Asian Review of Mechanical Engineering
ISSN: 2249-6289 (P), Vol.12 No.2, 2023, pp.1-14

DOI: https://doi.org/10.51983/arme-2023.12.2.3849

Fault Tolerance Conceptual Strategy for a Quadcopter Drone with Rotor Failure

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(Received 9 November 2023; Accepted 17 November 2023; Available online 25 November 2023)

Abstract - **The ability of a quadcopter drone to maintain its attitude relies solely on its four rotors. If even one motor fails, the drone loses its ability to hold attitude and altitude. This paper explores a new fault tolerance solution to enhance attitude control for quadcopter drones following the complete loss of a single rotor. By following the fundamental principle of balancing forces and moments on a quadrotor drone, the paper demonstrates that it is feasible to land the drone safely by minimizing roll, pitch, and yaw when a rotor fails. The concept centers around thrust vectoring, which allows an opposite motor to tilt independently. The results indicate that tilting the opposite rotor by 45º provides better management of the drone's roll, pitch, and yaw, enabling the incapacitated drone to land in a more controlled and manageable manner. The paper includes simulation results and a summary table of the novel idea's performance enhancements.**
Keywords: **UAV Fault Tolerance, Quadrotor Malfunction, Drone Damage Control**

I. INTRODUCTION

The aerospace industry has shown great interest in the study of fault tolerance for vehicles, with the aim of preventing catastrophic failures. For aircraft, the primary objective of flight control systems is to ensure stability, while navigation remains a secondary objective. In the event of a failure that could compromise stability, it is crucial that the controller can address the issue and restore stability immediately, thus ensuring the safety of the aircraft.

Drones are no exception, and identifying and troubleshooting issues with them involves exploring various factors such as faulty sensors, airframes, computer systems, and communication systems [1,2]. The aerospace community has addressed two areas of study in this field: failure detection, which seeks to identify the faulty part of the vehicle, and fault tolerance, which aims to address the fault. Correct diagnosis is crucial for administering the correct corrective action on a drone that has been rendered inoperable due to a fault. This paper presents work that was done on fault tolerance for single-rotor failure on Quadcopter Drones (QD).

QD utilize 4 spinning rotors to achieve its vertical thrust and control its attitude at 6 degrees of freedom. It can maintain its position in the air by carefully balancing forces and moments, ensuring their sums equal zero during flight. However, the drone's stability is dependent on these rotors, leaving little room for error in case of malfunction. If one of the rotors fail, the drone's equilibrium will be disrupted, potentially causing it to veer off course. Operators were trained to immediately land the drone if this occurred, preventing any accidents. During such situations, it is crucial for the operator to quickly restore balance to the forces and moments, allowing the drone to land safely and without delay.

Dealing with a single rotor failure on a QD is a challenging task. It is difficult to recover from this failure with a typical QD setup. Experts have agreed that unless the drone was over-actuated, there was little chance of recovering the drone's stability from a single rotor failure [3]. One suggestion on how to over-actuate a QD was to install a dual motor system at each corner. However, this technique increased the weight and power requirement of the drone. Other experts addressed the issue by assuming that the failed rotor did not completely fail but instead failed only by a certain percentage [4, 5, 6, 7]. They used terms like 'partial failure' or 'loss of effectiveness (LOE)' to describe this type of failure. This meant that the failed rotor still provided some thrust, but it was limited due to the failure. In one study [8], a QD experienced a single motor malfunction, and the authors performed control reconfiguration. However, using the reconfigured controller, they had to sacrifice the yaw angle and the yaw rate. This could potentially be damaging to the drone's airframe during touchdown.

For other types of drones, experts discussed rotor failure on a hexacopter drone [9, 10, 11]. In those studies, other available rotors could support the missing contribution of forces and moments from the failed rotors. By choosing which motor should continue to operate and which should be 'switched off' to regain stability, the safety of the hexacopter drone could be managed and recovered.

In another study [12], a tricopter drone was tested with a stuck rear rotor. The rotor was able to spin; however, when the tilting mechanism jammed, the drone was in danger. The study showed that by reconfiguring the controller to take the new situation into account, the safety of the drone could be recovered. Regardless of the types of drones investigated, the common theme of these studies revolved around restoring the forces and moments lost during the rotor failure.

In a conventional QD configuration, the motors are fixed in place, which can limit the drone's ability to recover from a single rotor failure. A new idea experimented in the work presented in this paper, is to allow the rotors to 'tilt', enabling each rotor's thrust to 'vector' independently. This capability allows for more maneuverability, and, in the event of a single rotor failure, the drone can attempt to maintain its equilibrium by making the sum of forces and the sum of moments equal to zero or very close to zero, for safer landing.

In this paper, the terms 'motor' and 'propeller' are used interchangeably to describe the failure, while the term 'rotor' refers to the combined action of the motor and propeller.

II. PROBLEM STATEMENT

If a quadcopter drone loses one of its rotors, it becomes unbalanced and begins to roll, pitch, and yaw uncontrollably, ultimately resulting in a crash. To regain balance, it is necessary to compensate for the loss of forces and moments provided by the faulty rotor. This paper presents results from a unique approach to regain balance in which the functional opposite rotor adjusted its thrust vector by changing its orientation, thereby restoring enough of the missing forces and moments to minimize changes in roll, pitch, and yaw of the drone. The aim of the study was to safely and quickly land by keeping the drone's rolling, pitching, yawing, and their rates of change as close to zero as possible, thus preventing any further complications.

III. METHODOLOGY AND EXPERIMENTAL SETUP

In this section, the equations that dictate the movement of a quadcopter drone are provided based on [3, 13, 14, 15]. These equations are utilized to construct a MATLAB/Simulink block diagram model. The model is based on previous research published in [16] but has been modified in this work to integrate proposed concepts and changes in the thrust vector and torque from relevant rotors.

Eqn (1) describes the QD's translational motion in its body-fixed coordinate frame, assuming a constant body mass.

$$F_b = m\left(\frac{d}{dt}V_b + \omega \times V_b\right) \tag{1}$$

Eqn (2) elucidates the rotational dynamics of the body-fixed frame, where applied moments exist in the body-fixed frame and the inertial tensor is relative to the center of gravity of the body-fixed frame.

$$M_b = I\frac{d}{dt}\omega + \omega \times (I\omega) \tag{2}$$

Eqn (3) details the relationship between the body-fixed angular velocity vector and the Euler angles' rate of change, with equations (4) and (5) providing further specifics.

$$\frac{d}{dt}\begin{bmatrix}\phi\\ \theta\\ \psi\end{bmatrix} = \begin{bmatrix}1 & (\sin\phi\tan\theta) & (\cos\phi\tan\theta)\\ 0 & \cos\phi & -\sin\phi\\ 0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta}\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix} \tag{3}$$

$$\omega = \begin{bmatrix}p\\ q\\ r\end{bmatrix} \tag{4}$$

$$I = \begin{bmatrix}I_{XX} & -I_{XY} & -I_{XZ}\\ -I_{YX} & I_{YY} & -I_{YZ}\\ -I_{ZX} & -I_{ZY} & I_{ZZ}\end{bmatrix} \tag{5}$$

The assumptions made during the model's implementation are as follows: (1) The quadcopter's position is in an inertial reference frame. (2) Velocity is acquired from the body reference frame. (3) Rotation occurs around the center of gravity, which is expressed in the body reference frame. (4) Euler angles are used for analysis. (5) The mass is constant. (6) The Euler angles have a singularity when cosine is zero.

