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Fault Tolerant Design of a Quadcopter through Run Time Transformation

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Abstract: The Project deals with the development of a fault tolerant design to make the quadcopter not susceptible to failure due to the loss of a single propeller. The fundamental problem arises due to the dislocation of the centre of gravity when the four balancing forces that makes the system stable gets reduced to three. This creates instability in the system that makes the quadcopter to spin abnormally. To overcome this problem, an inertial measurement unit is interfaced with a microcontroller which completes the closed loop. The Cascade control system designed stabilizes the roll and the pitch rotations of the system. The available six pulse width modulation pins are used to power four motors whose speeds are controlled by four electronic speed controllers. Suitable propellers are used to generate the necessary thus is made available for the system to become air borne. A couple of servo motors are placed at the mid-point of two aluminum rods. On account of failure of a single propeller, the system becomes unstable and the servo motor attached to the support rotates the failed motor to the centre of Gravity with another motor extending out. Further, the motors are energized only at 70% of its capacity to increase the durability and longevity. The servo library in the arduino integrated development environment is utilized in developing PID controllers.
Keywords: Quadcopter, CoG, propeller, Arduino control, PID controller

I. INTRODUCTION

Quadcopters are four-rotor helicopters that fly with two pairs of blades spinning in opposite directions. Unlike a traditional helicopter, all four rotors on a quadcopter work to generate upward thrust. The quadcopter's movement is controlled by differing the relative pushes of every rotor. This configuration makes a more steady stage than conventional helicopters, making quadcopters perfect for applications, for example, reconnaissance and elevated photography. Quadcopter is a multi rotor air vehicle which has denoted its hobbies for the advantage of both common and military areas. It's astonishing mobility and the straightforwardness to fly in contracted areas has accomplished itself a momentous position in the flying part.

With a specific end goal to be adjusted, the quadcopter should constantly make minute acclimations to the rate of every rotor to keep the whole art level. Since performing these alterations physically progressively would be to a great degree troublesome, a flyable quadcopter must have the capacity to make this modification independently. This requires the quadcopter be about impeccably adjusted and have an advanced control framework that is constantly making modification. A quadcopter is split between four separate rotors, two

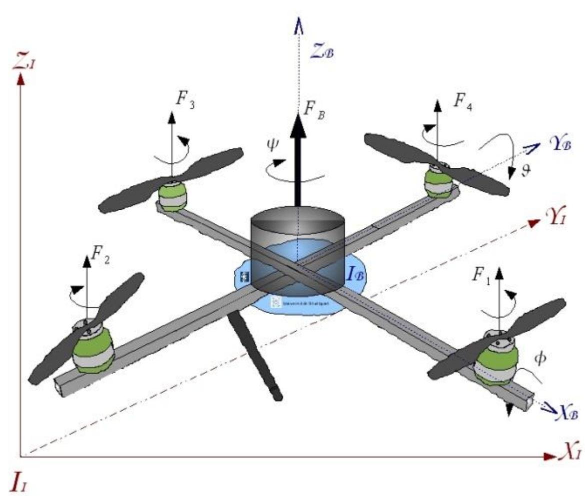

Fig 1 Forces acting on a quadcopter

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Of which rotate opposite the other two. Because each rotor generates a portion of the whole lift and the flight of a quadcopter is restricted by varying the relative lift and torque of each rotor. The basic forces acting are shown in Fig 1.

II. BASIC SYSTEM

The fundamental block diagram of a quadcopter as shown in Fig. 2, includes four motors, four speed controllers, a power supply and a flight controller. The objective is to create a fault tolerant machine which eliminates the necessity to utilize a receiver – transmitter alongside a flight controller. Four propellers of dimensions 10 x 4.5 inch with two pairs of CW and CCW blades are mounted in the system so that to achieve conversion, two servo motors are connected to the aluminum shafts. The servo motors are first checked with the available torque necessary to rotate the servo in both forward as well as reverse.

