Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

Modelling and Simulation of a Multi-Quadcopter Concept

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***Abstract*— This paper presents the modelling and simulation of the flight dynamics of four physically linked, tilting quadcopters. This conceptual drone is one that is composed of four quadcopters connected to a rigid frame and allowed to tilt about a revolute hinge attached to the frame. This new design concept of a drone is not limited to a swarm of four quadcopters and can be extended to two or more. It is believed to encompass several advantages, including enhanced stability, horizontal flight, and a wide stabilized platform which can be used for in-flight power generation and payload. The tilting of each of the quadcopters is achieved using the rotors of the quadcopter itself and controlled using its flight controller. The flight stability and control of the entire drone is achieved using the net thrust produced by the quadcopters' rotors and is controlled using a central flight controller which determines the required titling angles and rotational speeds of each quadcopter. In this paper, we develop a flight dynamics model of this drone. PID control algorithms for the quadcopters' tilting controllers and the entire drone flight controller. The flight of the drone and its response to instability is tested via simulation.**

Keywords- Quadcopter; flight dynamics; simulation; flight control

I. INTRODUCTION

A number of scholars have studied the relationship of quadcopter modelling and its working mechanism. It consists of two clockwise and two counter clockwise rotating motors that are opposite each other. Roll, pitch and yaw is controlled by varying motor speed.

Conventionally, quadcopters or quad-rotors work with varying RPM and VTOL (Vertical Take-off and Landing). Nemati and Kumar, in their research paper [4] studied the relationship between the tilting-rotor angles and derived the quadcopter orientation using the dynamic model. The paper explained the concept of motion and hovering with controlled pitch and roll angles that resulted in achieving desired orientation of a quadcopter.

The multi tilting quadcopter design is unique in its concept, that combines and distributes the work of one quadcopter into many; performing as a single unit. With this configuration, tilting rotor mechanism is applied to each quadcopter, and they perform their function in response to take-off, cruise and landing of the physically connected quadcopters as a whole. This mechanism adds to a more stable drone, doubling in strength and response methods.

II. MULTI-QUADCOPTER DRONE

The proposed multi quadcopter design is similar in its working to a single quadcopter however presents multiple advantages over a simple quadcopter in some areas of requirement. The design includes four individual quadcopters each with their own flight controllers, a central microcontroller, and a frame which remains fixed during flight. The flight controller on each quadcopter acts as an inertial measurement unit (IMU), controls the four electronic speed controllers and hence the motors, uses the compass and GPS module in order to understand its position in space and directional heading and most importantly serves as the means of connection to the central microcontroller.

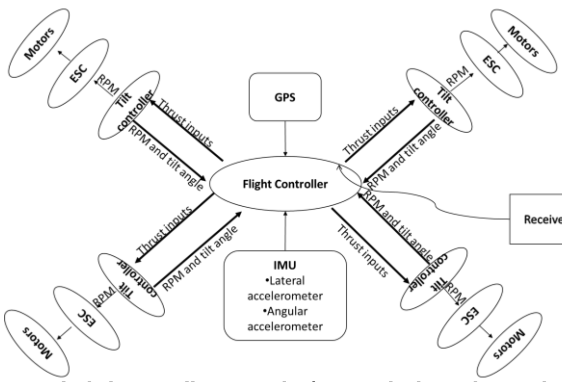

Figure 1. Block diagram illustrating the functional relationships in the Multi-Quadcopter Drone

Through the central microcontroller, a link is created between the four individual quadcopters on the frame. This relation enables the quadcopters to comprehend each other's position and the overall systems position in space. The central microcontroller, through the use of an algorithm that holds the controller, should be capable of assigning the flight controllers specific instructions for each of the quadcopters when an instability is detected in the frame or when motion needs to occur. When the quadcopter flight controller receives the instructions, they must follow through until it is detected that the frame is in the correct position to perform the required motion. This is detected through the IMUs of both the quadcopters and the microcontroller and the relation is one which is that of a feedback loop.

