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Dynamic Thrust Redistribution System for Coaxial Hexacopter H-Frame Under Motor Failure Contingencies N-1

Shankar Subramaniam[1], Mohd Aifaa bin Mohd Ariff[1*]

[1] Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, Parit Raja, 86400, Johor, MALAYSIA

*Corresponding Author Designation

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Abstract: Unmanned aerial vehicles (UAVs) have crucial applications across industries, emphasizing the importance of maintaining stability and preventing crashes, particularly in the event of motor failure. The research highlights motor failure as a significant cause of UAV crashes and its potential consequences, such as damage to batteries and agricultural productivity. The research involves creating a simulation model of a coaxial hexacopter's propulsion system, designing a control system for stability during motor failure, and analyzing the system's performance in terms of pitch, roll, and yaw axis and speed of motor. The project's scope focuses on a specific motor failure scenario in a coaxial hexacopter with an H-frame configuration, utilizing Simcenter Amesim software for comprehensive modeling and analysis. The findings demonstrate that the hexacopter successfully stabilized after applying the contingency counter, which involved increasing motor speed to generate more thrust and stabilize the frame. The hexacopter briefly descended by 0.2 meters, then slowly returned to the desired altitude. This showed that the hexacopter could keep its altitude stable even with a defective motor. The coaxial configuration and selective motor activation facilitated easy stabilization by redistributing thrust. The future works of this research include validating the simulation model with real-world data, enhancing the hexacopter response and stability with advanced control algorithms, and refining the simulation model with advanced techniques and data.

Keywords: Coaxial Hexacopter, PID Tuner, Thrust Redistribution,

1. Introduction

The project revolves around unmanned aerial vehicles (UAVs), specifically multirotor drones, which are commonly used in various industries and sectors [1]. These drones offer operational efficiency and precise controls, making them suitable for tasks such as crop monitoring, land mapping, and aerial surveillance [2]. However, the limitations of current battery technology result in shorter flight times when carrying heavier loads.

**Corresponding author: aifaa@uthm.edu.my*

To address the issue of reliability and prevent crashes, the research aims to develop a contingency counter to maintain stability in the event of motor failure. Motor failure can lead to catastrophic damage to both the drone and its payload. The project will focus on managing motor failure-related contingencies to ensure safe landings or returns to launch. The research emphasizes the significance of stability and safety, as drone crashes can have damaging consequences, including environmental impacts and compromised agricultural productivity [3]. The research includes creating a simulation model of a coaxial hexacopter's propulsion system in an H-frame configuration [4], designing a control system to redistribute thrust during motor failure, and analysing the performance of the control system in terms of pitch, roll, yaw axis and motor speed. The scope of the project specifically focuses on the configuration of a coaxial hexacopter in an H-frame design, which provides stability and lifting capability [5]. The coaxial rotor configuration with dual rotors positioned both above and below the arm structure contributes to enhanced stability, reduced noise, and increased lifting capacity [6]. The project utilizes the Simcenter Amesim software to model the hexacopter's propulsion system accurately. The propulsion system configuration is crucial for maintaining stability during contingencies, and the thrust output is determined by factors such as the rotational speed of the brushless DC motor and the pitch and diameter of the propellers [7].

Overall, the research aims to develop a control system and simulation model that ensure stability and prevent crashes during motor failure contingencies in multirotor drones, specifically the coaxial hexacopter in an H-frame configuration.

2. Materials and Methods

2.1. Block Diagram

The block diagram presented in Figure 1 showcased the intricate equipment configuration involved in modeling a coaxial hexacopter, emphasizing the technical aspects of the system. To attain accurate control over the motor and propeller speed, a Proportional Integral Derivative (PID) controller was employed. This controller acted as a crucial component, receiving set point or trajectory instructions that guided the desired behaviour of the hexacopter. It diligently tuned the motor and propeller speed based on the feedback received from dedicated sensors.

