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Tutorial:

A Review on Recent Development of Multirotor UAV Fault-Tolerant Control Systems

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The past decades have witnessed an increase in the use of multirotor unmanned aerial vehicles (UAVs). This has led the way to the development of fault-tolerant control (FTC) algorithms to service the different applications provided by these UAVs in different situations and circumstances. This tutorial is concerned with theoretical approaches and real practices for fault detection and diagnosis (FDD) and FTC of multirotor UAVs, namely, quadrotors, hexarotors, and octorotors. The topic is addressed by identifying the most significant faults and failures on these vehicles, the different FDD and FTC architectures, as well as the experimental real-time validations available in the published literature. A review of some challenges in the general area of multirotor UAV FTC design is further concluded.

INTRODUCTION

Multirotor unmanned aerial vehicles (UAVs) are vertical take-off and landing aerial vehicles with many potential applications ranging from search and rescue missions to inspection of power lines, bridges, and barrages [1]. Commercial corporations are researching, for example, the use of quadrotors for packages delivery [2], and medical groups for quick delivering of medical supplies to areas with limited road access [3]. Multirotor UAVs are mainly characterized by their hovering, vertical take-off and landing, and aggressive maneuvering abilities. They consist typically of an even number of propellers arranged in pairs of counter-rotating ones to afford directional control. Their motion control is performed by varying the rotation rate of the propellers, thereby changing their thrust and torque load characteristics. The quadrotor (see Figure 1) is a popular multirotor that is propelled by four rotors. It uses two clockwise and two counterclockwise fixed-pitch propellers. Due to their small size, mechanical simplicity, and agile maneuverability, quadrotors have become very popular in UAVs research. As the interest in quadrotors as testbeds grows, a lot of papers are published on more efficient and new control methodologies. Among the several proposed techniques for fault-free case, we can cite, for example, the linear quadratic [4], H-infinity [5], backstepping [6], or sliding mode [7]. Although redundant multirotors (hexarotors and octorotors) (see Figure 1) may present a weight and energy consumption augmentation compared with the quadrotors because of the extra motors, they have increased load capacities and improved survivability and reliability due to the motors redundancy [8]. The modeling and controller design problems of these systems are similar to those of a quadrotor with only the differences resulting from the aerodynamic forces and torques generated by the rotors (See [9] and [10] for hexarotors and [11] and [12] for octorotors). Other unmanned vehicles can be also considered a type of multirotor UAV, but with additional capabilities, such as the tail-sitter UAV that consists of two rotors. It combines features of both fixed-wing aircraft and multirotor drones. It takes off and lands vertically like a multirotor, but transitions to horizontal flight like a fixed-wing aircraft [13].

The introduction of these systems into the airspace that has been traditionally dominated by manned flights leads to multiple safety matters, such as potential ground and air

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collisions [14], [15]. Multiple crashes of commercial UAVs were reported during the last years [16], leading to injuries and losses of the UAVs [17], [18]. It is necessary to ensure that these vehicles fail less often, and in the worst scenario, they are able to recover and complete the mission. This has led the way to large studies in the field of fault-tolerant control (FTC) and diagnosis for these systems. Besides fault prediction, fault prevention, and fault elimination, FTC is one of the means to attain dependability [19] by allowing the system to perform its operation correctly even in the presence of faults. A bibliographical overview on FTC architectures can be found in [20].

FTC and fault diagnosis are crucial aspects of ensuring safe and reliable operation of UAVs. Fault tolerance involves designing control systems that can continue to operate effectively in the presence of faults or failures, such as a motor or sensor failure. This can involve using redundant components or developing algorithms that can adapt to changes in the system.

Fault diagnosis, on the other hand, involves detecting and identifying faults or failures in the system as soon as possible. This is critical for maintaining the safety and reliability of the UAV. Fault diagnosis can be achieved through various methods, including sensor fusion, observer-based methods, and model-based methods.

For multirotor UAVs, these aspects can be particularly challenging due to the complex dynamics and the large number of components involved. However, there has been significant research in this area, with various approaches being proposed, such as model-based fault diagnosis, adaptive control, and redundancy-based FTC.

FTC techniques can be categorized into passive and active approaches [21], [22]. The passive architecture is achieved without any need for online fault information, and is based on a fixed robust controller that can compensate for some faults that are supposed to be known prior to the controller design step [23]. This technique is easy to implement, however, it presents a limited fault-tolerance capability, and achieves robustness to faults at the cost of reduced nominal performance. The active FTC architecture is carried out via error detection and system recovery. It compensates for the effect of the fault by using a reconfiguration mechanism to synthesize a new control law online or to select a precomputed control law [24]. The critical matters in this architecture are the restricted time available to detect the fault, the accuracy of the fault identification, and the time needed to reconfigure the control schemes.