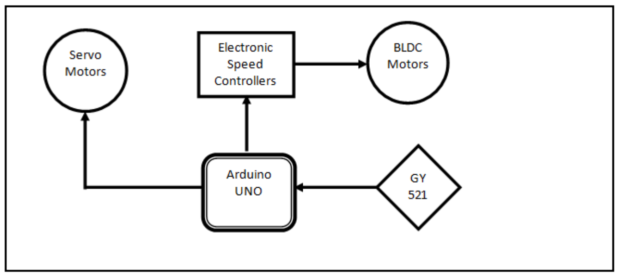

Fig 2 Simplified block diagram of system

Stability issues of quadcopter: These issues includes problem that is also associated with the loss of center of gravity. The center gravity is dislocated when the balancing forces goes unbalanced. The randomness in the system is due to the change of resultant direction of the center of gravity which will be perpendicular when all the balancing forces are present. The resultant of the stable system is shown in Fig 3. If one of the forces is lost, the resultant angle changes. A basic PID controller is utilized to stabilize the system by computing the erro from the gyroscope and the set-point given through the joystick.
A new approach can be followed to maintain the stability by shifting the mass in the system.

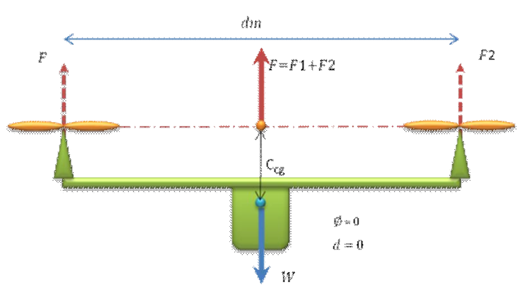

Fig 3 Resultant force of CoG

III. THEORETICAL ANALYSIS & DESIGN

This deals with the theoretical calculation and simulation of the quadcopter using state space theory. Using MATLAB R2012b, simulation is performed on the linearised state space model. Once the transfer function is obtained, the system is checked for controllability. The methodology is followed for both the quadcopter and the transformed structure. Further, the analysis and design of hardware components will be discussed at the end of the chapter. It includes an analysis on centre of gravity of the quadcopter and the transformed structure. Simple calculation that determines the net thrust available in the system will be computed. Transformation design includes a fundamental idea in which the mass that is not working is shifted to the centre of gravity from the corner. Feasibility Analysis: An approach was made by analyzing various designs of multicomputer. The main criterion is to establish the same center of gravity even after the transformation of the system. To check whether the system is feasible or not, a state space model was developed. The state space model includes the necessary forces that act on the quadcopter.
The state space model includes four matrices shown in eqn 1.1, 1.2, 1.3, 1.4. Since the system is considered to be linear, the D matrix is initialized to zero. The various states assumed to simulate the system are,

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$[\varphi, \theta, \psi, \dot{\varphi}, \dot{\theta}, \dot{\psi}, M_{\varphi}, M_{\theta}] = [0, 0, 0, 0, 0, 0, 1d, 1d]$. The state space model consists of a system matrix 'A', input matrix 'B' and output matrix C'.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (1.1)$$

$$B = \begin{bmatrix} 0 & 0 \\ \frac{1}{I_{xx}} & 0 \\ 0 & 0 \\ 0 & \frac{1}{I_{yy}} \end{bmatrix} \quad (1.2)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (1.3)$$

$$D = 0 \quad (1.4)$$

In the input matrix 'B', there are two variables that vary in every quadcopter design called as the Moment of Inertia, $I_{xx}$and I_{yy}. These two components of inertia have to be calculated for every design. The primary reason is to compute the inertial matrix of the quadcopter based on the equations of motion. The various components of the inertial matrix include the products of moment of inertia about x, y and z axes. The remaining elements of the matrix include the products of moment of inertia such as xy, xz, yx, yz, zx, zy which are assumed as zero since the values are computed from the principal axis. The state space model is given in the equations 1.1, 1.2, 1.3

$$I_{xx} = \sum_i m_i \left(y_i^2 + z_i^2\right) \quad (1.5)$$

$$I_{yy} = \sum_i m_i \left(x_i^2 + z_i^2\right) \quad (1.6)$$

$$I_{zz} = \sum_i m_i \left(x_i^2 + y_i^2\right) \quad (1.7)$$

The formula to calculate the moment of inertia is given in the equations 1.5, 1.6, 1.7.