Finally, the state equations used for this work are presented in equations (6), (7) and (8).

$$\frac{d}{dt}\begin{bmatrix}x\\ y\\ z\end{bmatrix} = R^T(\theta,\phi,\psi)\begin{bmatrix}u\\ v\\ w\end{bmatrix} \tag{6}$$

$$\frac{d}{dt}\begin{bmatrix}u\\ v\\ w\end{bmatrix} = -\begin{bmatrix}p\\ q\\ r\end{bmatrix} \times \begin{bmatrix}u\\ v\\ w\end{bmatrix} + \frac{1}{m}\begin{bmatrix}F_X\\ F_Y\\ F_Z\end{bmatrix} \tag{7}$$

$$\frac{d}{dt}\begin{bmatrix}p\\ q\\ r\end{bmatrix} = \begin{bmatrix}I_{XX} & -I_{XY} & -I_{XZ}\\ -I_{YX} & I_{YY} & -I_{YZ}\\ -I_{ZX} & -I_{ZY} & I_{ZZ}\end{bmatrix}^{-1}\left(\begin{bmatrix}M_X\\ M_Y\\ M_Z\end{bmatrix} - \begin{bmatrix}p\\ q\\ r\end{bmatrix} \times \begin{bmatrix}I_{XX} & -I_{XY} & -I_{XZ}\\ -I_{YX} & I_{YY} & -I_{YZ}\\ -I_{ZX} & -I_{ZY} & I_{ZZ}\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix}\right) \tag{8}$$

A. Commanded Position and Feedback Loops

The simple thrust level (throttle change) is derived from commanded desired position. The use of feedback about the actual position derives the appropriate thrust level required from each rotor. The thrust (Figure 1) is modelled based on Eqn (9).

$$Th = -mg + k_P(z_{desired} - z) + k_D\left(0 - \frac{dz}{dt}\right) \tag{9}$$

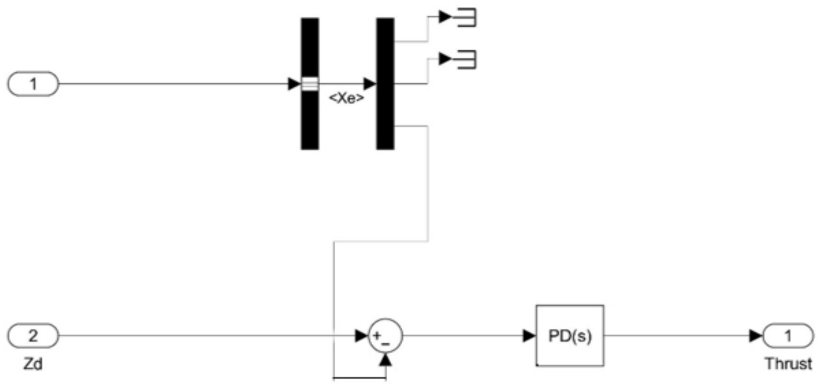


Fig. 1 Thrust input based on z-position of QD

To control roll, pitch and yaw, Proportional (P)+Derivative(D) controllers are used respectively, illustrated in Figure 2. And feedforward loop is used to provide throttle/thrust to compensate for the weight of the drone (1kg) shown in Figure 3.

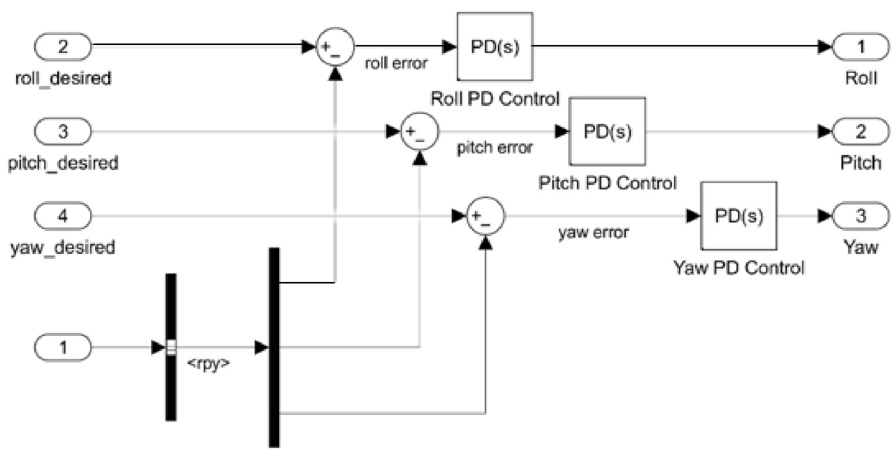


Fig. 2 Roll, pitch, and yaw PD controllers

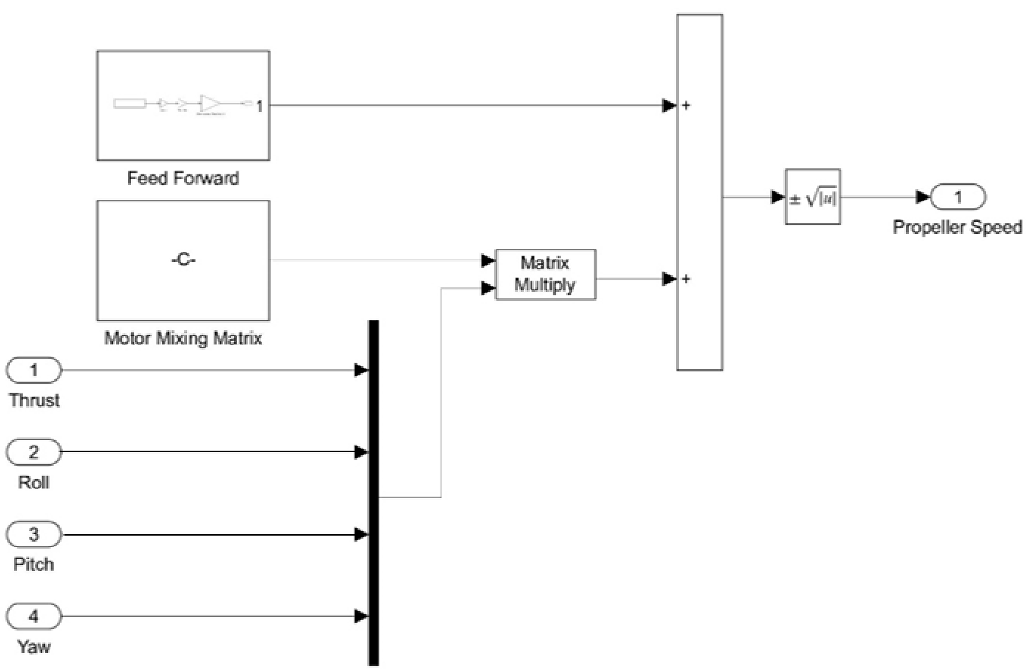


Fig. 3 The use of feed forward block as throttle/thrust commanded input

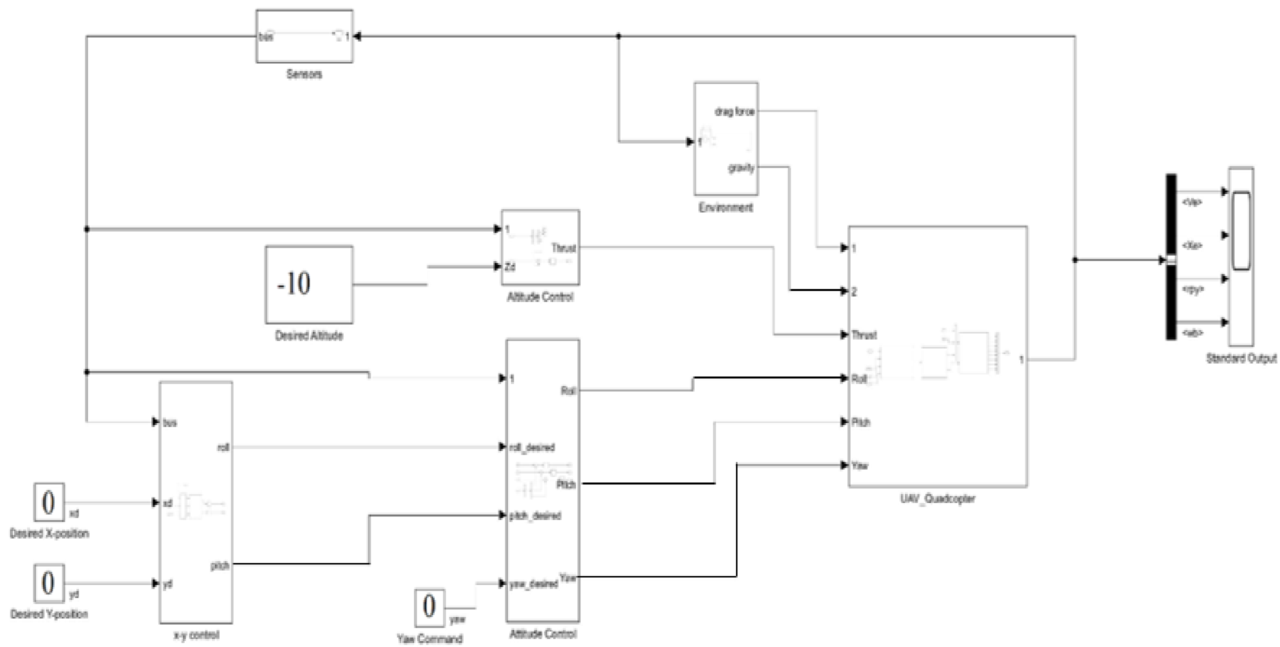


Fig. 4 MATLAB/Simulink block diagram used in the fault tolerant QD study

All the relevant equations are translated into MATLAB/Simulink block diagrams shown in Figure 4.