MOTIVATION AND CONTRIBUTION

Various survey papers are published prior to 2013, and multiple fault detection and diagnosis (FDD) and FTC techniques applied on manned, fixed-wing, and quadrotor UAVs are summarized [25], [26], [27], [28]. Since then, an extensive number of FTC related publications have appeared on other configurations of UAVs [9], [29], [30]. Besides, some extra effort has examined the real-time implementation [30], differences between active and

Figure 1.
Multirotor UAVs: quadrotor, hexarotor, star-shaped octorotor, and coaxial octorotor.

passive FTC designs [31] and data-driven-based diagnosis [32]. This review considers all these new aspects.

The main contribution of this work is to provide a comprehensive review and analysis of existing literature, highlight the current state-of-the-art FDD and FTC techniques applied on UAV systems, identify gaps in existing technologies, provide insights into the challenges and opportunities of FTC in UAVs applications, and propose future research directions.

ORGANIZATION

The rest of this article is organized as follows. Section "Modeling" presents the general model of a P-rotor vehicle. Section "Fault Classification and Models in Multirotor UAVs" summarizes the potential failure modes of a multirotor UAV. Next, a review on controllability studies, FDD and FTC techniques applied on such systems and published in around 200 papers is presented in sections "Controllability Analysis," "Recent Progress in Multirotor Fault Diagnosis Design," and "Recent Progress in Multirotor Fault-Tolerant Control Design," respectively. Several key open problems are further discussed in the section "Open Problems in Multirotor UAVs Fault-Tolerant Control." Finally, we provide the section "Conclusion."

MODELING

A multirotor is generally composed of several well-modularized components, such as the airframe, propulsion system, sensors, and communication and control modules [33]. It is a complex mechanical system that collects numerous physical effects from the aerodynamics and the mechanics domains and its model should consider all these effects.

Classical methods used to model a multirotor system are the Newton–Euler formulation or the Lagrange equations [34], [35], [36]. The modeling starts by defining the forces and moments that are considered enough to derive a realistic model of the vehicle, such as the forces produced by the motors, the gravity, the gyroscopic effects, and the drag forces and moments.

Multirotor dynamics are given below [37]:

$$\begin{aligned}
&\dot{\zeta} = v \\
&\ddot{\zeta} = -\mathrm{mg} + \mathcal{R}\mathcal{U} \\
&\dot{\mathcal{W}} = \mathcal{T}\Omega \\
&J\dot{\Omega} + \Omega \times J\Omega = \tau
\end{aligned} \tag{1}$$

where $\zeta = [xyz]^T$ and v are the center of mass position and velocity vectors in the inertial frame $R_I\{O_I, x_I, y_I\}$, respectively, $\mathcal{W} = [\phi\theta\ \psi]^T$ is the vector of Euler angles, and $\Omega = [pqr]^T$ is the vector of angular velocities in the body-fixed frame $R_B\{O_B, x_B, y_B\}$. $\mathcal{R}$ is the rotation matrix from the body frame to the inertial frame and $\mathcal{T}$ is the transformation velocity matrix. The multirotor mass is m and $g = [00-9.81]^T$. J is the moment of inertia matrix. $\mathcal{U} = [00u_f]^T$ is the lift vector and $\tau = [\tau_\phi \tau_\theta \tau_\psi]^T$ is the torque vector. τ_ϕ, τ_θ, and τ_ψ are the torques inputs around the body frame axes.

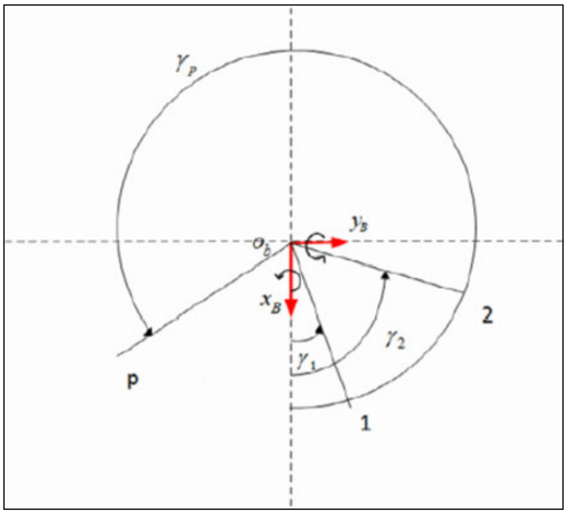


Figure 2.
General P-rotor vehicle.

