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# Hovering Recovery Strategies for Single Rotor Inoperative Quadcopter

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**Abstract**

Quadcopter; a four rotors helicopter is commonly used for Unmanned Aircraft System (UAS) mission and popular amongst hobbyists. However, in the event of single rotor failure, the quadcopter loses 25% of its lifting capability and enters roll and yaw motions before falling to the ground. Thus, an immediate response is for the quadcopter to regain its hovering capability. The objective of this paper is to examine the available hovering recovery strategies in order to prevent a quadcopter from losing its altitude and attitude in the event of single rotor failure. The advantages and disadvantages of each of these strategies are evaluated. It is concluded that Center of Mass Re-adjustment Strategy is the best hovering recovery strategy as it provides stable roll and pitch in hovering flight with minor yaw and spin motions.

**Keywords:** Center of Mass Re-adjustment, hovering recovery strategy, single rotor failure, quadcopter.

## INTRODUCTION

Quadcopter is a multi-rotor helicopter, which operates with four vertically oriented rotors. By controlling each of its propeller speed and rotational direction, a quadcopter has the capability in performing Six Degrees of Freedom (6-DOF) flying motions. Owing to its agility, quadcopter is used in several Unmanned Aircraft System (UAS) missions such as reconnaissance, surveillance, photogrammetry, and cinematography. The aircraft is also popular amongst hobbyists due to its easiness to fly and affordability [1]. With proven quadcopter technology, a Chinese unmanned-aircraft manufacturer, Ehang introduced an autonomous single-passenger air taxi in July 2017 [2].

Quadcopter rotors configuration has four identical motors, turning either counter-clockwise (CCW) or clockwise (CW). These rotors produce thrusts to lift the aircraft while the vehicle motions are controlled by regulating the thrust as illustrated in Figure. 1.

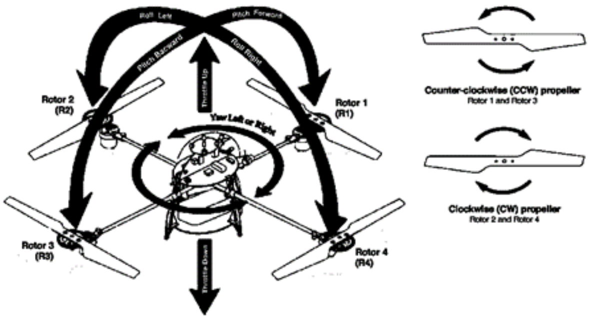


**Figure 1:** Quadcopter Hardware and its Range of Motions

Propulsion control in quadcopter flight control system regulates each rotor speed values, $\varpi_i$ to achieve specific control objectives, which governs the vehicle motion. The control objectives are resultant thrust $F_T$, roll torque $M_\phi$, pitch torque $M_\theta$, yaw torque $M_\psi$, propeller thrust coefficient factor $c_T$, propeller drag coefficient factor $c_Q$ and d is the length from quadcopter center to rotor, as illustrated in Figure 2.

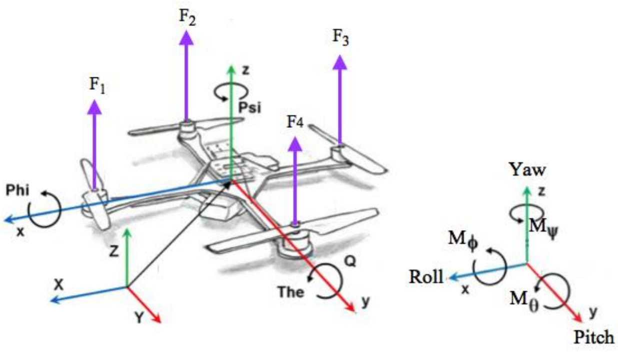


**Figure 2:** Quadcopter Body-fixed Frame

Adopting equations introduced by [3] and [4], all the control objectives can be written in matrix form as shown below.

$$\begin{bmatrix} F_T \\ M_\phi \\ M_\theta \\ M_\psi \end{bmatrix} = \underbrace{\begin{bmatrix} c_T & c_T & c_T & c_T \\ 0 & -dc_T & 0 & dc_T \\ -dc_T & 0 & dc_T & 0 \\ -c_Q & c_Q & -c_Q & c_Q \end{bmatrix}}_{\Gamma} \begin{bmatrix} \varpi_1{}^2 \\ \varpi_2{}^2 \\ \varpi_3{}^2 \\ \varpi_4{}^2 \end{bmatrix} \quad (1)$$