The presence of the feedback system allows to control each drone if necessary as an individual quadcopter and to move opposite to external forces to stabilize the structure.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

III. MATHEMATICAL MODELING

To analyze the flight dynamics of the multi-quadcopter drone, we first consider the flight dynamics of one of the quadcopters making the drone, then we consider the flight dynamics of the drone as a whole.

A. *Single Quadcopter Model*

We assume all four quadcopters are identical. Each quadcopter has four rotors which are driven by electric motors. The rotational speed of the electric motors is controlled by a flight controller (APM for example). Each spinning rotor produces an upward thrust. Opposite rotors spin in opposite directions to cancel out the resultant moment arising from each. Rotors spinning clockwise, as viewed from the top, produce a moment in the –z axis and the motors spinning anti-clockwise direction produce a moment in the +z axis. The quadcopters will be numbered 1, 2, 3, and 4 as illustrated in Fig. (3).

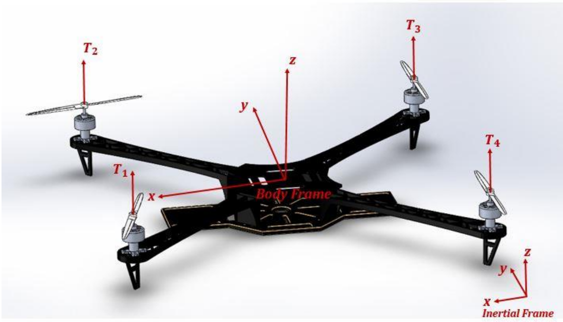

Figure 2. Single quadcopter axes and thrust vectors

Let $(x_{q,i}, y_{q,i}, z_{q,i})$ be the body axes of the i[th] quadcopter, where i = 1, 2, 3, 4. We take $x_{q,i}$ to be pointing forward and $z_{q,i}$ to be pointing upward (as shown in the figure).

We define the following rotor thrust vectors:

$T_{i,j}$, i (quadcopter)= 1, 2, 3, 4, j (rotor) = 1, 2, 3, 4

Where in the i[th] quadcopter frame (q,i), we have the net thrust and net moment vectors expressed in the quadcopter frame as

$$\mathbf{T}_i|_{q,i} = \begin{bmatrix} 0 \\ 0 \\ \sum_{j=1}^{4} T_{i,j} \end{bmatrix}, T_{i,j} = k\omega_{i,j}^2 \qquad (1)$$

$$\mathbf{M}_i|_{q,i} = \begin{bmatrix} (T_{i,1} + T_{i,4} - T_{i,2} - T_{i,3}) l_q \\ (T_{i,1} + T_{i,2} - T_{i,3} - T_{i,4}) l_q \\ M_{i,1} + M_{i,3} - M_{i,2} - M_{i,4} \end{bmatrix}, M_{i,j} = k_m\omega_{i,j}^2 \quad (2)$$

Where l_q is half the rotor-to-rotor side distance in each quadcopter; and k and k_m are the thrust and moment constants of the rotor, respectively.

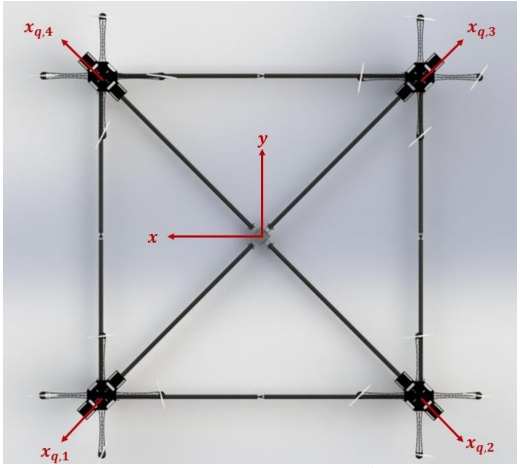

Figure 3. Orientation and numbering of quadcopters

We restrict our model to the case in which each quad is allowed to tilt only about its own y-axis (y_q). Then, the attitude of the quadcopter frame (q-frame) with respect to the multi-quadcopter drone frame (b-frame) is given by the following two successive rotations:

