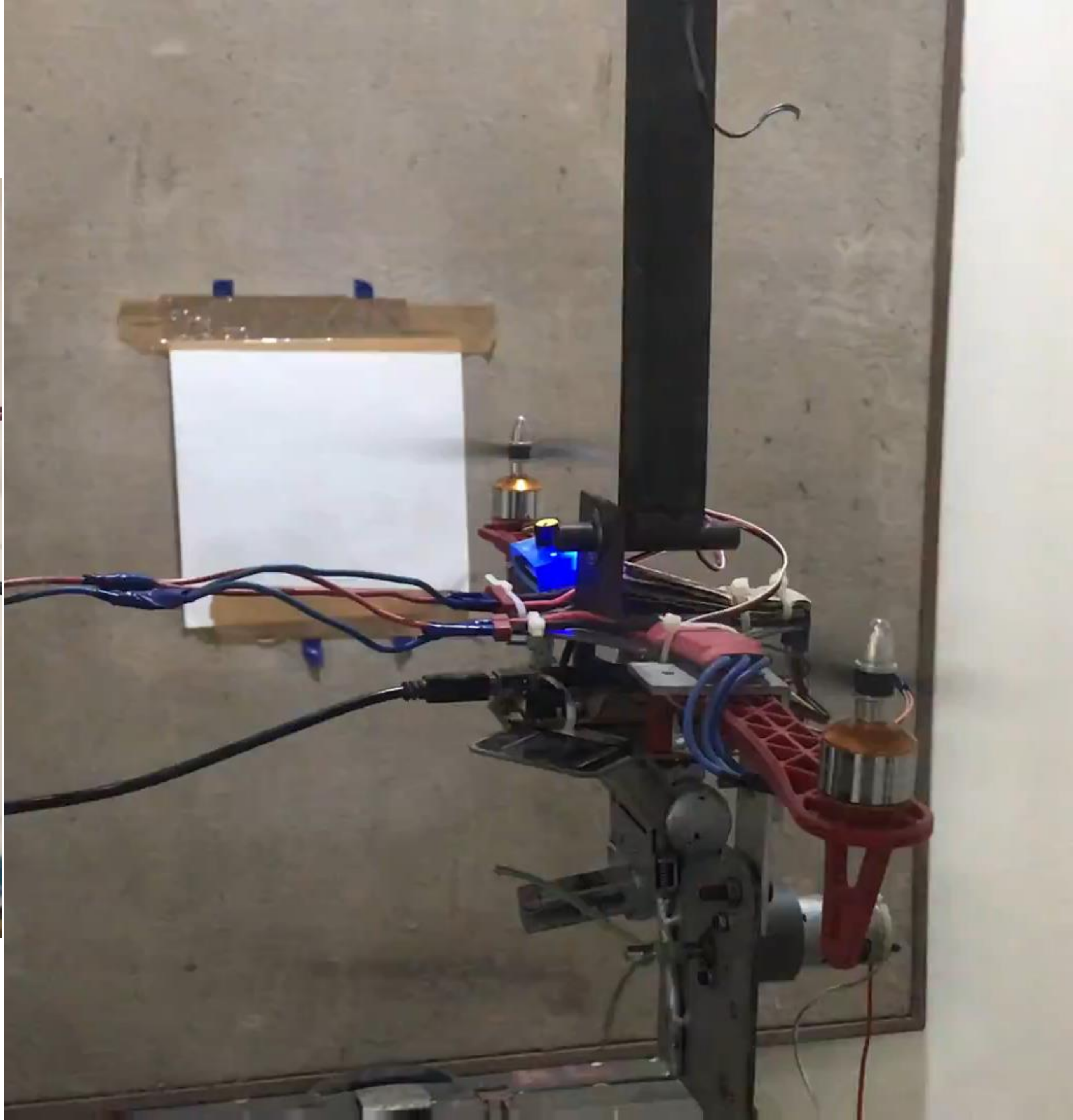


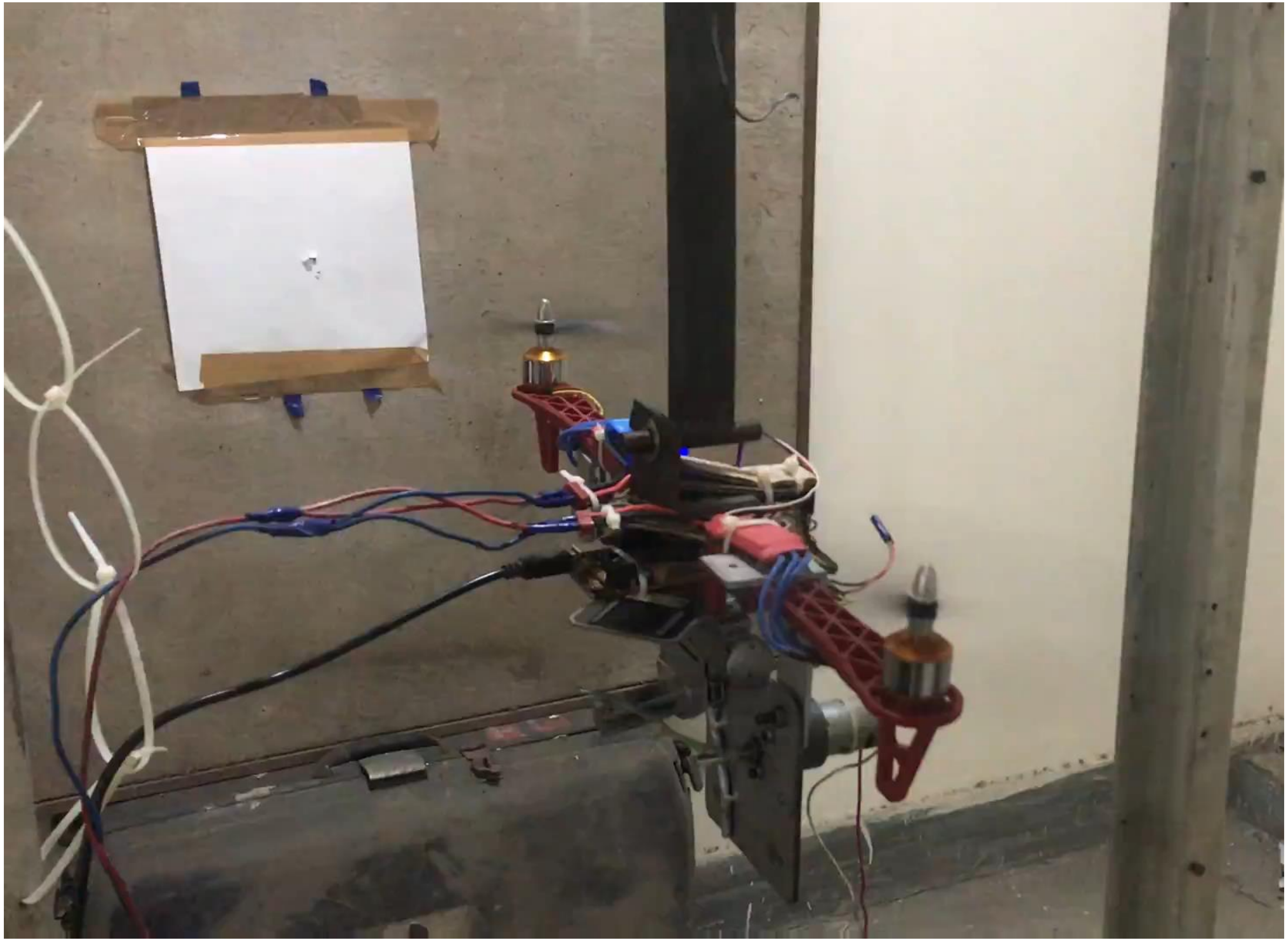
Setup for Quadcoptor Made (Video Left)

P Controller implemented – Oscillations (Video)