A. Governing Equations for Rotors

The force created by each rotor in the z-direction is as follows:

$$F_Z = k_p \omega^2 \quad (10)$$

The torque created by each rotor spinning about z-direction is given as:

$$M_Z = k_m \omega^2 \quad (11)$$

B. Positions of Rotors

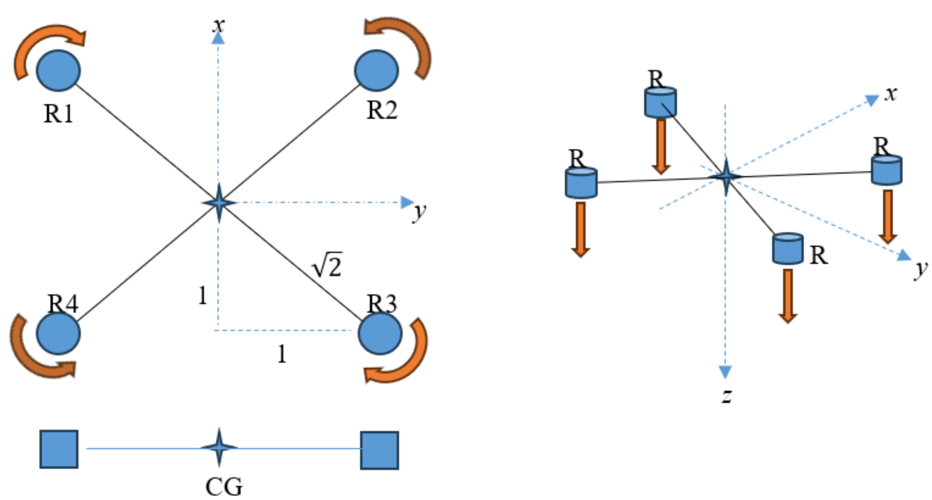


Fig. 5 Relative position of rotors with their respective thrusts and torques

Figure 5 illustrates the rotors positions used in the simulation, along with the relevant dimensions with respect to the body-axis. The QD configuration adopted in the work is the conventional 'X' as shown.

The torques, that resulted from the rotors' thrusts in z-direction from its distance from Center of Gravity (CG), are shown in Eqn 12 as follows.

$$M = r \times F_z \quad (12)$$

For quadrotor drones, the sum of moments can be written as

$$M = \sum_{n=1}^{4} r_n \times F_n \quad (13)$$

Lastly, the QD applied forces and applied moments can be deduced as follows.

$$F = \sum_{n=1}^{4} F_{z,n} \tag{14}$$

$$M = \sum_{n=1}^{4} M_{z,n} + \sum_{n=1}^{4} r_n \times F_n \tag{15}$$

When the drone is hovering, the total force provided by the 4 rotors equal the weight of the drone, hence,

$$F_{fwd,total} = -mg \tag{16}$$

From each rotor, therefore,

$$F_{fwd} = -\frac{mg}{4} \tag{17}$$

The total F_{fwd} is as follows,

$$-2mg \leq F_z \leq 0 \tag{18}$$

Therefore, from each rotor,

$$-\frac{mg}{2} \leq F_z \leq 0 \tag{19}$$

For the work presented in this article, the feedforward thrust is combined with the applied thrust (applied thrust for maneuvering the drone roll, pitch, yaw and up/down). This is illustrated in Figure 3. Hence,

$$F_z = F_{fwd} + T \tag{20}$$

So, the controllable portion of the force can be expressed as,

$$-\frac{mg}{4} \leq T \leq \frac{mg}{4} \tag{21}$$

To assign the contribution from each rotor, a Motor Mixing Matrix is used in the design and shown below,

$$2v_0 \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \end{bmatrix} \begin{bmatrix} T \\ R \\ P \\ Y \end{bmatrix} \tag{22}$$

Finally, the QD thrust, roll, pitch and yaw can be summarized as follows:

$$F = T \tag{23}$$

$$M_X = R \tag{24}$$

$$M_Y = P \tag{25}$$

$$M_Z = Y \tag{26}$$

The scenarios that were tested and discussed in this article are as follows.

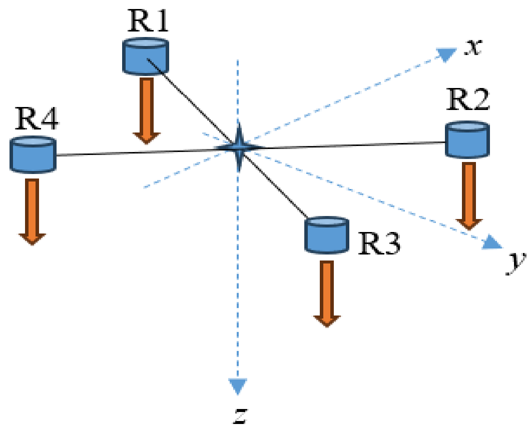


Fig. 6 During Normal Operation of Quadcopter Drone when ALL rotors functioning properly

When all rotors are working as designed, the thrust from all rotors act downwards in positive z-axis direction as illustrated in Figure 6. The torque from each rotor function as illustrated in Figure 5.

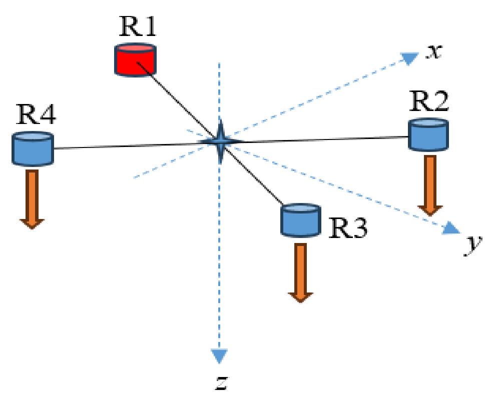


Fig. 7 When R1 failed and completely stopped

When R1 stops completely, both the thrust and the torque from that rotors are removed from the system. The removal of the thrust and torque from the rotors upset the balance of forces and moment previously shown in Figure 5 and Figure 6.

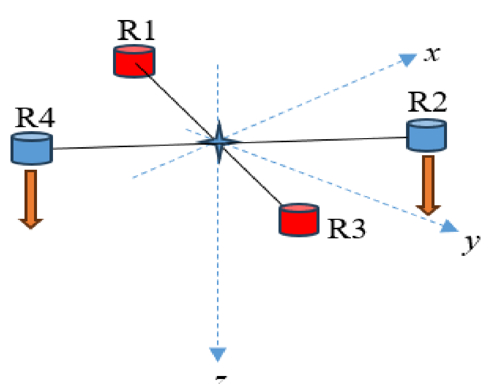


Fig. 8 When R1 fail and R3 is switched off

One of the cases investigated is illustrated in Figure 8. In attempt to reduce the rolling and pitching of the drone as a result of complete failure of rotor R1, R3 was switched off intentionally.