1. Rotation about z_b -axis through angle $\left(\psi_{q,i} = \frac{\pi}{4}(2i - 1), i = 1,2,3,4\right)$
2. Rotation about y_q -axis through angle $\left(\theta_{q,i}, i = 1,2,3,4\right)$

Then,

$$R_b^q = \begin{bmatrix} C_{\theta_q} & 0 & -S_{\theta_q} \\ 0 & 1 & 0 \\ S_{\theta_q} & 0 & C_{\theta_q} \end{bmatrix} \begin{bmatrix} C_{\psi_q} & S_{\psi_q} & 0 \\ -S_{\psi_q} & C_{\psi_q} & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_{\theta_q} C_{\psi_q} & C_{\theta_q} S_{\psi_q} & S_{\theta_q} \\ -S_{\psi_q} & C_{\psi_q} & 0 \\ S_{\theta_q} C_{\psi_q} & S_{\theta_q} S_{\psi_q} & C_{\theta_q} \end{bmatrix} \qquad (3)$$

Since R_b^q is an orthogonal matrix, then the inverse rotation is given by

$$R_q^b = (R_b^q)^T \qquad (4)$$

The inertial frame is represented by W and the body frame of the quadcopter is represented by B. The Euler angles are defined by θ (pitch), ϕ (roll) and φ (yaw). Each motor produces an upwards force, when it is spinning. Opposite motors spin in opposite directions, to cancel out the resultant moment arising from each. The motors spinning in the clockwise direction, produce a moment in the –Z direction and the motors spinning in the anti-clockwise direction, produce a moment in the +Z direction.

The rotational matrix for transformation from drone body frame (b-frame) to inertial frame (w-frame) is given in terms of the Euler's angles (ϕ, θ, ψ) as

$$R_b^W = \begin{bmatrix} C_\theta C_\psi & S_\phi S_\theta C_\psi - C_\phi S_\psi & S_\phi S_\psi + C_\phi S_\theta C_\psi \\ C_\theta S_\psi & C_\phi C_\psi + S_\phi S_\theta S_\psi & C_\phi S_\theta S_\psi - S_\phi C_\psi \\ -S_\theta & S_\phi C_\theta & C_\phi C_\theta \end{bmatrix} \qquad (5)$$

Where $C_\phi = \cos\phi$, $S_\phi = \sin\phi$

The relation between the rates of Euler's angles and angular velocity vector about body axes $\boldsymbol{\omega} = (p, q, r)$ is given by

$$\begin{bmatrix} \dot{\theta} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & S_\phi T_\theta & C_\phi T_\theta \\ 0 & C_\phi & -S_\phi \\ 0 & S_\phi / C_\theta & C_\phi / C_\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{6}$$

Where $T_\phi = \tan \phi$

Taking the We further consider the following special cases of the quadcopter:

1) Special Case 1

The rotors of each quadcopter are assumed to spin in such a way that the thrust vectors and moments will result in pure pitching of the quadcopter about its own y_q-axis. This implies the following conditions:

1. $T_{i,1} + T_{i,4} - T_{i,2} - T_{i,3} = 0 \rightarrow \omega_{i,1}^2 + \omega_{i,4}^2 - \omega_{i,2}^2 - \omega_{i,3}^2 = 0$
2. $M_{i,1} + M_{i,3} - M_{i,2} - M_{i,4} = 0 \rightarrow \omega_{i,1}^2 + \omega_{i,3}^2 - \omega_{i,2}^2 - \omega_{i,4}^2 = 0$

Which results in
$\omega_{i,1} = \omega_{i,2}$ and $\omega_{i,3} = \omega_{i,4}$

Substituting this into the net thrust and moment vectors, we get:

$$\mathbf{T}_i|_{q,i} = \begin{bmatrix} 0 \\ 0 \\ 2(T_{i,1} + T_{i,3}) \end{bmatrix}, T_{i,j} = k\omega_{i,j}^2 \tag{7}$$

$$\mathbf{M}_i|_{q,i} = \begin{bmatrix} 0 \\ 2(T_{i,1} - T_{i,3}) l_q \\ 0 \end{bmatrix}, M_{i,j} = k_m \omega_{i,j}^2 \tag{8}$$