Based on the aforementioned formula, the inertial components are calculated for the quadcopter. The basic design of this quadcopter includes a mass of 60g situated at every corner of the holding structure. The distances x_i, $y_i$and z_i are distance of the mass from the principal axes (body frame). Various values are shown below in the Table I,

Table I
Perpendicular Distance from Principal Axes and Moment of Inertia

S.No	x_i (m)	y_i (m)	z_i (m)	I_{xx} (kg/m^2)	I_{yy} (kg/m^2)
1	0.2	0.2	0.007	2.694e-3	2.694e-3

The calculated values of $I_{xx}$and $I_{yy}$are substituted in the inertial matrix which is the 'B' matrix. The values of $I_{xx}$and $I_{yy}$are multiplied by four since all masses are identical at each corner. The computed matrix is shown in equation 1.8,

$$B=\begin{bmatrix} 0 & 0 \\ \frac{1}{0.0107} & 0 \\ 0 & \frac{1}{0.0107} \end{bmatrix} \qquad (1.8)$$

The objective was to linearize the developed state model, then to convert it into transfer function and add a step input to it. Finally, design a PID controller and obtain the Kp, Ki, Kd values using MATLAB. The following picture depicts the code used to simulate the system in MATLAB.

The code is also written to check the controllability of the system using Kalman's method. The determinant value obtained was non-zero. Hence the designed system was controllable. Similarly, the transformed system has a change in the radius of rotation, causing the moment of inertia to increase and a decrease in angular velocity simultaneously. The controllability of the newly transformed system was verified by recalculating the moment of inertia. The input matrix 'B' is given in the equation 1.9,

$$B=\begin{bmatrix} 0 & 0 \\ \frac{1}{0.0149} & 0 \\ 0 & \frac{1}{5.39e^{-3}} \end{bmatrix} \qquad (1.9)$$

The same script is run with the moment of inertia being changed to new value for the transformed system. After performing Kalman's test, the system is adjudged as whether it is controllable or uncontrollable by checking the rank or by taking the determinant values. If the determinant of the matrix is not equal to zero, then it is controllable, vice versa if it is zero. The determinant values of both the basic system and the transformed system is listed below in Table II,

Table II
Determinant Values of Controllability Matrices

Quadcopter	-7.6289e+07
Transformed Tricopter	-1.5504e+08

IV. CENTER OF GRAVITY ANALYSIS

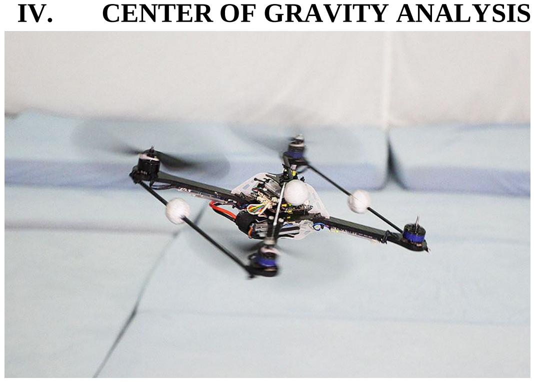

Fig 4 Image depicting the loss of a single propeller

The basic problem as shown in Fig 4 arises due to the dislocation of center of gravity in a quadcopter. When the four forces acting at the four ends of a square in a system, that tries to keep the square at (0,0,0) which is the set-point, gets as disturbed, the center of gravity gets dislocated. These balancing forces are controlled around the set-point always.

Likewise, in a quadcopter the four balancing forces that keeps the quacopter stable when disturbed loses its stability. This loss in stability is primarily due to the dislocation of the center of gravity. The main reason behind this stability issue is that the resultant generated by the system when the center of gravity is not the same when the system loses one of the forces. Also when it tries to compensate with the conventional feedback control loop, the direction of the resultant goes random.