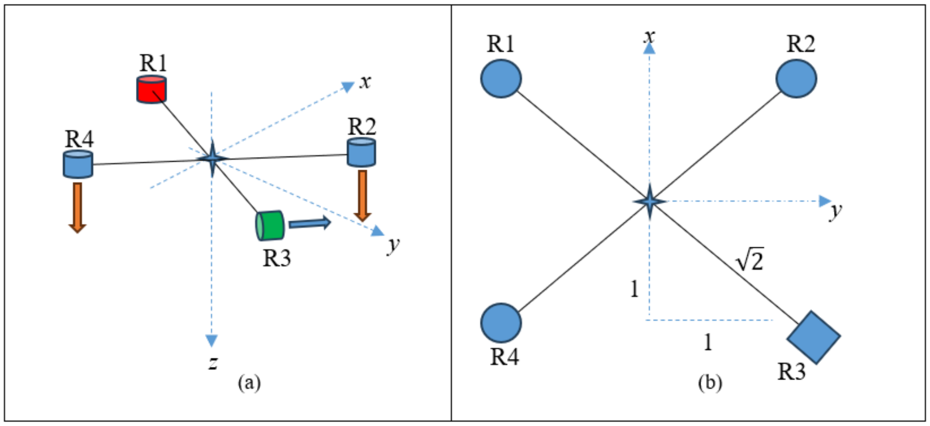


Fig. 9 When R1 fail and R3 is flipped 90o and re-engaged (b) was view from the top

The next test conducted was to simulate the QD flight responses if rotor R3 was flipped 90°, illustrated in Figure 9. The test was to attempt to counter yawing produced when rotor R1 failed, leaving only rotors R2 and R4 in their original orientation.

The last test conducted is shown in Figure 10 where rotor R3 was tilted 45 degrees in the attempt to re-balance the forces and moments on the QD when rotor R1 completely failed but rotors R2 and R4 were still functioning in their respective orientations.

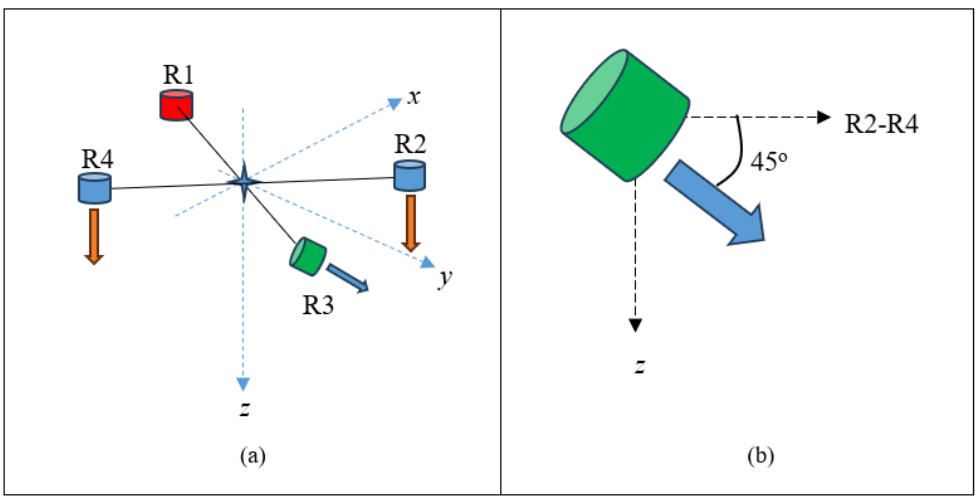


Fig. 10 When R1 fail and R3 is flipped 45deg and re-engaged (b) tilted R3 rotor

IV. RESULTS AND DISCUSSION

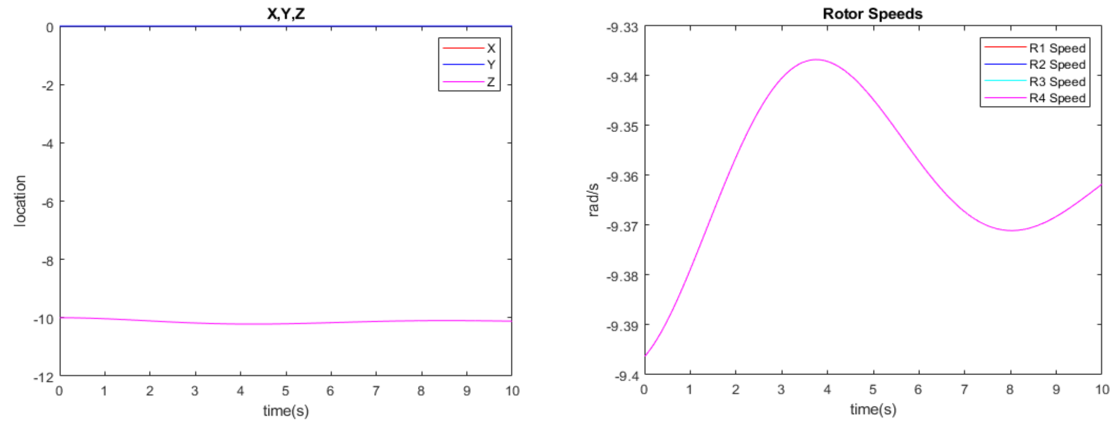
In this section, the outcomes of the tests are presented and discussed. To facilitate clear identification and discussion, the tests have been organized into categories.

Unless otherwise stated, all tests utilized the Proportional (P) and Derivative (D) gains outlined in Table I. Furthermore, the throttle feedforward settings were uniformly set at '36' for all rotors.

TABLE I PID SETTINGS FOR ROLL, PITCH AND YAW, DESIRED ALTITUDE AND X-Y LOCATIONS LOOPS

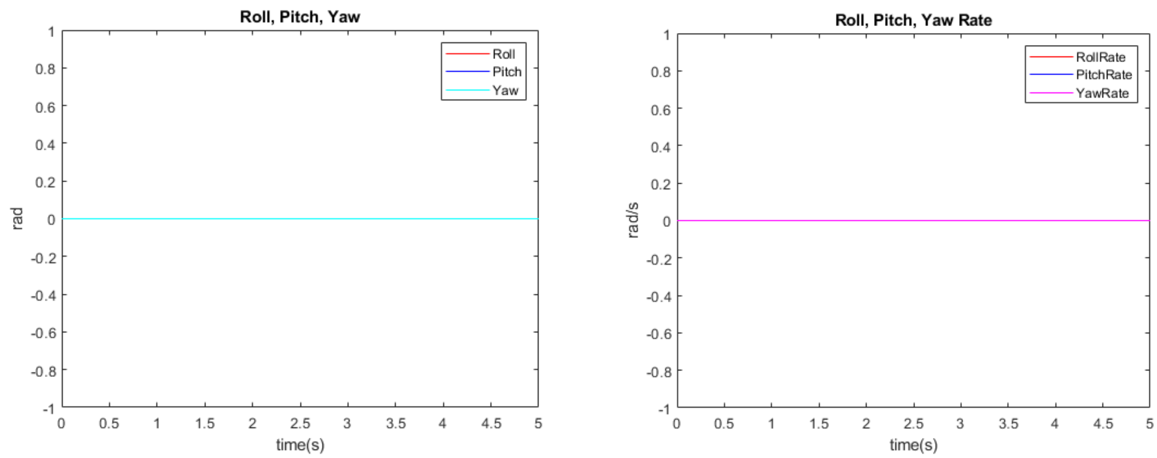
Particulars	Proportional (P)	Integral (I)	Derivative (D)
Roll, Pitch, Yaw	1	0	2
Desired Altitude (Z)	10	0	5
Desired X, Y	1	0	2

A. Case A: Responses when ALL Rotors R1, R2, R3 and R4 were Working



(a) (b)

Fig. 11 The QD maintained relatively steady height at 10m above ground level while all rotors worked together providing thrust

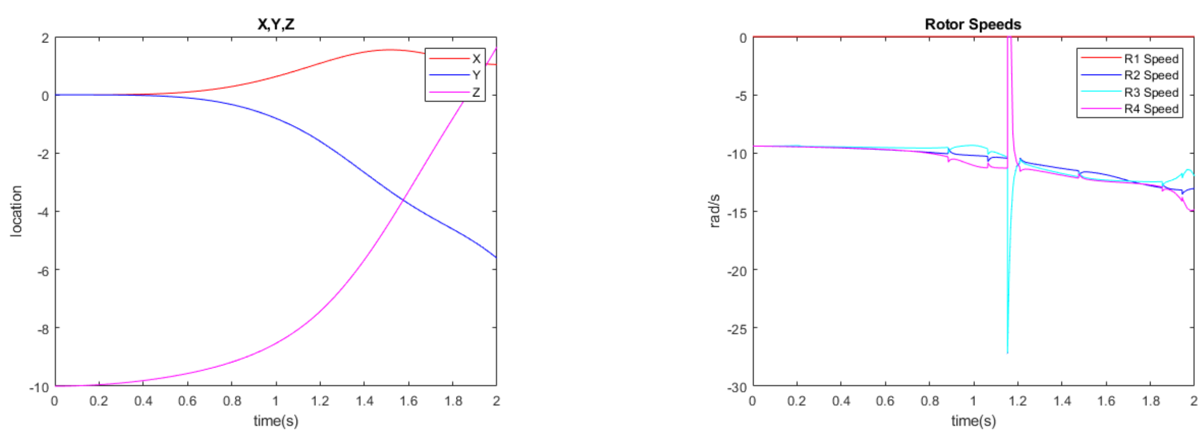


(a) (b)