2) Special Case 2

If we further assume that the i^th quad hinge is a frictionless, then when the quad reaches steady-state tilting attitude, we will have

$\mathbf{M}_i|_{q,i} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$ and $T_{i,1} = T_{i,3}$, or in terms of rotor speeds

$$\omega_{i,1} = \omega_{i,2} = \omega_{i,3} = \omega_{i,4}$$

During the tilting of the quad, $T_{i,1} \neq T_{i,3}$. However, pitch moment cannot be transferred through the hinge, and therefore

$$\mathbf{M}_i|_b = \mathbf{0}$$

Each quadcopter is assumed to have symmetry about the $x_q z_q$ and $y_q z_q$ planes. Thus, the inertia matrix will be diagonal

$$\mathbf{I}_q = \begin{bmatrix} I_{x,q} & 0 & 0 \\ 0 & I_{y,q} & 0 \\ 0 & 0 & I_{z,q} \end{bmatrix} \tag{9}$$

We further conclude that $I_{xx,q} = I_{yy,q}$

We are only concerned with the rotational equations of motion. So, we can express the rotational equations of motion as

$$\mathbf{I}_q \dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathbf{I}_q \boldsymbol{\omega}) + \mathbf{M}_{\mathbf{gyro}}|_q = \mathbf{M}|_q \tag{10}$$

Note that due to the spinning of the rotors, the pitching of the quad will result in gyroscopic torque.

$$\mathbf{M}_{\mathbf{gyro}}|_q = \boldsymbol{\omega}_{\mathbf{q}} \times \mathbf{H}_m = \begin{bmatrix} 0 \\ \dot{\theta}_q \\ 0 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ I_{rotor}(\omega_1 + \omega_3 - \omega_2 - \omega_4) \end{bmatrix} \tag{11}$$

in such a way to maintain $\omega_1 = \omega_2$ and $\omega_3 = \omega_4$; then $\omega_1 + \omega_3 - \omega_2 - \omega_4 = 0$ and

$$\mathbf{M}_{\mathbf{gyro}}|_q = \mathbf{0}$$

Therefore, the rotational equations of motion reduce to

$$\mathbf{I}_q \dot{\boldsymbol{\omega}} + \boldsymbol{\omega}_{\mathbf{q}} \times (\mathbf{I}_q \boldsymbol{\omega}_{\mathbf{q}}) = \mathbf{M}|_q \tag{12}$$

From which we can find $\dot{\boldsymbol{\omega}}$ as follows

$$\dot{\boldsymbol{\omega}_{\mathbf{q}}} = \mathbf{I}_q^{-1}[-\boldsymbol{\omega}_{\mathbf{q}} \times (\mathbf{I}_q \boldsymbol{\omega}_{\mathbf{q}}) + \mathbf{M}|_q] \tag{13}$$

Since we assume the quadcopter rotation is restricted except for the pitching about the y_q-axis, then $p_q = r_q = \dot{p_q} = \dot{r_q} = 0$.

Therefore, the rotational equations of motion reduce to

$$\dot{q}_q = \ddot{\theta_q} = \frac{(T_{i,1} - T_{i,3}) l_q}{I_{y,q}} \tag{15}$$

Taking ω as the angular velocity of the motor and k as a constant, the upward thrust produced by the motors can be written as:

$$T_i = k\omega_i{}^2 \tag{16}$$

The equations of motion for each of the quadcopters can be written as follows:

$$m\dot{V_B} + \omega \times (mV_B) = R^T G + T_B \tag{17}$$

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = -g \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{\Sigma T_{i,j}}{m} \begin{bmatrix} S\psi S\phi + C\psi S\theta C\phi \\ S\psi S\theta C\phi - C\psi S\phi \\ C\theta C\phi \end{bmatrix} \tag{18}$$