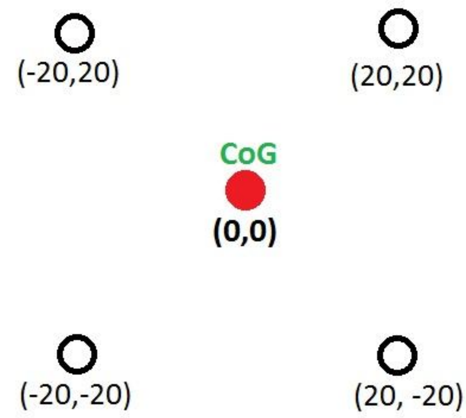

Fig 5 Location of CoG on the primary system

The software based solution cited in the paper does provide maneuverability but the data that are streamed from the system to the station will not be valid. Therefore, the only approach is to shift the mass to attain a stable roll, pitch and yaw. For which a thorough knowledge on the center of gravity of both the basic system and the system which provides the solution to this problem has to be computed. In summation of the centre of gravities, both the systems should have the center of gravity at the same point.
The Fig 5 depicts the location of the center of gravity in a quadcopter. It is obtained through the basic formula to determine the center of gravity of any object. The procedure to determine the center of gravity is quite simple. Four co-ordinates are chosen namely {(20, 20), (-20, 20), (-20, -20), (20, -20)}. The masses are fixed at all these points (60g) and the sum of products of the X axis co-ordinates and the Y axis co-ordinates are identified.

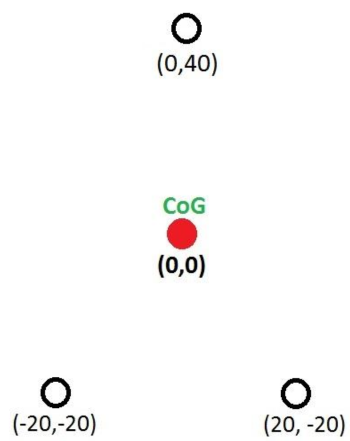

Fig 6 Location of CoG of the transformed system

Once the system goes unstable, the transformation is made and the general analysis of properties of various geometrical shapes proved conclusive to select the transformational system. The analysis includes the selection of a feasible system that has the same center of gravity as of the previous. Failing the criteria could result in creating a demand for shifting the more masses to compensate for stability.As depicted in Fig 6, the failed motor is shifted inside (i.e) to the center of gravity. The failed mass has no effect since it is shifted to the center of gravity of the system. Similar to the basic quadcopter system, the center of gravity of this transformable system is computed. The X co-ordinate for the CoG and the Y co-ordinate for the CoG are computed.

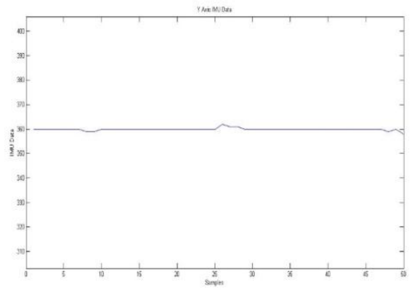

Fig 7 Graph from the GY-521 during static test of basic system

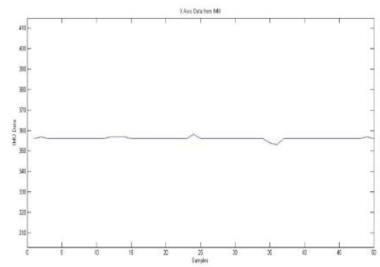

Fig 8 Graph from GY-521 of the transformed system during static test

The results as shown in 7, 8 where conclusive and it showed that the CoG for both the systems are located at one single point. Static stability tests were performed on both the systems and the graphs below shows the stability of the system as obtained after interfacing the gyroscope with the Arduino and MATLAB.

V. DESIGN SPECIFICATIONS

The Hardware design involves several aspects that are to be calculated. Unlike a simple Quadcopter design, this fault tolerant machine has to be slightly modified. The fundamental design has a distance of 40 cm from every propeller in horizontal or vertical directions. The rotors should be positioned exactly at the ends. In order to select the hardware components, the design of a quadcopter requires certain calculations to be made. The calculation includes the dimensions and weight of the quadcopter and the required thrust that has to be generated in order to make the quadcopter airborne.