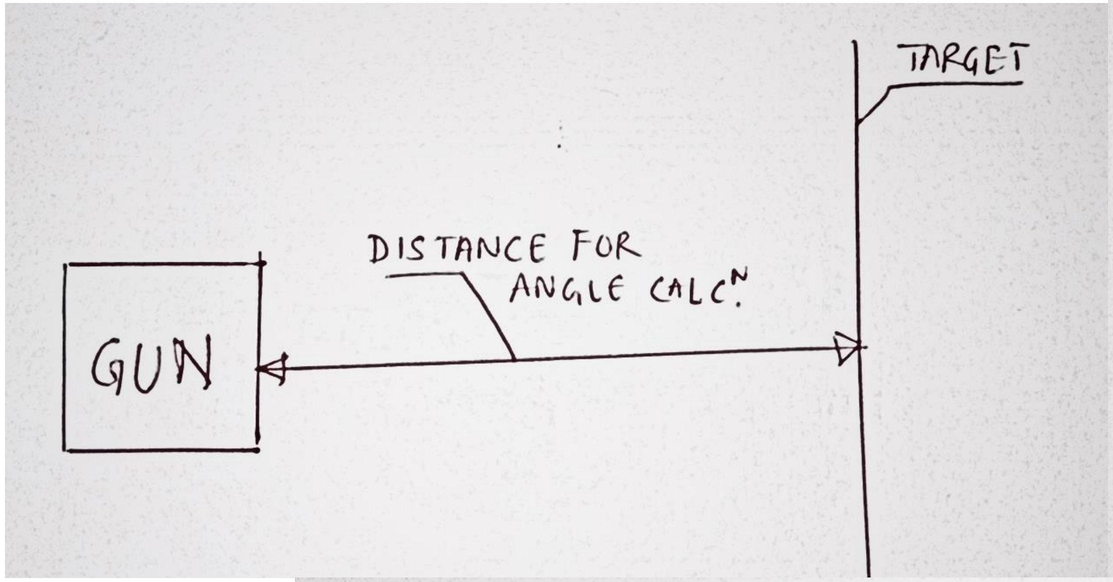
PD Controller implemented –Initial Tuning ok(Video)