The angular velocities relation between the inertial and body coordinates are expressed as below [37]:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}. \tag{2}$$

According to the multirotor geometry, the mapping between the total torques and thrust inputs and the rotors lifts is given by the effectiveness matrix B

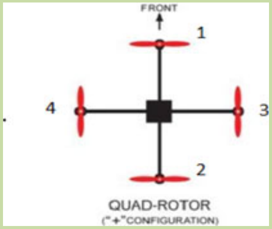
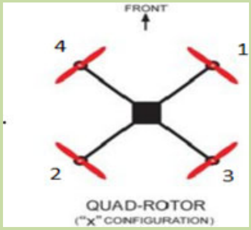
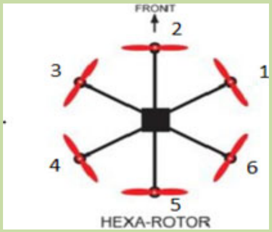
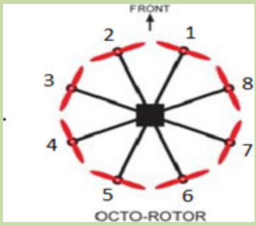
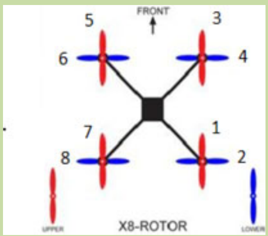
$$\begin{bmatrix} u_f \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = B. \begin{bmatrix} F_1 \\ F_2 \\ . \\ . \\ F_p \end{bmatrix} \tag{3}$$

where F_i is the lift generated by the ith actuator. For any P-rotor UAV (see Figure 2), the control effectiveness matrix in a parametrized form is

$$B = \begin{bmatrix} 1 & 1 & \dots & 1 \\ l_1\sin\gamma_1 & l_2\gamma_2 & \dots & l_P\sin\gamma_P \\ -l_1\cos\gamma_1 & -l_2\cos\gamma_2 & \dots & -l_P\cos\gamma_P \\ \pm K_t/K_f & \pm K_t/K_f & \dots & \pm K_t/K_f \end{bmatrix} \tag{4}$$

where l_i is the length of the ith arm. γ_i is the angle subtended by the ith arm with the x-axis, as shown in Figure 2. The B matrices of the different existing multirotor configurations are given in Table 1. The rotor thrust F_i

Table 1.

Mathematical Models of Different Multirotor Configurations	
	$B=\begin{bmatrix}1&1&1&1\\0&0&l&-l\\-l&l&0&0\\-K_t/K_f&-K_t/K_f&K_t/K_f&K_t/K_f\end{bmatrix}$
	$B=\begin{bmatrix}1&1&1&1\\l\sqrt{2}/2&-l\sqrt{2}/2&l\sqrt{2}/2&-l\sqrt{2}/2\\l\sqrt{2}/2&-l\sqrt{2}/2&-l\sqrt{2}/2&l\sqrt{2}/2\\-K_t/K_f&-K_t/K_f&K_t/K_f&K_t/K_f\end{bmatrix}$
	$B=\begin{bmatrix}1&1&1&1&1&1\\l\sqrt{3}/2&0&-l\sqrt{3}/2&-l\sqrt{3}/2&0&l\sqrt{3}/2\\l/2&l&l/2&-l/2&l&l/2\\-K_t/K_f&K_t/K_f&-K_t/K_f&K_t/K_f&-K_t/K_f&K_t/K_f\end{bmatrix}$
	$B=\begin{bmatrix}1&1&1&1&1&1&1&1\\l\sin\frac{\pi}{8}&-l\sin\frac{\pi}{8}&-l\sin\frac{3\pi}{8}&-l\sin\frac{3\pi}{8}&-l\sin\frac{\pi}{8}&l\sin\frac{\pi}{8}&l\sin\frac{3\pi}{8}&l\sin\frac{3\pi}{8}\\l\cos\frac{\pi}{8}&l\cos\frac{\pi}{8}&l\cos\frac{3\pi}{8}&-l\cos\frac{3\pi}{8}&-l\cos\frac{\pi}{8}&-l\cos\frac{\pi}{8}&-l\cos\frac{3\pi}{8}&l\cos\frac{3\pi}{8}\\-K_t/K_f&K_t/K_f&-K_t/K_f&K_t/K_f&-K_t/K_f&K_t/K_f&-K_t/K_f&K_t/K_f\end{bmatrix}$
	$B=\begin{bmatrix}1&1&1&1&1&1&1&1\\l\sqrt{2}/2&l\sqrt{2}/2&l\sqrt{2}/2&l\sqrt{2}/2&-l\sqrt{2}/2&-l\sqrt{2}/2&-l\sqrt{2}/2&-l\sqrt{2}/2\\-l\sqrt{2}/2&-l\sqrt{2}/2&l\sqrt{2}/2&l\sqrt{2}/2&l\sqrt{2}/2&l\sqrt{2}/2&-l\sqrt{2}/2&-l\sqrt{2}/2\\-K_t/K_f&-K_t/K_f&K_t/K_f&K_t/K_f&-K_t/K_f&-K_t/K_f&K_t/K_f&K_t/K_f\end{bmatrix}$