Table III
Weight Distribution of the System

S. No	Components	Mass (g)
1	Foam Sheet	140
2	Motors (x4)	240
3	ESC (x4)	100
4	Aluminum bar (x2)	30
5	Arduino	25
6	Servo motor (x2)	100
7	Miscellaneous	50
Total		685

The design as aforementioned is basically like a square of side 40cm and transformation which created an isosceles triangle with bigger sides measuring 45cm (approx). It is also made sure that the non-working motor's propeller blade won't cause any hindrance to the other three working propellers. The trajectories of the propellers were calculated using Google Layout. The propeller is available at variety of sizes and trajectories were plotted providing high degree of safety to the propeller blades. he blades are generally of 10 inch diameter and trajectory is plotted using the 5 inch radius of the failed motor at the center of gravity and a single working motor at one end of the aluminum bar. The thrust that is being generated using the 10x4.5 inch propeller is higher than a 7x4.5 inch propeller. Based on all the criteria, the model as shown in Fig 9 was developed.

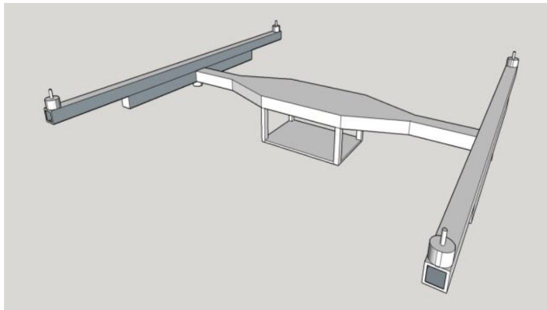

Fig 9 Design of the system developed in Google Sketch up Pro 2015

According to Newtonian mechanics, when the upward force is greater than the downward force, the system flies. Therefore to determine the required thrust it is necessary to compute the entire mass of the system. Using the basic formula, the upward and the downward forces are computed. Subtracting the two forces could tell the net thrust and the direction of the force as well. The weight distribution is shown in Table III,Based on this weight downward force can be calculated. The downward force is given by the equation 1.11,

$F = m * a$ (1.10)

$F_{down} = 0.685 * 9.8 = 6.713$ N (1.11)

The downward force is calculated and the upward force is generally based on the maximum thrust each motor could produce. The hardware has to be chosen in such a way that it can minimum produce a combined thrust of 6. 714N. Consider a motor that produces a maximum thrust of 750g and the motor is ran at 70% of maximum capacity to have longevity and durability.

70% of Max Thrust = 750 * 0.7 = 525g (1.12)

Therefore, upward force is given by,

$F = m * g$ (1.13)

$F = 0.525 * 9.8 = 5.145$ N (1.14)

Thrust generated by 4 motors is equal to,

$F = F_1 + F_2 + F_3 + F_4$ (1.15)

$F_{up} = 5.145 + 5.145 + 5.145 + 5.145 = 20.580$ N (1.16)

The net force is given by calculating the difference between the equations (1.16) and (1.11).

$F_{net} = F_{up} - F_{down}$ (1.17)

$20.580 – 6.713 = 13.867$ N (1.18)

The net force, F_{net}generated is greater than zero and it is positive. Therefore the system is positive buoyant and it can be made airborne. The loss of one propeller force could result in the reduction 5.145 N from the available 20.580 N. Recalculating the thrust by reducing F_1,

From (3.15), $F = F_2 + F_3 + F_4 - F_1$ (1.19)

Therefore, $F_{up} = 20.580 – 5.145 = 15.435$ N (1.20)

$F_{net} = F_{up} – F_{down}$ (1.21)

$= 15.435 – 6.713 = 8.722$ N (1.22)

From equation (1.22), it is understood that the system is capable of being air borne even after the loss of a single propeller force. Both the equations (1.18) and (1.22) are shows the system will be positive buoyant. The Table IV briefs the values.

Table IV
Nature of Buoyancy of both Systems

S. No	System	Net Thrust (N)	Buoyancy
1	Quadcopter	13.867	Positive
2	Transformed Tricopter	8.722	Positive

VI. BLOCK DIAGRAM

The block diagram shown in Fig 10 of the quadcopter consists of four Brushless DC Motors driven by four 30A speed controllers. The Speed controllers consists of three pins, out of which white wire is used to give PWM signals from the Arduino Uno at pins 5, 6, 9, 10. The Black wires are shorted and then grounded at the Arduino Gnd.The speed controllers are provided with a common power supply of 2200 mAh from a LiPo battery. A Gyroscope is interfaed with the UNO that uses an I^2C communication protocol. The Power supply given to the MPU 6050 is of 5v and Analog Input pins of the Arduino UNO are used (A4, A5). The Digital pin 2 is used as an interrupt pin to the gyroscope. The gyroscope provides real time data on the orientation of the system and a PID controller is designed using the feedback from this sensor. Two servo motors are connected to a separate power supply of 6V and the ground is connected to the common ground in the Arduino. The PWM signals are provided from the pins 3 and 11.