Fig. 12 Roll, pitch and yaw remained zero and their respective rates implied that the sum of forces and moments about the CG are zero

After analyzing Figures 11 and 12, the simulation showed that the quadcopter drone exhibited the expected behavior. It maintained a stable 10-meter altitude while all four rotors adjusted their speed in unison to offset the weight. There were no discernible changes in roll, pitch, yaw, or their corresponding rates during the flight.

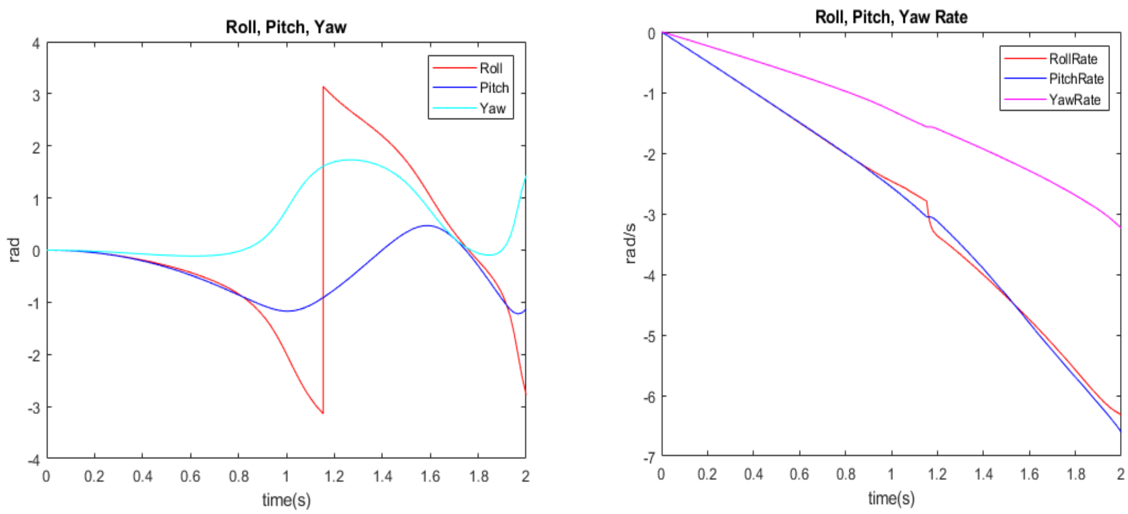
B. Case B: Responses when R1 Completely Stopped, but R2, R3 and R4 were Working



(a) (b)

Fig. 13 Responses in location change and rotor speeds when rotor R1 stopped

In Figure 13(a), when rotor R1 came to a halt, the QD descended rapidly and made contact with the ground in less than two seconds. Figure 13(b) indicates that R3 and R4 reached their maximum speeds at 1.18 seconds while attempting to recover both altitude and orientation.



(a) (b)

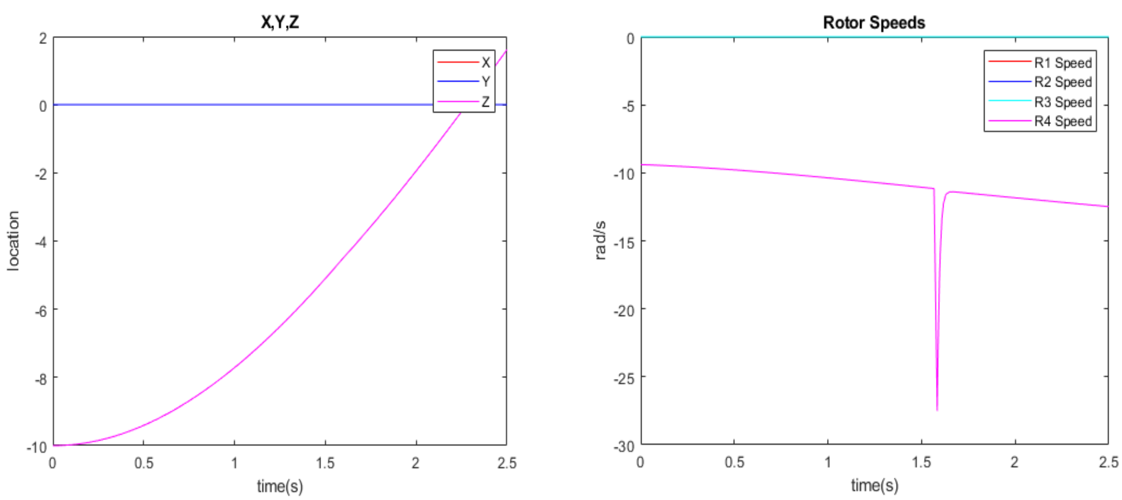
Fig. 14 Attitude responses and their respective rates when rotor R1 Stopped

Figure 14 shows that the drone showed significant increase in roll compared to pitch and yaw within one second. It can be observed also that roll, pitch, and yaw rates gradually increased as the drone reached the ground.

Clearly attempting safe landing in these states could potentially be detrimental to the drone.

C. Case C: Responses when R1 and R3 Completely Stopped, but R2 and R4 were Working

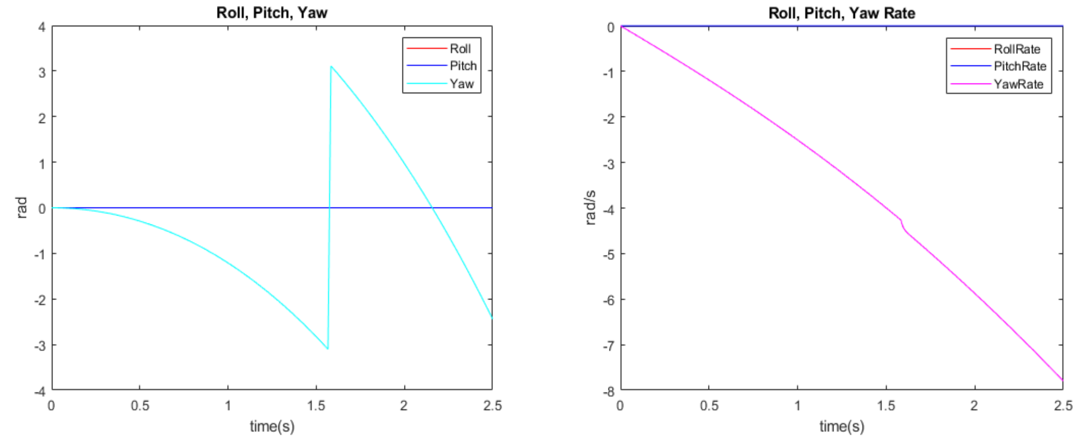
In [10,11], one of the ways to regain the balance of hexacopter drones with failed rotor was to 'switch-off' the rotor opposite the failed one. In this next test, the same was attempted for QD. The rotor opposite to R1 was R3 and hence, purposely switched off. With only R2 and R4 working, the results are shown in Figure 15.



(a) (b)

Fig. 15 Responses in location change and rotor speeds when rotor R1 and R3 Stopped

Figure 15(a) shows that the drone reached the ground from 10m altitude in 2.3 seconds. Both rotors R2 and R4 speeds peaked just after 1.5 seconds in an attempt to restore both attitude and altitude, as shown in Figure 15(b).