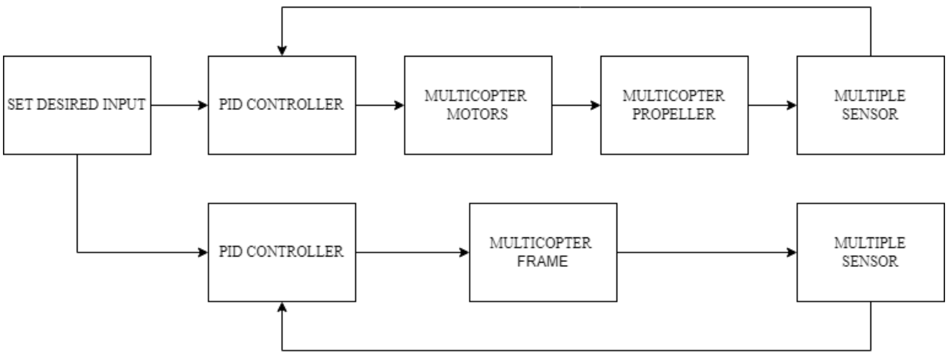

Figure 1: The operational block diagram of the Coaxial Hexacopter H-Frame

However, controlling the hexacopter's motor and propeller speed was just one aspect of ensuring stable and controlled flight. An additional PID controller was implemented to further refine the stability and movement of the hexacopter's body. This second controller operated in conjunction with the sensor feedback to actively adjust the hexacopter's dynamics. By analyzing the information obtained from the sensors, the PID controller was capable of making precise corrections to optimize the hexacopter's stability and trajectory. By integrating PID control with sophisticated sensor feedback mechanisms, the coaxial hexacopter achieved exceptional levels of performance and maneuverability. The PID controllers acted as intelligent regulators, constantly monitoring the hexacopter's behaviour and making timely adjustments to maintain stability and adherence to the desired trajectory. This level of control empowered the hexacopter to execute complex maneuvers with precision, enabling it to navigate through challenging environments and execute intricate flight patterns.

2.2. Materials

The propulsion system of the coaxial hexacopter (H-frame) consists of six arms, each mounted with three pairs of fixed pitch propellers. The motors used in the project are brushless DC slot-less motors from the brand Portescap, specifically the 30ECT64 Ultra EC model [8]. These motors are simulated in Simcenter Amesim using the functional electric drive - quasi-static model. The hexacopter is powered by a battery pack consisting of 8 lithium-ion cells in series and 2 cells in parallel. The specific battery cells used are 3.7V 18650 lithium-ion cells NCR18650G from Panasonic [9]. This battery was preferred more compared to lithium polymer due to higher energy density as it can store more energy per unit of weight for longer flight times [10]. The battery parameters include a state of charge of 60%, cell capacity of 3.6Ah, and a temperature of 20°C. The propellers used for the hexacopter are fixed-wing propellers in a coaxial configuration.

Figure 2 shows three pairs of propellers rotating in a clockwise direction, while the other pair rotates in a counter-clockwise direction. The propeller radius is 0.2 meters as the frame size of the hexacopter was designed to accommodate the propeller size [11]. The propellers rotate in the same direction. The motors are positioned with a length of 0.8 meters apart from left to right and 0.8 meter from top to bottom. The motor mixing algorithm for the hexacopter-H frame is different from a quadcopter's motor mixing algorithm. The algorithm accounts for the specific configuration and angles of the hexacopter's motors to control the pitch, roll, altitude, and yaw movements.

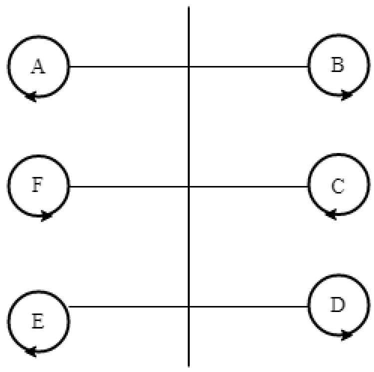

Figure 2: The direction of rotation of the propellers for both top and bottom motors

Table 1 shows the power distribution to the motors is determined based on the desired movements. The hexacopter's trajectory is defined by desired set points, which specify the pitch distance, roll distance, altitude distance, and yaw rotation at specific time intervals. The control loop of the hexacopter includes sensors for measuring position, velocity, stability, angular velocity and motor speed. The control system utilizes various controllers, such as P, PI, PD, and P controllers, to control the hexacopter's movements based on the feedback from the sensors.