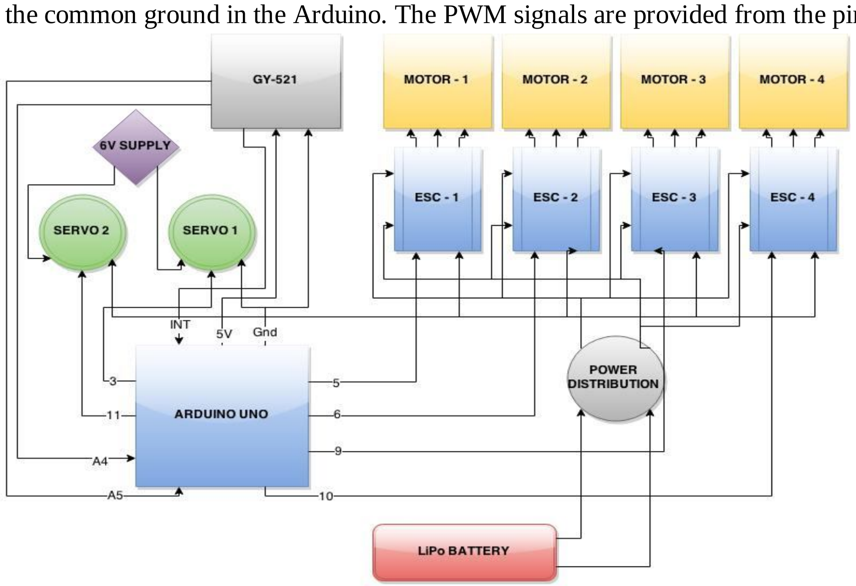

Fig 10 Block diagram of the Quadcopter

Arduino Integrated Development Environment is used to program the UNO board and the data acquisition is performed by making Arduino as a server for MATLAB to be used. The separate power supply is provided to reduce the complexity associated with the various circuits to provide the required power from the LiPo battery.

VII. RESULTS & CONCLUSION

A. Tests Performed on the System

There are have been carried out from the beginning and these include static tests, open loop tests and closed loop. Also a heretical test that shows the various parameters of the closed loop control of the system as the dynamics changes when a propeller fails.

1) Analog Data vs RPM:The analog data is the Pulse Width Modulated value is given to each motor so as to force them. Three pairs of stator is there in BLDC motor.

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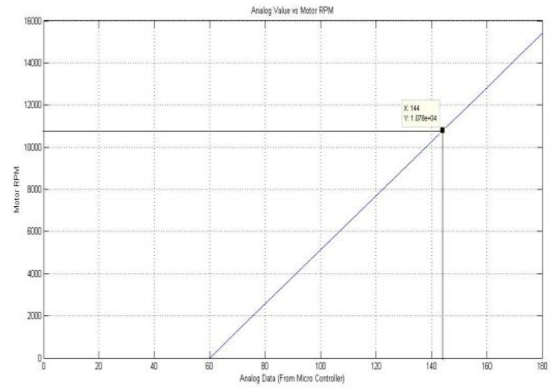

Fig 11 Analog data vs RPM Characteristics

coils that are switched continuously to achieve rotation. The switching time between two stator coils is determined by the width of this pulse (i.e) the analog data sent to the electronic speed controller helps to determine the speed at which the BLDC motor would rotate. The graph as shown in Fig 11 is linear which means that the RPM is zero at 60 and maximum at 180. Though 180 is the maximum RPM that can be achieved, to increase durability only 70% of the maximum capacity is being used which has a PWM value of 144.

2) RPM vs Thrust: Similar to the analog data vs RPM characteristics, the RPM at which the motor rotates can be identified. This is completely based on interpreting the data that are available in graph Fig 12. Obtaining the PWM values could give the RPM and inturn cross verifying those RPM values with this plot could give the load at which the motor is running currently.