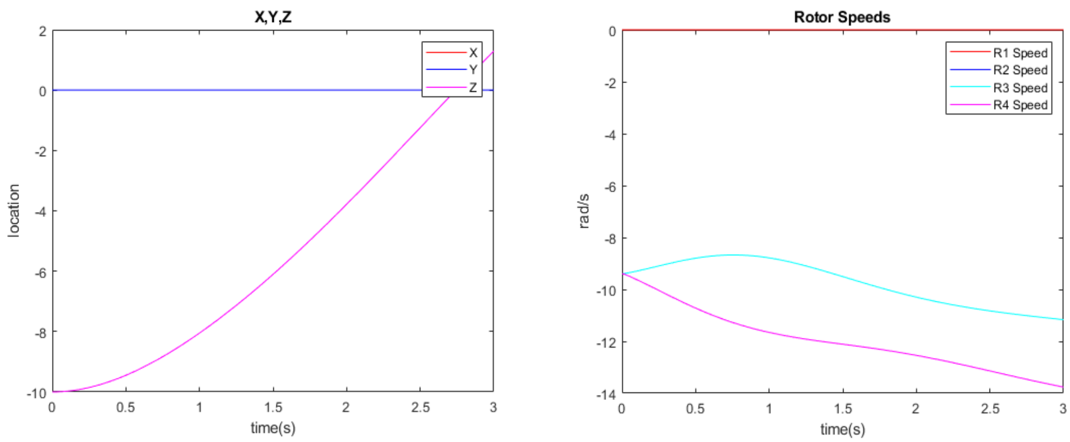


(a) (b)

Fig. 16 Attitude responses and their respective rates when rotor R1 and R3 stopped.

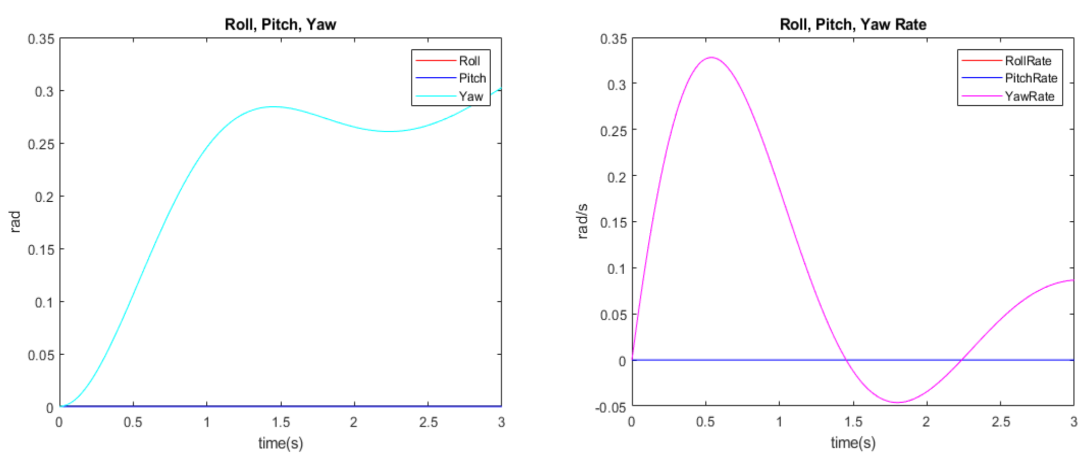
The simulation accurately displayed the resulting yaw moment created by the torques from rotors R2 and R4, as shown in Figure 16(a). Furthermore, the drone's yaw rate steadily increased as it descended towards the ground. As in Case B, landing the drone while experiencing such high yaw rates could cause considerable damage to the device. Clearly, the technique applied to hexacopter drones are not applicable for QD.

D. Case D: Responses when R2 and R4 were Working, but R3 was Flipped 90 Degrees without Torque



(a) (b)

Fig. 17 Responses in location change and rotor speeds when rotor R1 stopped but R3 is flipped 90º without the effect of R3 torque included.

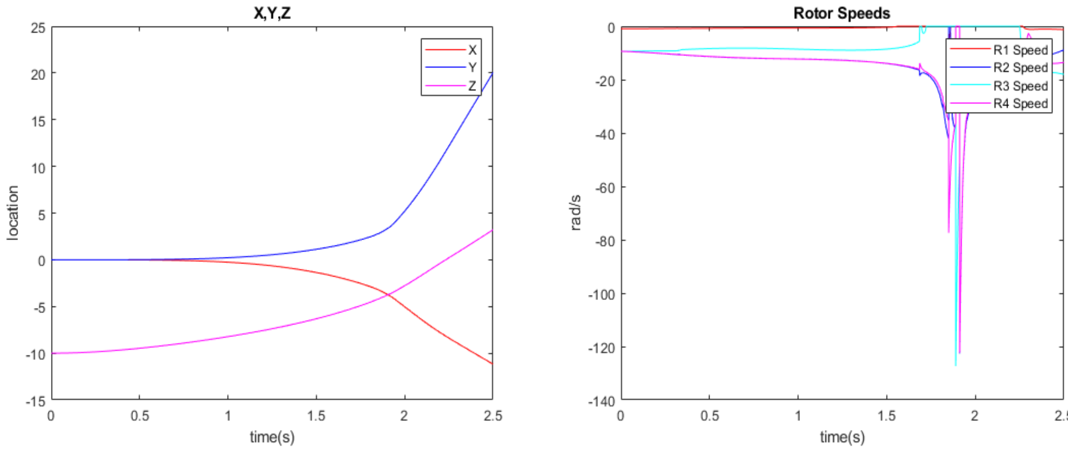


(a) (b)

Fig. 18 Attitude responses and their respective rates when rotor R1 stopped but R3 is flipped 90deg without the effect of R3 torque included.

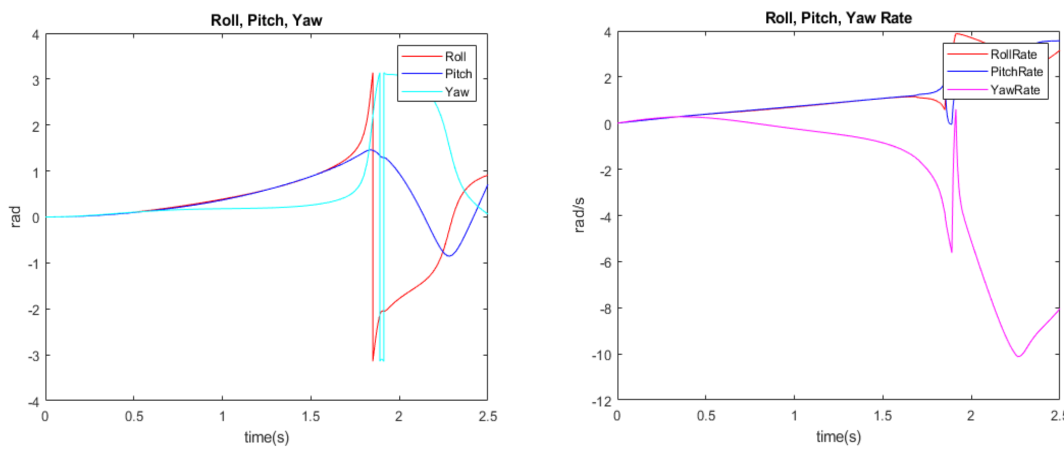
The aim of this test was to investigate and understand the significance of torque contribution from rotors on QD, if the rotor was to be used in an unconventional way to cancel out resultant forces and moments. The initial plan was to use the trust generated by flipped rotor R3 to mitigate or eliminate the yawing effect caused by rotors R2 and R4. The results of the test showed that the drone took slightly longer descent time to reach the ground, as seen in Figure 17(a), as well as a relatively minor yawing motion and low yaw rate. However, this test did not account for the torque generated by rotor R3, making it unrealistic. In the subsequent test, Case E, the torque generated by flipped rotor R3 was included to obtain more accurate and reliable results.

E. Case E: Responses when R1 Stopped, R2 and R4 were Working, but R3 was Flipped 90 Degrees with Torque Included



(a) (b)

Fig. 19 Responses in location change and rotor speeds when rotor R1 stopped but R3 is flipped 90º with the effect of R3 torque included.