Table 1: The motor mixing configuration for hexacopter in H-Frame

Motors	Pitch	Roll	Altitude	Yaw
Motor A	+x	+y	+z	-0.5
Motor B	+x	-y	+z	+0.5
Motor C	0	-y	+z	-1
Motor D	-x	-y	+z	+0.5
Motor E	-x	+y	+z	-0.5
Motor F	0	+y	+z	1

2.3 Counter Contingency Algorithm

Figure 3 shows the contingency counter algorithm during motor failure. The hexacopter was initially designed with a single rotor configuration, but it soon became evident that it lacked the necessary thrust to perform optimally. As a result, a coaxial configuration was adopted, which proved to be more effective. The coaxial setup offers a more even distribution of thrust, with 50% of the output thrust generated by the top rotors and 50% by the bottom rotors, all rotating in the same direction. This distribution helps to minimize torque and ensures a balanced thrust output. In the event of a motor failure, such as one of the top rotors turning off due to a malfunction, the corresponding clockwise top rotor will also cease operation. Similarly, all the counter-clockwise bottom rotors will stop functioning. Consequently, only the bottom clockwise motors will remain active, along with the top counter-clockwise motors. This configuration ensures a consistent and even distribution of thrust, allowing the hexacopter to maintain its hovering position steadily and efficiently.

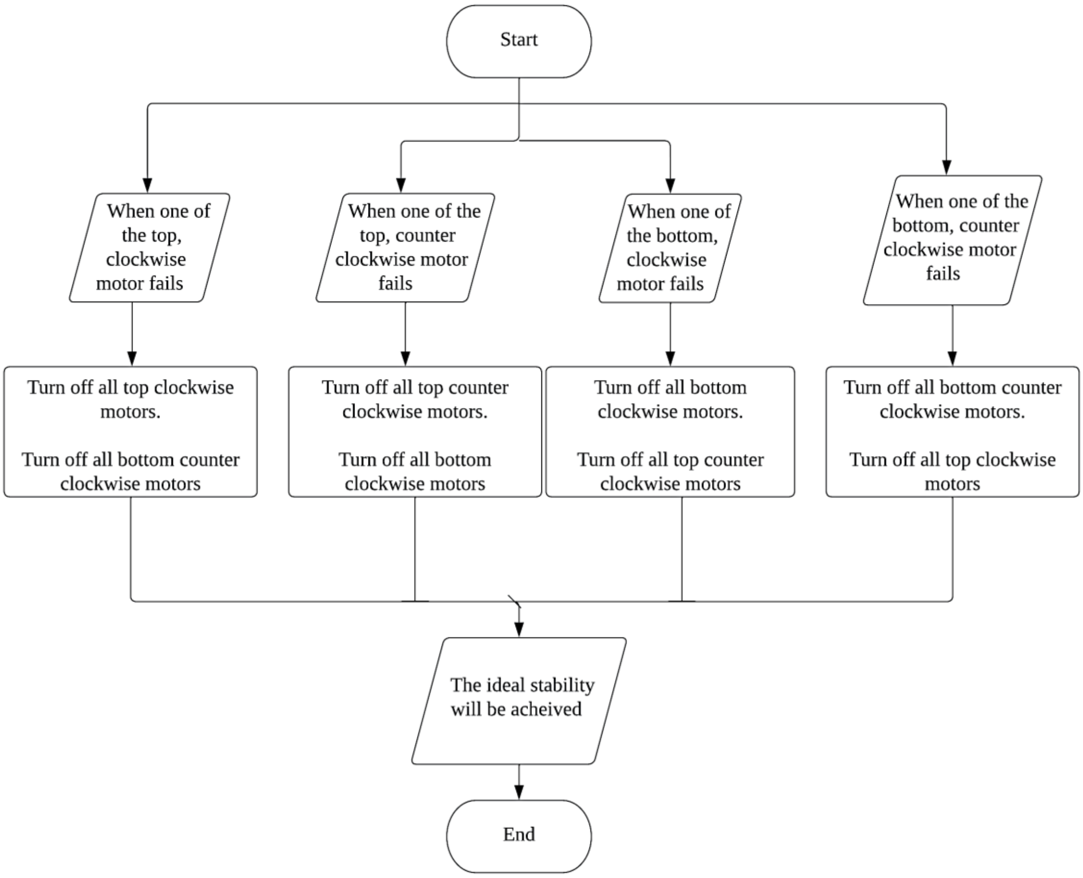

Figure 3: Contingency counter during motor failure flowchart

3. Results and Discussion

This study aims to analyze the stability of a hexacopter in three distinct scenarios which is during pre-motor activation, motor failure, and post-implementation of a motor failure contingency countermeasure. The assessment will focus on roll, pitch, and yaw stability, along with motor active status analysis. These investigations will provide valuable insights into the hexacopter's dynamic behaviour, enhancing its overall effectiveness and reliability.