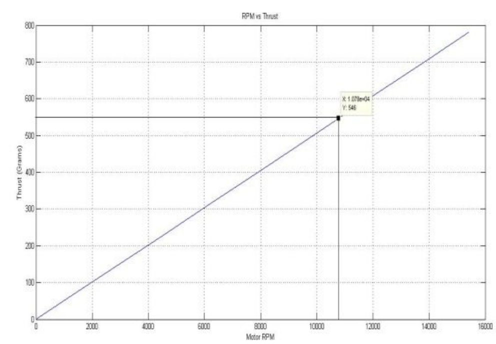

Fig 12 RPM vs Thrust characteristics

3) MATLAB – Simulink Results

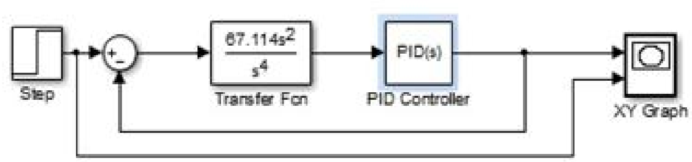

Fig 13 Simulink model of the system

The theoretical analysis is performed in Simulink model as shown in Fig 13 and the given state models as mentioned in Section III are utilized and it is converted into transfer function and the step input is given to the system that has the PID Controller block in cascade with it. The results are shown below in Fig 14 and 15 and Table V and VI shows the parameters of simulation depicting the PID controller for both the systems.

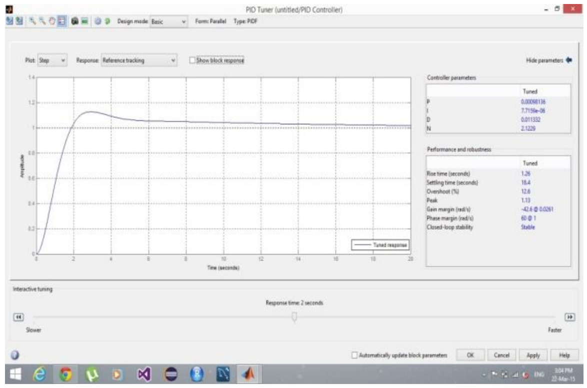

Fig 14 PID controller of the Quadcopter

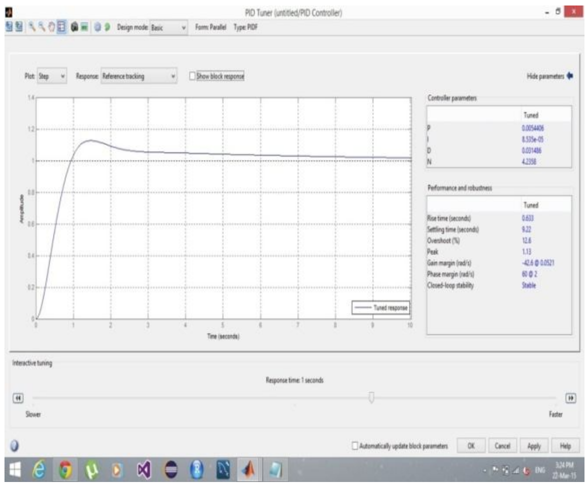

Fig 15 PID controller of the transformed tricopter

Table V

Parameters of the Quadcopter Simulation

Kp	0.00098136
Ki	7.7159e-06
Kd	0.011332
Rise time	1.26 s
System status	Tuned

Table VI

Parameters of the transformed system

Kp	0.0054406
Ki	8.535e-05
Kd	0.031486
Rise time	0.633 s
System status	Tuned

VIII. CONCLUSION

The concept of landing safely was the ultimate problem previously associated with the instabilities in the machine. The algorithm tries to eliminate the problem by automatically stabilizing itself by transforming into another structure. Various tests prove that the system is capable of stabilizing itself if it loses one propeller force. As a reference to the paper cited in [5], the software results showed the system was hindered by an uncontrolled yaw motion that resulted in the error of certain utility sensors such as the accelerometers, on board cameras etc. These test results prove that, the system is stable and the yaw motion is controlled and maneuverability is possible until the system loses another propeller is possible.