In the event of single rotor failure, the coefficients in each row of matrix Γ associated to the rotor will become zero. For example, if Rotor 4 fails, $\varpi_4$ becomes zero and (1) becomes;

$$\begin{bmatrix} F_T \\ M_\phi \\ M_\theta \\ M_\psi \end{bmatrix} = \underbrace{\begin{bmatrix} c_T & c_T & c_T & 0 \\ 0 & -dc_T & 0 & 0 \\ -dc_T & 0 & dc_T & 0 \\ -c_Q & c_Q & -c_Q & 0 \end{bmatrix}}_{\Gamma} \begin{bmatrix} \varpi_1^2 \\ \varpi_2^2 \\ \varpi_3^2 \\ \varpi_4^2 \end{bmatrix} \quad (2)$$

Immediate effect of single rotor failure is the quadcopter experiences 25% loss in its lifting capability, followed by unbalanced roll and yaw torques. The quadcopter starts to lose its altitude and experiences roll and yawing moments. Since quadcopter is commonly flown in civil airspace, safety consideration is the utmost top priority to ensure that any rotor failure occurrence during flight would not endanger the vehicle itself, properties and civilians. Thus, an immediate response is for the quadcopter to be able to hover before resuming its initial tasks. A robust control is needed to address this situation.

## HOVERING RECOVERY STRATEGIES

There are several hovering recovery strategies that can be employed in the event of single rotor failure. Each recovery strategy is thoroughly discussed and its advantages and disadvantages highlighted.

### 1 Rotor redundancy

The simplest way to reduce the risk of losing altitude in the event of single rotor failure is to introduce rotor redundancy which leads to the design of hexacopter and octocopter; a six rotors and an eight rotors helicopters. According to [5] and [6], Control Allocation (CA) technique is applied in these helicopters to accommodate with rotor failure. CA will determine an optimal set of rotor speed combination to back-up the loss rotor thrusts.

Another advantage of hexacopter and octocopter is their ability to transport heavier payload than quadcopter since rotor redundancy offers higher thrust output. Nevertheless, due to heavier and higher power consumption, both vehicles have minor differences in flight endurance when compared to a quadcopter [7].

Thus, there is no significant advantage on using hexacopter or octocopter over quadcopter. Furthermore, these helicopters are more expensive than quadcopter.

### 2 Oversized motor strategy

Contrary from the Rotor Redundancy Strategy, Oversized Motor Strategy works by turning off the motor located opposite to the failed rotor while at the same time, the two remaining rotors lifting capacities are raised by 200% to compensate for the loss of lift. Although this strategy able to solve the quadcopter hovering and spinning problems, it's not effective as all rotors can only operate at half of its capacity during normal operation. Quadcopter not only becomes very heavy and has shorter endurance, but also expensive because it is equipped with a larger motor.

### 3 Yaw spinning strategy

Yaw spinning strategy was first introduced by [8] and further improved in terms of control optimization by [9], [10] and [11]. The idea behind this strategy was to employ its degraded motion, which is the unstoppable spin in yaw direction into an advantage by conserving its vertical momentum. Thus, a success flight was achieved by sacrificing its yaw stability. The following is the propulsion control law for the yaw spinning strategy in the event of Rotor 4 failed.

$$\begin{bmatrix} F_T \\ M_\theta \\ M_\psi \end{bmatrix} = \begin{bmatrix} c_T & c_T & c_T \\ -dc_T & 0 & dc_T \\ -c_Q & c_Q & -c_Q \end{bmatrix} \begin{bmatrix} \varpi_1^2 \\ \varpi_2^2 \\ \varpi_3^2 \end{bmatrix} \quad (3)$$

From (3), the control law has only three control objectives ($F_T$, $M_\theta$ and $M_\psi$) to regulate the required rotor speeds $\varpi_1, \varpi_2, \varpi_3$. This motion is obtained when another rotor laying on the same axis of failed rotor, continue its velocity until the angle value of the affected axis is zero. Meanwhile, the opposite axis healthy pair of rotors controls the lift for altitude correction.

Mueller succeeded in using this strategy for single rotor failure situations [12]. This method was also proved by [13] and [14] to obtain a successful safe emergency landing to the ground. Although spinning motion strategy could only correct the altitude level and not eliminating the residual yaw motion, it is the most relevant non-hardware intrusive method as of now in stabilizing a quadcopter experiencing single rotor failure.

### 4 Controllable pitch propeller strategy

Controllable pitch propeller is a unique propeller, which can produce positive and negative thrust output without changing the rotor rotation direction. A servo will change the propeller pitch while it is rotating. Lo proposed this strategy in order to reverse the thrust while maintaining the same rotor rotation direction to balance the vehicle yaw [15]. This will reduce the pitch effect with negative thrust.

$$\begin{bmatrix} F_T \\ M_\phi \\ M_\theta \end{bmatrix} = \begin{bmatrix} c_T & c_T & c_T \\ 0 & -d\varpi_2{}^2 & 0 \\ -dc_T & 0 & dc_T \end{bmatrix} \begin{bmatrix} \varpi_1{}^2 \\ -\frac{M_\phi}{d\varpi_2{}^2} \\ \varpi_3{}^2 \end{bmatrix} \qquad (4)$$

As seen in (4), the controllable pitch propeller requires virtual speed regulation in order to control Rotor 2. Thus, roll and pitch stabilization is achieved. However, the vehicle still spins in the yaw direction in high frequency. This strategy also requires special motor which able to control the propeller pitch angle.