3.1 Motor Active Status.

The provided motor configuration Table 2 showcases the status of each motor before motor failure, during motor failure, and after the motor failure contingency countermeasure implementation. The "1" values indicate motors that are functioning, while the "0" values indicate motors that are turned off. In the coaxial hexacopter design, a configuration was adopted where 50% of the thrust output is generated by the top rotors and 50% by the bottom rotors. This arrangement ensures a balanced distribution of thrust and minimizes torque effects. The top and bottom rotors rotate in the same direction to maintain stability.

During motor failure, if a top rotor fails and turns off, the corresponding clockwise top rotor will also cease operation. Likewise, all counterclockwise bottom rotors will stop functioning. This configuration ensures that only the bottom clockwise motors and the top counterclockwise motors remain active. This design approach guarantees a consistent and even distribution of thrust, even in the event of a motor failure. By having a combination of active top and bottom motors, the hexacopter can maintain its hovering position steadily and efficiently, compensating for the loss of thrust caused by the failed motors.

Table 2: The motor active status before motor failure, during motor failure and after counter contingency implemented

Motor	Before Motor Failure	During Motor Failure	Counter Contingency
Top Motor B	1	1	1
Top Motor D	1	1	1
Top Motor A	1	0	0
Top Motor E	1	1	0
Top Motor F	1	1	1
Top Motor C	1	1	0
Bottom Motor B	1	1	0
Bottom Motor D	1	1	0
Bottom Motor A	1	1	1
Bottom Motor E	1	1	1
Bottom Motor F	1	1	0
Bottom Motor C	1	1	1

3.2 Altitude Trajectory

Figure 4 shows throughout the 120 seconds, before any motor failure occurred, the hexacopter showcased a relatively consistent trajectory in the altitude axis, closely following the set point. However, slight deviations were observed, attributed to the system's response time in adjusting the motor speed to modify the hexacopter's altitude. Additionally, the presence of wind disturbance at a 6th scale on the Beaufort scale contributed to the non-smooth trajectory line.

When an actual motor failure occurred at the 72nd second, the hexacopter's altitude trajectory significantly diverged from the set point. It experienced a crash landing initially and then deviated to the left by approximately 100 meters. At the 82nd second, the hexacopter attempted to compensate for the power imbalance caused by the motor failure by increasing its hovering altitude. However, it failed to maintain stability, leading to a further deviation from the set point. Upon activating the motor failure contingency countermeasure, the hexacopter's altitude dropped momentarily by 0.2 meters before gradually regaining the set point altitude. This countermeasure demonstrated some effectiveness in stabilizing the hexacopter's altitude despite the motor failure.

Overall, the trajectory analysis indicated that the hexacopter exhibited relatively similar altitude trajectories before and after motor failure, with minimal deviation when six motors were operational instead of all twelve. This suggests that the coaxial hexacopter design showed promising reliability in adhering to the desired altitude set points, albeit with some limitations and challenges during motor failure scenarios.