IX. FUTURE WORK

The Quadcopter fail safe algorithms are always a promising research area. The algorithm utilized can be executed to safe watch the framework for the loss of one and only propeller. It can be further expanded to create a complete fail safety of the machine. Since the components mounted on the machine becomes expensive day by day, it is similar to safe guarding a nuclear reactor to make the machine completely non susceptible to failures. The algorithm can also be optimized to achieve better results in the future as well.

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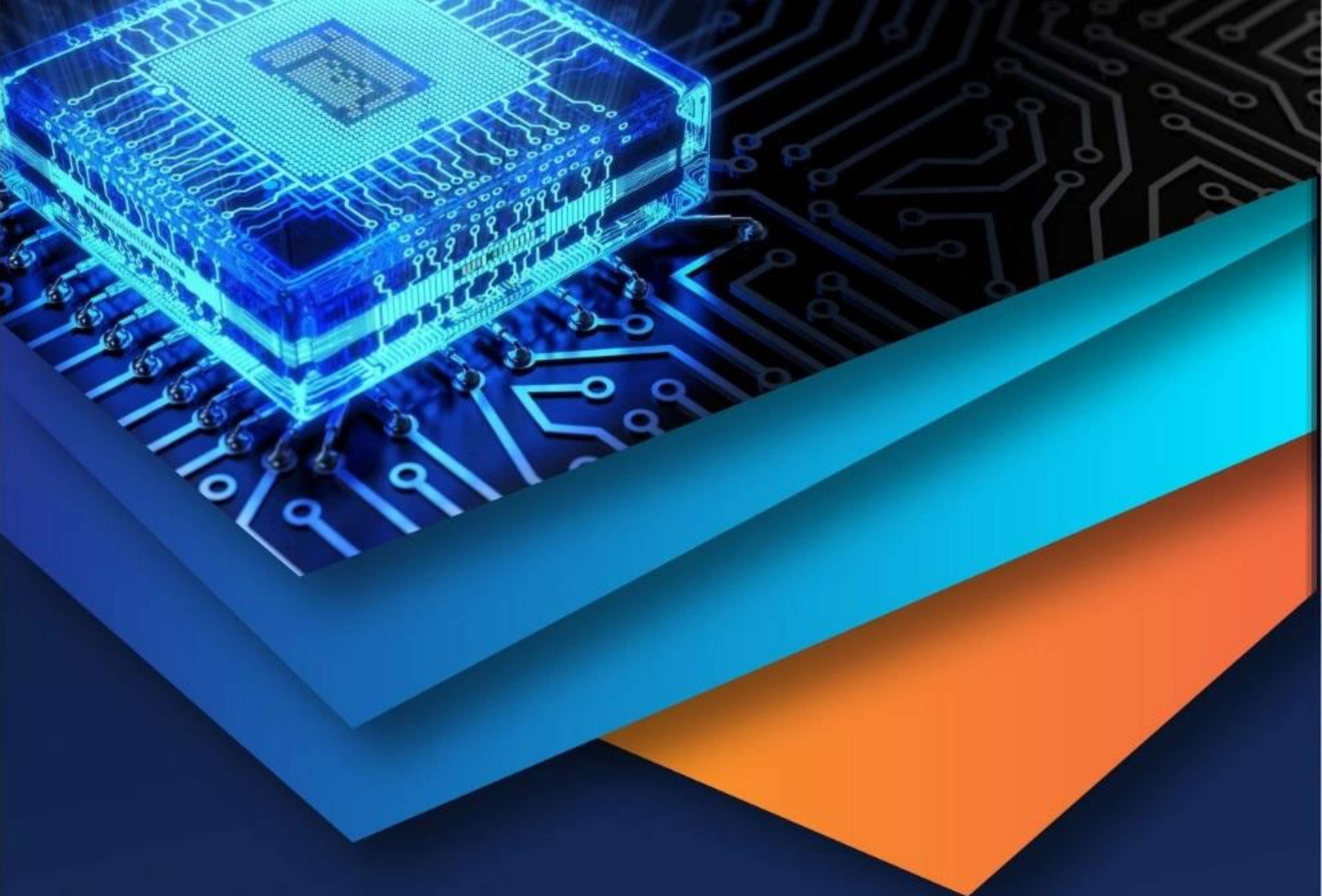

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