Similarly, the angular accelerations of the quadcopter are given by the following:

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

$$I\dot{\omega} + \omega \times (I\omega) = \tau \tag{19}$$

$$\begin{bmatrix} I_x\ddot{\phi} \\ I_y\ddot{\theta} \\ I_z\ddot{\psi} \end{bmatrix} = \begin{bmatrix} (T_{i,3} - T_{i,1})l_q \\ (T_{i,4} - T_{i,2})l_q \\ M_{i,1} + M_{i,3} - M_{i,2} - M_{i,4} \end{bmatrix} \tag{20}$$

Taking k_m as the constant, the moment produced by the rotating motors can be represented with respect to their angular velocities, as below:

$$M_i = K_m {\omega_i}^2 \tag{21}$$

Since, there is no pitching, rolling or yawing moment during hovering of a basic quadcopter, the values of θ, ϕ *and* ψ are assumed to be zero. Thus, substituting this in equation (3), it gives us the following equation;

$$T_i = \frac{mg}{4} \tag{22}$$

The thrust from each drone is equal to the combined vertical thrusts of the four motors and are equal to the weight of the quadcopter, when hovering:

$$F_i = 4T_i = mg \tag{23}$$

B. Quad-quadcopter Configuration

In case of the concept configuration, it is composed of four quadcopters, arranged at the ends of a square-shaped frame. The quadcopters are placed with their 'faces' outwards, such that they all are pointing at four opposite directions. The drones are placed on the static frame through a hinge, which allows the drone to have only single axis motion. This motion is the ability of the drone to pitch forward and backward, around the y-axis. This angle is called 'θ_q'. For rolling motion (along x-axis), the angle along this direction is called 'ϕ_q'. For yawing motion (along z-axis), the angle along this direction is called 'ψ_q' The four drones in their respective orientations, fitted on the square frame through their hinges form the basis of our configuration and the model can be seen below:

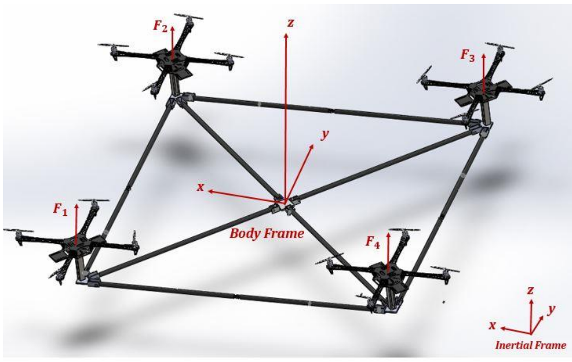

Figure 4. Orientation and numbering of quadcopters

The equations of motion for the drone are:

$$\mathbf{T}_i|_b = R^b_{q,i}\mathbf{T}_i|_{q,i} \tag{24}$$

$$\begin{bmatrix} 0 \\ 0 \\ \ddot{z} \end{bmatrix} = -g \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{\Sigma T}{m} \begin{bmatrix} C_{\psi_q}C_{\theta_q} & S_{\psi_q} & C_{\psi_q}S_{\theta_q} \\ -S_{\psi_q}C_{\theta_q} & C_{\psi_q} & -S_{\psi_q}S_{\theta_q} \\ -S_{\theta_q} & 0 & C_{\theta_q} \end{bmatrix} \tag{25}$$

We know that since $\psi_q = 0$;

$$\ddot{z} = -g + \frac{\Sigma T(C_{\theta_q} - S_{\theta_q})}{m} \tag{26}$$

The equations of angular acceleration are given by the following equation:

$$\ddot{\theta_q} = \frac{(T_{i,1} - T_{i,3})l_q}{I_{y,q}} \tag{27}$$

The reason for only a single equation for angular acceleration to exist is because the quadcopter only pitches and has no roll or yaw.