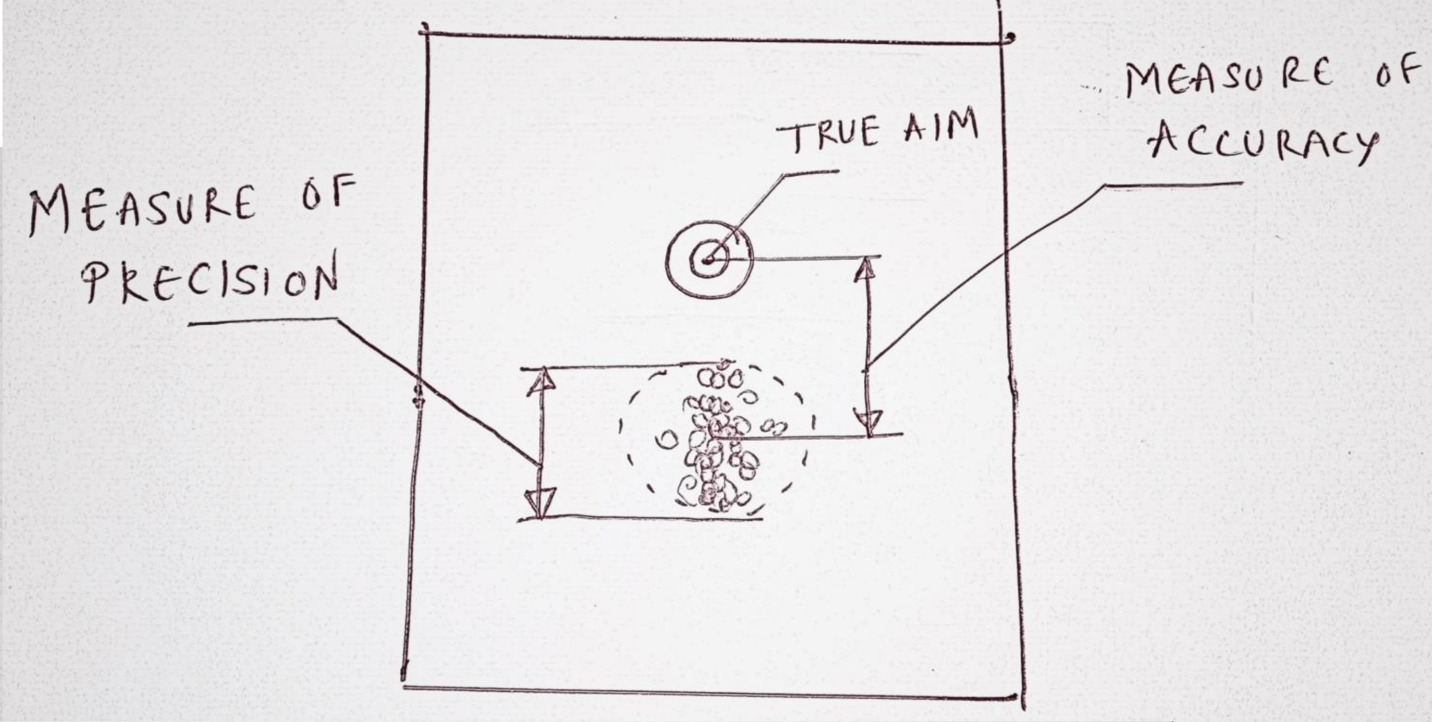


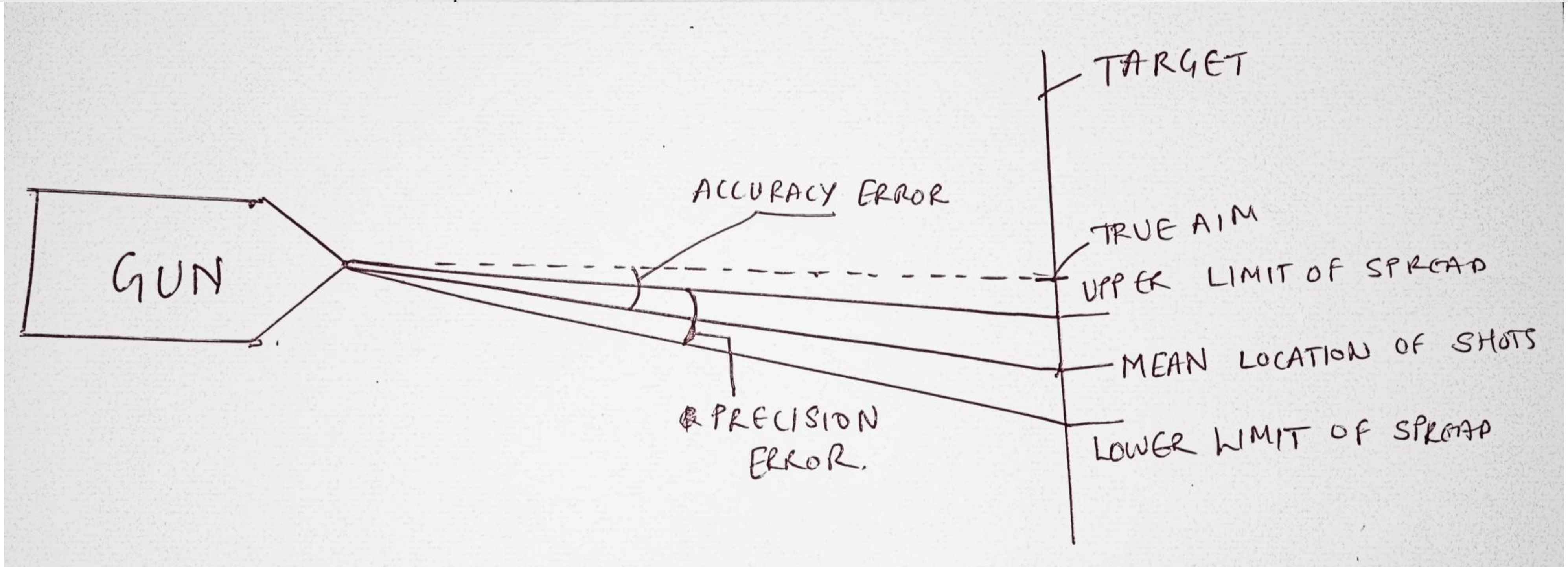




Spread Calculation







Parameters of Experiment										
Experiment No.	Type of Experiment	KP for θ state	KD for θ state	KI for θ state	KP for x state	KD for x state	KI for x state	Precision in degrees	Accuracy offset in Degrees	Settling Time in Seconds
1	Bench-marking Ground	NA	NA	NA	NA	NA	NA	1.5	NA	NA
2	Bench-marking Setup	NA	NA	NA	NA	NA	NA	1.5	0.5	2
3	PD controller for θ state	10	0.1	NA	NA	NA	NA	8.5	0.5	1.7
4	PD controller for θ state	100	0.05	NA	NA	NA	NA	8	0.5	1.8
5	PID controller for θ state	100	0.05	0.005	NA	NA	NA	5.166	1.03	1.8
6	PID controller for θ state	100	0.5	0.05	NA	NA	NA	3.044	0	1.9
7	PID controller for θ and x state	100	0.5	0.05	50	NA	NA	3.348	0	0.5
8	PID controller for θ and x state	100	0.5	0.05	50	0.5	NA	3.025	0	0.41