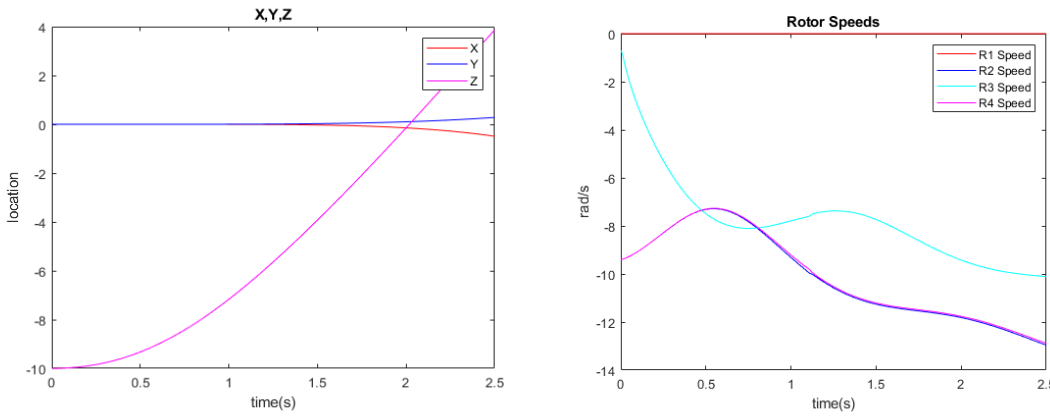
(a) (b)

Fig. 20 Attitude responses and their respective rates when rotor R1 stopped but R3 is flipped 90º without the effect of R3 Torque Included

Figures 19 and 20 illustrate the impact of torque and thrust generated by the flipped rotor R3 when integrated into a system with a stationary rotor R1, while rotors R2 and R4 remained operational in their original positions. The uncontrolled increase in roll, pitch, yaw, and their rates in Figure 20(a) suggests that the drone could not be landed safely in the event of a malfunction, even with remedial action taken. Therefore, it is crucial to effectively manage the torque contributed by the flipped rotor R3 to ensure the safe landing of the crippled drone, as seen in the comparison to the results in Case D.

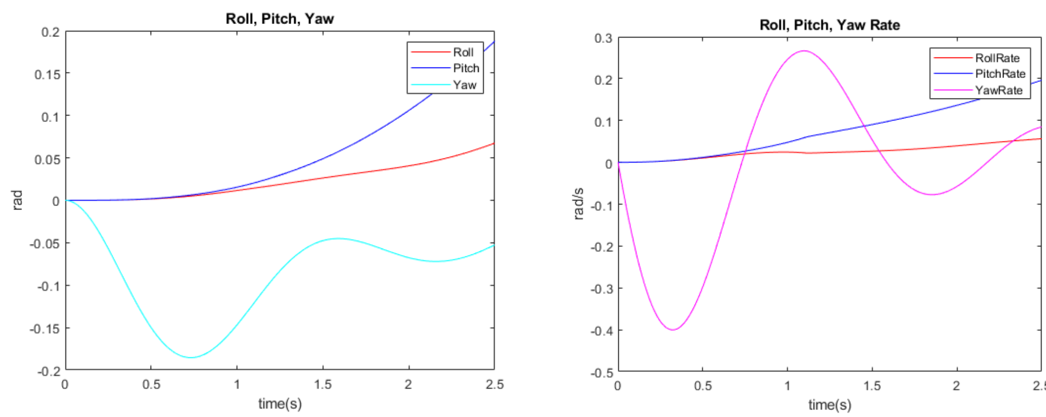
F. Case F: Responses when R1 Stopped, R2 and R4 were Working, but R3 was Tilted 45 Degrees with Torque Included

After observing responses from Case E, test in Case F was conducted to experiment the effect of tilting rotor R3. The rotor was tilted 45 degrees, resulting in a notable shift in both thrust and torque. Additionally, the feedforward throttle settings were adjusted. The R3 feedforward throttle was intentionally reduced to 0.2, and the throttle feedforward for R4 was reduced to 26. However, the feedforward throttle for R2 remained at 36.



(a) (b)

Fig. 21 Responses in location change and rotor speeds when rotor R1 stopped but R3 is flipped 45° with the effect of R3 torque included.



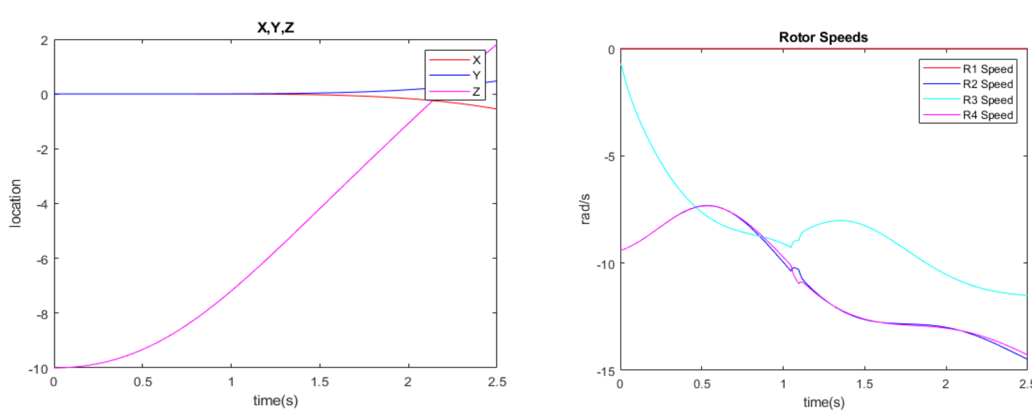
(a) (b)

Fig. 22 Attitude responses and their respective rates when rotor R1 stopped but R3 is flipped 45° without the effect of R3 torque included.

In this case, the simulation results show signs of improvement in the effort to land the drone as safely as possible. The drone reached the ground in 2.1 seconds, but the obvious difference compared to the previous cases is the much smaller roll, pitch, yaw and their rates when the drone touched down. It also appears that the 'component' of torque and thrust from tilted R3 contributed to balancing the roll, pitch and yaw, improving the drone performance better than previous cases. Next, experiments denoted as Cases G and H were conducted to attempt to penalize further, these attitude changes, by increasing the Proportional (P) and Derivative (D) gains for roll, pitch, and yaw feedback loops.

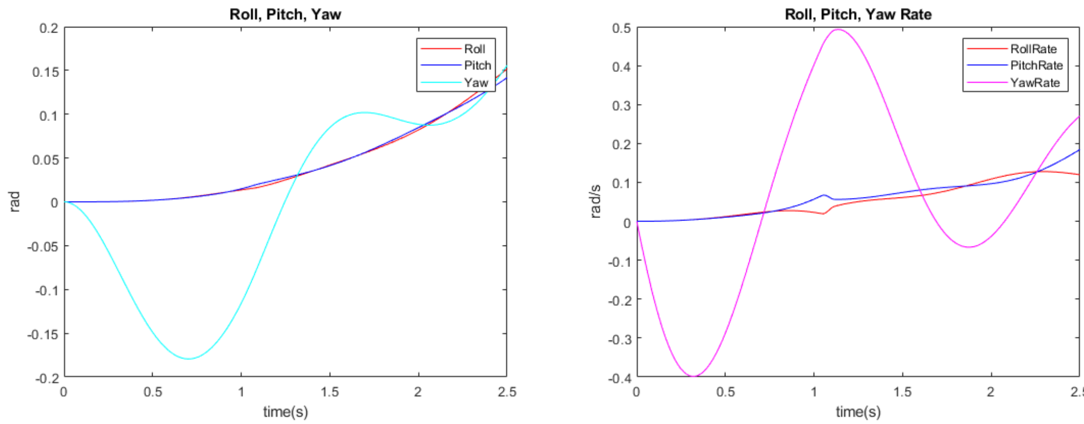
G. Case G: Penalizing Roll and Pitch Feedback Loop

Case G was an extension of Case F, but the difference was in the PD gains for roll and pitch. For Case G, the Proportional (P) gains for roll and pitch were set high to 500, and the Derivative (D) gains for roll and pitch were set to 50. The justification for the changes made was to attempt to reduce further the roll and pitch caused by the tilted rotor R3.