For our configuration, as the platform tilts, the forces from the four quadcopters need to vary accordingly, to keep the platform in hovering position. This is shown in the following section.

IV. CONTROL ALGORITHM

$T_1 = T_2$, $T_3 = T_4$ for first quad and the same logic extends to all four. Thus, for the first quadcopter we can say that:

$$\omega_1 = \omega_2 \text{ and } \omega_3 = \omega_4 \tag{28}$$

Thus, the dynamic model can be made as:

$$\begin{bmatrix} \omega_1 \\ \omega_3 \\ \omega_5 \\ \omega_7 \\ \omega_9 \\ \omega_{11} \\ \omega_{13} \\ \omega_{15} \end{bmatrix} = \begin{bmatrix} \omega_2 \\ \omega_4 \\ \omega_6 \\ \omega_8 \\ \omega_{10} \\ \omega_{12} \\ \omega_{14} \\ \omega_{16} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 1 \\ 1 & -1 & 0 & -1 \\ 1 & 0 & -1 & 1 \\ 1 & 0 & 1 & -1 \\ 1 & -1 & 0 & 1 \\ 1 & 1 & 0 & -1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & -1 & -1 \end{bmatrix} * \begin{bmatrix} \omega_h + \Delta\omega_f \\ \Delta\omega_\theta \\ \Delta\omega_\phi \\ \Delta\omega_\psi \end{bmatrix} \tag{29}$$

The angular velocity for each rotor during hover can be written in terms of the entire drone, as follows:

$$\omega_h = \omega_i = \sqrt{\frac{mg}{16k\cos\theta_q}} \tag{30}$$

The change in angular velocities are established by the following PD laws:

$$\Delta\omega_\theta = k_{p,\theta}({\theta^{des}}_h \text{-} \theta_d)\text{-} k_{d,\theta}({q^{des}}_d \text{-} q_d) \tag{31}$$

$$\Delta\omega_\phi = k_{p,\phi}({\phi^{des}}_h \text{-} \phi_d)\text{-} k_{d,\phi}({q^{des}}_d \text{-} q_d) \tag{32}$$

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

$$\Delta\omega_{\psi} = k_{p,\psi}(\psi^{des}{}_{h} - \psi_{d}) - k_{d,\phi}(r^{des}{}_{d} - r_{d}) \qquad (33)$$

The deviation in the z-axis is defined by the following control law:

$$\Delta\omega_{f} = \frac{m}{8k_{f}F_{h}}(\ddot{r}^{des}) \qquad (34)$$

Where 'm' is the mass of the quad, 'k_f' is the lift constant, 'F_n' is the net force of each quad during hover and we get $\ddot{r}^{des}$ from the following equation:

$$\ddot{r}^{des} = \mathrm{d/dt}\left(\frac{8K_{m}\omega_{h}}{Iz}\Delta\omega_{\psi}\right) \qquad (35)$$

Thus, in this way the angular velocities of all 16 motors can be controlled centrally to hover the drone in its position.

TABLE 1. Values of parameters used in the simulation.

Fixed Parameters in Simulation		
Parameter	**Value**	**Unit**
g	9.81	m/s^2
m	5.3	kg
l	0.707	m
k	8.63×10^{-5}	-
b	3.62×10^{-7}	-
I_{xx}	3.24	kg m^2
I_{yy}	6.34	kg m^2
I_{zz}	3.24	kg m^2
A_x	0.30	kg/s
A_y	0.30	kg/s
A_z	0.30	kg/s

Inertia Matrix for the platform:

$$\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ Iyx & Iyy & Iyz \\ Izx & Izy & Izz \end{bmatrix} = \begin{bmatrix} 3.24 & -0.26 & 1.77 \\ -0.26 & 6.34 & -0.26 \\ 1.77 & -0.26 & 3.24 \end{bmatrix}$$

V. SIMULATION RESULTS

Figure 5. Simulink Block Model

To demonstrate if the above concept and mathematical model works, Simulink was used as a program to test the drones at different flight conditions. The outputs are plotted in graphs as shown in Figs. 7-9.