Conclusions

- Increase the accuracy, precision and firing rate of Multi-rotor UCAV’s
- The Angular states affect the accuracy and precision while the Linear states significantly affect the settling time – Firing Rate
- the performance of a Multi-rotor UCAV is strongly correlated to only a subset of the states involved in the full model - ”analogous spring-mass-damper” is very effective in obtaining a ”critically damped behaviour of the UCAV’s
- Future work in field – Full Quadcoptor with real gun

Backup Slides

Backup Slide

- The methodology used in this report can be used to increase the accuracy, precision and firing rate of Multi-rotor UCAV's.
- The control strategies explored, while very rudimentary show that having prior knowledge of the dynamics of the Multi-rotor and the gun recoil can significantly improve the behaviour of the Multi-rotor UCAV's.
- The Angular states majorly affect the accuracy and precision of the Quadcoptor while the Linear states significantly affect the settling time thereby having an impact on the firing rate.
- The models developed in the course of this report show that the performance of a Multi-rotor UCAV is strongly correlated to only a subset of the states involved in the full model. This approach can be used to simplify the tuning of the UCAV and save on computational time.
- The method of ”analogous spring-mass-damper” is very effective in obtaining a ”critically damped behaviour of the UCAV's, which in turn optimised the accuracy, precision and settling time. This method also makes it easier to tune control gains in an otherwise very complex Non-Linear system.
- In the future, a more conclusive experimental setup can be built which can take into account more of the complex effects of rotational drag forces, blade flapping and bulk wind velocity. Further inclusion of these effects in the simplified model will also allow for higher fidelity simulations which will reduce the time required for finding control gains. Having more sensors like multiple IMU's and cameras with sensor fusion techniques will allow for better estimation of states leading to better overall control. Having a real gun or an equivalent mechanism that can reproduce the effects of a real gun will make the experiments more realistic and take into picture the effect of various actuating mechanisms used in real guns

Syntax

```
rsys = modred(sys,elim)
rsys = modred(sys,elim,'method')
```

Description

`rsys = modred(sys,elim)` reduces the order of a continuous or discrete state-space model `sys` by eliminating the states found in the vector `elim`. The full state vector X is partitioned as $X = [X1;X2]$ where $X1$ is the reduced state vector and $X2$ is discarded.

`elim` can be a vector of indices or a logical vector commensurate with X where true values mark states to be discarded. This function is usually used in conjunction with `balreal`. Use `balreal` to first isolate states with negligible contribution to the I/O response. If `sys` has been balanced with `balreal` and the vector `g` of Hankel singular values has M small entries, you can use `modred` to eliminate the corresponding M states. For example:

```
[sys,g] = balreal(sys)  % Compute balanced realization
elim = (g<1e-8)         % Small entries of g are negligible states
rsys = modred(sys,elim) % Remove negligible states
```

`rsys = modred(sys,elim,'method')` also specifies the state elimination method. Choices for `'method'` include

- `'MatchDC'` (default): Enforce matching DC gains. The state-space matrices are recomputed as described in Algorithms.
- `'Truncate'`: Simply delete $X2$.

The `'Truncate'` option tends to produces a better approximation in the frequency domain, but the DC gains are not guaranteed to match.

If the state-space model `sys` has been balanced with `balreal` and the grammians have m small diagonal entries, you can reduce the model order by eliminating the last m states with `modred`.

4.5.10.2 Analog Out

OFF: Data is collected at 0.5 second intervals. From one to 4 channels can be displayed. This mode provides the longest battery life, since excitation is on only during the A/D conversion.

Ch1 – Ch4: Data is collected at approximately 2ms intervals (480 samples/sec) and the reduced data is available to the analog output connector. This mode significantly decreases battery life, since the A/D converter and excitation is constantly on. Only one channel can be active at a time.

4.5.10.3 Rejection

The digital filters in the Model P3 can be tuned to optimize the noise rejection from power line frequencies. Choose between 50Hz and 60Hz