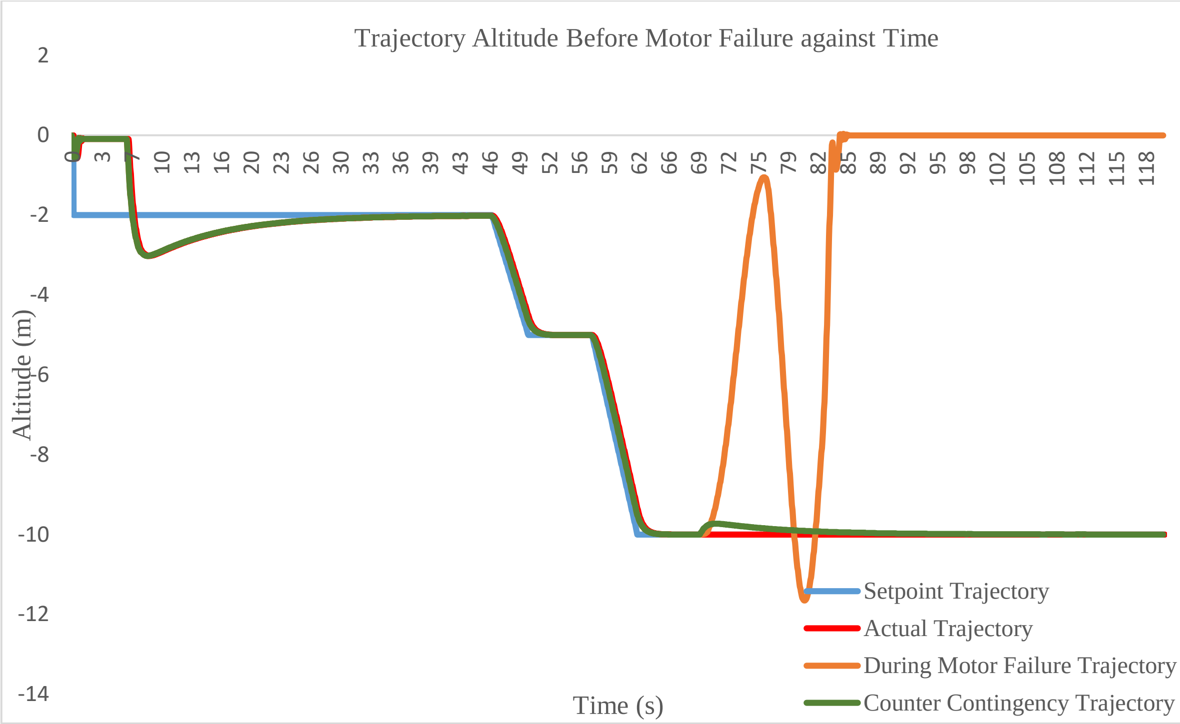

Figure 4: Altitude trajectory for setpoint, actual, during motor failure and after counter contingency were implemented

3.3 Axes Stability.

Table 3 shows the rotary position sensor was utilized to measure the angle of the roll, pitch, and yaw axes before, during, and after motor failure contingency. Prior to motor failure, the roll axis showed a slight deviation of -0.426446°, while the pitch axis remained relatively stable at 0.423545°. The yaw axis exhibited a minor angular deviation of1.36772°. However, during motor failure contingency, significant deviations were observed. The roll axis experienced an average angle of 0.609473°, the pitch axis suffered a severe disruption of -179.614000°, and the yaw axis encountered a substantial deviation of -122.009000°. After implementing the failure contingency measures, the roll axis returned to a slightly deviated state of -0.433149°, the pitch axis recovered to 0.411302°, and the yaw axis reached a deviated angle of -0.946685°. These findings emphasize the impact of motor failure on the hexacopter's orientation and highlight the effectiveness of the implemented measures in restoring the desired positions, although deviations remained.

Table 3: The average degree of angle in terms of roll, pitch and yaw axes during before motor failure, during motor failure and after failure contingency counter

Axes	Average Degree of Angle (°) (Before Motor Failure)	Average Degree of Angle (°) (During Motor Failure)	Average Degree of Angle (°) (After Failure Contingency Counter)
Roll	-0.426446	0.609473	-0.433149
Pitch	0.423545	-179.614000	0.411302
Yaw	1.36772	-122.009000	-0.946685

These measurements provide valuable insights into the behaviour of the rotary position along different axes before, during, and after motor failure. They illustrate the impact of motor failure on the hexacopter's orientation and highlight the effectiveness of the implemented contingency measures in restoring the desired position. When a motor failure occurred, disturbing the balance and symmetry of the hexacopter system, it had a significant impact on stability. The PID controller, which relied on the assumption that all motors functioning properly, struggled to correct the imbalance. As a result, the hexacopter deviated from its intended flight trajectory. These findings underscore the importance of maintaining all motors in proper working order for optimal hexacopter stability. They also highlight the need for robust contingency measures and controller adjustments to mitigate the effects of motor failures and restore the hexacopter's desired orientation and trajectory.

4. Conclusion

In conclusion, this study developed a precise simulation model of a hexacopter's propulsion system using Simcenter Amesim software. The model successfully analyzed the motor status and stability during a simulated motor failure event. By implementing asymmetrical motor shut down control, the hexacopter maintained stable hovering despite the motor failure. Motor speeds were adjusted using PID tuning and set point trajectory for precise control. The motor failure caused a loss of thrust and disturbed the hexacopter's balance, leading to a crash. However, the remaining active motors strategically compensated for the failure, showcasing adaptability and stability. Average motor speeds decreased during the failure but partially recovered afterward, indicating successful stabilization. The hexacopter briefly descended by 0.2 meters, then slowly returned to the desired altitude. This showed that the hexacopter could keep its altitude stable even with a broken motor. This research provides insights into hexacopter behaviour, aiding in refinement and optimization for improved reliability and performance. The findings contribute to advancing hexacopter technology, enabling safer and more efficient practical applications.

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