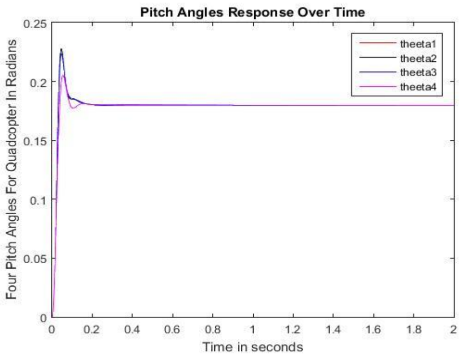

Figure 6. Desired Pitch Angle Response Over Time

Fig. 6 shows the desired pitch angle input from the drone dynamics. It can be inferred that the quad initially starts from zero degree and it goes to about 12.3 degrees +
which is slightly more than 20% overshoot. It then attains its settling time at 0.4 seconds.

A. *Disturbance Correction*

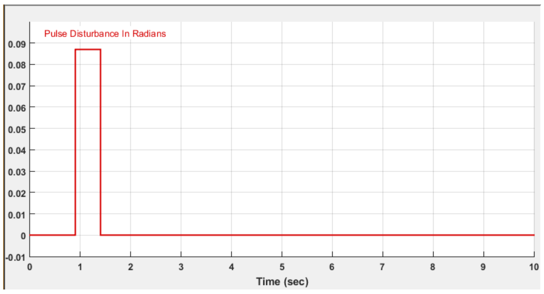

Figure 7: Disturbance Input Angle

Fig. 7 shows 5 degrees of disturbance angle.

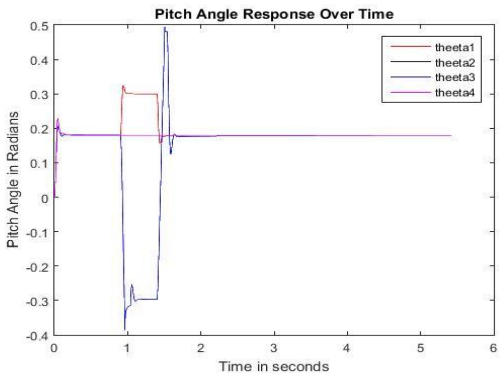

Figure 8. Pitch Angle Correction Response over Time

Fig. 8 shows the longitudinal disturbance at about 5 degrees. From the graph, it can be inferred that angle of the frame keeps changing till it is back to 0 degrees after which, the drone goes back to its initial pitch angle of 10 degrees.

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ISSN: 2278-0181
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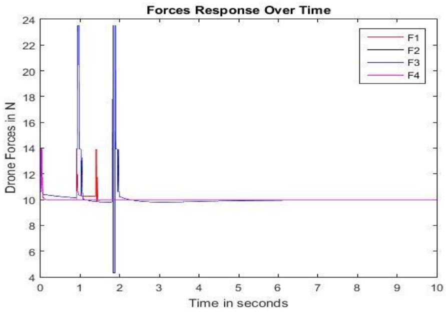

Figure 9. Forces Correction Response over Time

Fig. 9 shows the response of forces with time. As the disturbance of 5 degrees is reached, the forces in the quad changes and makes sure that the drone attains the stable position. there was a saturation block that has been used so that the force lies within the limit. There is a constant response by the quad to any disturbance that are encountered.

VI. CONCLUSION

This concept of tethered swarm robotics brings about a new method of drone control. By replicating what motors on servos do and extrapolating this to entire quadcopters, the control over the platform as a whole is greatly enhanced. Since the tilting of the quadcopters do not affect the attitude of the entire drone, a central control system has been established to co-relate the control of each quadcopter and the system of four quadcopters as a single entity. For this, a novel control algorithm was devised, which covers all aspects of drone control by varying thrusts, angles (of quads) and angular velocities (of motors). This, as simulation shows, results in stable response to any destabilizing moment. This also broadens the scope of how drones can work together and perform singular tasks as a constellation, making this concept ideal for future research.

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