(a) (b)

Fig. 23 Responses in location change and rotor speeds when rotor R1 stopped but R3 was flipped 45° with the effect of R3 torque included

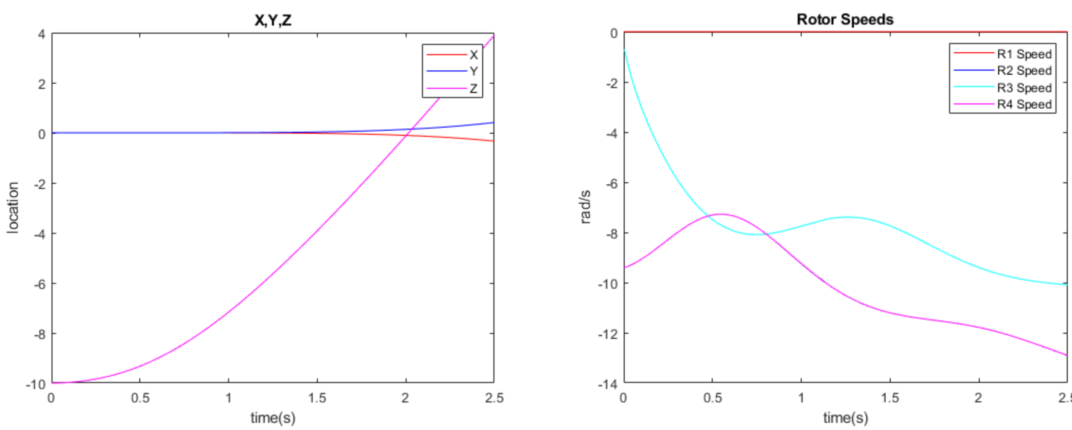


(a) (b)

Fig. 24 Attitude responses and their respective rates when rotor R1 stopped but R3 is flipped 45º without the effect of R3 torque included.

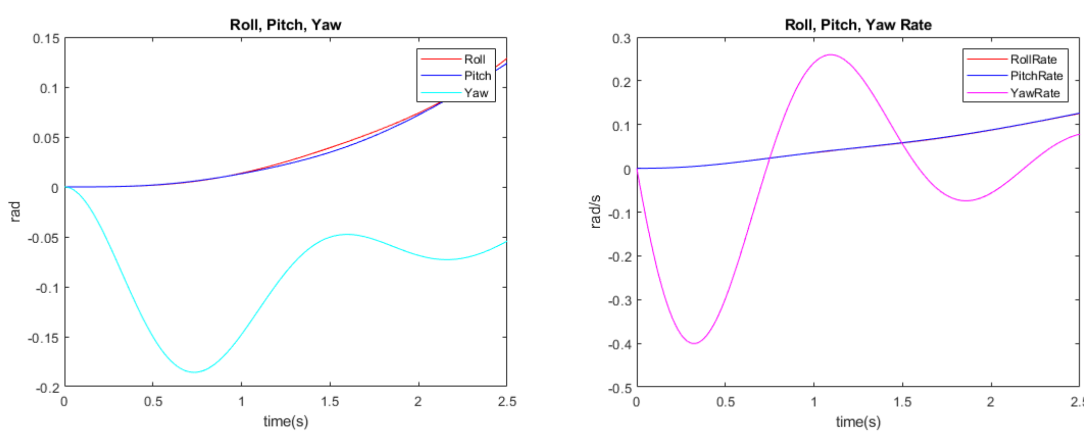
From the test, this effort appeared to have little effect on improving the performance of the drone to land as safely as possible. Case H showed that it was not the roll and pitch that should be penalized but instead, it was the yaw feedback loop that ultimately could improve the performance of the crippled drone.

H. Case H: Penalizing Yaw Feedback Loop



(a) (b)

Fig. 25 Responses in location change and rotor speeds when rotor R1 stopped but R3 is flipped 45º with the effect of R3 torque included



(a) (b)

Fig. 26 Attitude responses and their respective rates when rotor R1 stopped but R3 is flipped 45º without the effect of R3 torque included

Penalizing the yaw motion caused a slight improvement in drone responses compared to Case G and Case F. The results from all tested cases are tabulated in Table II and Table III. At this point it is beneficial to recall the purpose of these tests which is to attempt to land the QD as safely as possible by reducing altitude gradually and maintaining roll, pitch, yaw and their rates at zero or as close to zero as possible.

I. Landing as Safely as Possible (ASAP)

For a QD that has suffered some malfunction, some target on the quality of flight and landing is necessary for designers to aim. In this paper, that quality has been grossly simplified which is to simply land the drone as gradually as possible while keeping attitude change in roll, pitch, yaw, and their rates, as small as possible. Tables II and III shown below summarize the results from the QD simulation tests.

TABLE II PEAK VALUES RECORDED IN ROLL, PITCH, AND YAW AFTER FAILURE BEFORE TOUCH-DOWN FROM 10M

Cases	Time To Land (s)	Roll (rad)	Pitch (rad)	Yaw (rad)
B	1.8	3.2	-1.4	1.5
C	2.3	0	0	-3.3
D	2.7	0	0	0.3
E	2.4	-3.3	-1.5	-3.3
F	2.1	0.002	0.1	-0.18
G	2.3	0.1	0.1	-0.18
H	2.1	0.05	0.05	-0.18

TABLE III ROLL, PITCH AND YAW RATES DURING TOUCH-DOWN

Cases	Time To LaND (s)	Roll RatE (rad/s)	Pitch RatE (rad/s)	Yaw Rate (rad/s)
B	1.8	-5.5	-5.6	-2.5
C	2.3	0	0	-12
D	2.7	0	0	-0.05
E	2.4	3.3	3.4	-9
F	2.1	0.01	0.1	-0.05
G	2.3	0.1	0.1	0.1
H	2.1	0.05	0.05	-0.08

From Table II and Table III, an improvement in the control of roll, pitch, and yaw along with their rates is seen in Case H. Comparing Case B and Case H, tilting the rotor R3 by 45^o after R1 stopped improved the attitude of the drone. By penalizing heavily, the yawing moment, and adjusting the feedforward thrust separately in the remaining working rotors R2, R4 and the tilted R3, it was possible to accomplish 'better management of attitude control' of the crippled QD. Although it would be favorable to slow down the descent rate of the crippled drone, the technique proposed in this paper did not show significant improvement in producing that result. This was probably due to the limited option evaluated, i.e., tilting the rotor R3 by 45 degrees only was considered when the rotor could be made to not just tilt but also to pan at various angles. Much work can be explored in the future to improve this capability by considering full thrust vectoring on all 4 rotors, instead of just 1, in the attempt to rescue a crippled quadrotor drone.

V. CONCLUSION

This paper proposes a new method to tackle the problem of fault tolerance in quadcopter drones. A single faulty rotor upset the balance of forces and moments on the drone and the method considered tilting a rotor opposite the faulty rotor to restore the balance. The proposal is not conventional to existing quadrotor drones. 2 tilt angles were considered: 90^o and 45^o. The results showed a favorable outcome in rescuing the drone from uncontrollable descent. The study observed an improvement in managing the crippled drone's attitude. Additionally, studying the benefits of variable angle changes by panning and tilting individual rotors to rescue multiple-rotor failures on quadrotor drones can be an interesting idea to explore. Further research in this area, including actual flight testing, can help to validate and refine these theories.

NOMENCLATURE

F_b - sum of all forces in relation to body-axis (N)

m - mass of drone (1kg)

V_b - translational velocity (m/s)

ω - angular velocity (rad/s)

M_b - sum of all moments in relation to body-axis (Nm)

I - inertia matrix

I_{ii} - moment of inertia

I_{ij} - product of inertia $(i \neq j)$

ϕ - bank angle (rad)

θ - pitch angle (rad)

ψ - yaw angle (rad)

p, q, r - angular velocity components along body axis (rad/s)

x, y, z - drone relative location coordinates

u - forward velocity (m/s)

v - side velocity (m/s)

w - yawing velocity (rad/s)

F_x, F_y, F_z - force components along body-axis (N)

M_x - moment about rolling axis (Nm)

M_y - moment about pitching axis (Nm)

M_z - moment about yawing axis (Nm)

T_h - total thrust model for hovering (N)

k_P - Proportional gain

k_D - Derivative gain

g - gravitational acceleration (m/s^2)

k_p - propeller constant

k_m - motor constant

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