## 5 Center of mass re-adjustment strategy

Center of Mass (CM) is essential to the attitude stability of a flying vehicle including quadcopter. In a well-balanced quadcopter, CM usually located at the very center of a square body. Lo [15] and Merheb [16] proposed modifying the CM location of a quadcopter during single rotor failure The strategy was by adding a dead weight to a new vehicle's CM location fixed to specific point and varying the rotor speed to stabilize its roll and yaw. A tail rotor; denote as $R_2$ in Figure 3, is defined out of three operating rotors.

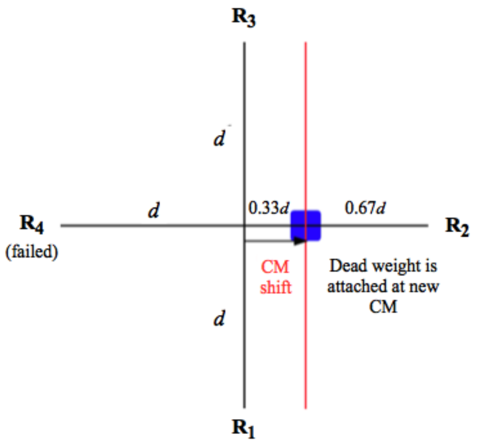


**Figure 3**: Location of Deadweight

The influence of the deadweight enables the CM to be adjusted at 1/3 length away from the previous CM and nearing towards designated tail rotor. With that, the input matrix established is

$$\begin{bmatrix} F_T \\ M_\phi \\ M_\theta \end{bmatrix} = \begin{bmatrix} c_T & c_T & c_T \\ -dc_T & 0 & dc_T \\ \frac{1}{3}dc_T & -\frac{2}{3}dc_T & \frac{1}{3}dc_T \end{bmatrix} \begin{bmatrix} \varpi_1{}^2 \\ \varpi_2{}^2 \\ \varpi_3{}^2 \end{bmatrix} \qquad (5)$$

In addition, attaching the dead weight on tail rotor shifts the CM towards tail rotor [16]. Both [15] and [16] simply adopt a tri-rotor helicopter control formulation with the yaw servo angle μ=0 and different rotor rotation pair. The input matrix established is

$$\begin{bmatrix} F_T \\ M_\phi \\ M_\theta \\ M_\psi \end{bmatrix} = \begin{bmatrix} c_T & c_T\cos\mu & c_T \\ -dc_T & 0 & dc_T \\ xc_T & -(d-x)c_T\cos\mu & xc_T \\ c_Q & -(1-\sin\mu)c_Q & -c_Q \end{bmatrix} \begin{bmatrix} \varpi_1{}^2 \\ \varpi_2{}^2 \\ \varpi_3{}^2 \end{bmatrix} \qquad (6)$$

Uniquely, stable roll and pitch in flight are achieved but minor yaw and spin motions still occur; similar to other strategies. However, this strategy introduces a new question the ideal location of the new CM location. In addition, each of the three remaining rotor must increase their lifting capability by 33.3%.

## CONCLUSION

Five hovering recovery strategies are discussed in this paper. The advantages and disadvantages of these strategies are tabulated in Table 1.

**Table 1**: Hovering Recovery Strategies Comparison

| **Strategy** | **Advantages** | **Disadvantages** |
|---|---|---|
| 1. Rotor Redundancy | • Able to hover with slight spinning motion<br>• Able to transport heavier payload. | • Heavy weight and higher power consumption.<br>• Expensive.<br>• No significant advantage in flight endurance. |
| 2. Oversized Motor | • Able to hover without spinning motion. | • Not effective as all rotors operate at half of its capacity during normal operation.<br>• Heavy and has shorter endurance.<br>• Expensive. |
| 3. Yaw Spinning Strategy | • Able to hover due to spinning motion<br>• Proven strategy | • Yaw and spinning motion. |
| 4. Controllable Pitch Propeller Strategy | • Able to hover in spinning motion | • Yaw and spinning motion.<br>• Requires special motor which able to control propeller pitch angle. |
| 5. Center of Mass Re-adjustment Strategy | • Able to hover with minor yaw and spin motions | • Carry dead weight and mechanism to move the dead weight. |

From this analysis, Center of Mass Re-adjustment Strategy is the preferred strategy since it provides stable roll and pitch in hovering flight with minor yaw and spin motion to the quadcopter in the event of single rotor failure. Although this strategy involves an additional dead weight and special mechanism to move the dead weight, most quadcopters are equipped with camera and the camera will act as the dead weight. Slightly bigger thrust generating motors are also required.

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