and torque τ_i generated by the motor i are given by [38]

$$\begin{aligned}F_i &= K_f\omega_i^2\\ \tau_i &= \pm K_t\omega_i^2\end{aligned} \tag{5}$$

where K_f and K_t are the thrust and reaction torques coefficients, respectively, and ω_i is the ith propeller speed. The sign of the torque generated by each motor depends on the rotation direction of the rotor.

FAULT CLASSIFICATION AND MODELS IN MULTIROTOR UAVS

A fault is defined as an unpermitted deviation of at least one characteristic property of a variable from an acceptable behavior. The major types of faults that may occur on the multirotor components listed in the previous section are mainly categorized into communication breakdown, software faults, and physical faults. Communication breakdown can be due to signal interference, router problems, going out of range or latency, and delay in data transmission. Software faults, such as the navigation and stabilization algorithms faults, could also affect the vehicle operation. The first type results from absence of data received over the data channel or failure in position or attitude estimation. A stabilization algorithm fault occurs if a linear control law is combined with fast dynamical flight (nonlinear effects), or in case of bad control gains when the system properties change due to a payload, for example. Studies in the literature have separated hardware faults according to their mathematical modeling, their physical location, and their behavior versus time [39].

LOCATION IN PHYSICAL SYSTEM

COMPONENT FAULTS

The component faults appear in the mechanical part of the system. They may be produced on the airframe, such as arm break, landing gear failure, or main chassis break [40], and on the components installed on the airframe, such as propellers damages [41], [42], swashplate failures [21], and connectors problems. These faults are mainly due to the aging of the chassis, quadrotor leakage [43], fatigue cycles, untreated rivets and screws [42], and collisions with obstacles in addition to the vibrations induced by the high motor speeds that weaken the multirotor structure over time. Component faults could lead to catastrophic loss of cyclic control [44], to voltage control failure of the actuators [22] and, typically, destruction of the vehicle.

ACTUATOR FAULTS

In multirotor systems, the actuators consist of the motors/propellers sets. A fault in an actuator in some multirotor configurations results in energy loss and may cause a total loss of control [9], [29], [30]. A motor failure could occur after its progressive degradation caused by prolonged use or particles in the motor housing. This could also be caused by electronic speed controller overheating due to an overdraw on current or hot environment [45]. The actuator faults on multirotor UAVs considered in the literature are modeled as follows.

1) *Multiplicative loss of effectiveness faults* [46], [47], [48]:

$$\bar{F}_i = (1-\epsilon_i)F_i \tag{6}$$

with $\bar{F}_i$ being the thrust generated by the faulty motor i, F_i the thrust generated by the healthy motor as expressed in (5), and ϵ_i the loss of effectiveness, where $\epsilon_i = 0$ and $\epsilon_i = 1$ indicate, respectively, that the actuator is completely healthy or fully failing.

2) *Additive faults on the motor thrust outputs* [49], [50]:

$$\bar{F}_i = F_i + f_i \tag{7}$$

where f_i is the additive fault that affects directly the performance of the actuator i that produces the thrust input F_i.

3) Additive faults representing the effects of the actuators faults as offsets on the attitude subsystem [51], [52], [53], [54]:

$$\dot{X}(t) = H(X(t),\tau) + \mathcal{F}f(t) \tag{8}$$

with X being the attitude state vector $X = [\phi\dot{\phi}\theta\dot{\theta}\psi\dot{\psi}]^T$, $\tau = [\tau_\phi\tau_\theta\tau_\psi]^T$, and $H(X(t),U)$ deduced from (1). $\mathcal{F}$ is known as the fault entry matrix, which represents the effect of faults on the system and f is the fault magnitude to be estimated.

4) Additive faults representing the effects of the actuator faults on the control input vector $V = [u_f\tau_\phi\tau_\theta\tau_\psi]^T$ [55]. According to [55], these faults include the external inputs, such as wind or other loads, the dampings from friction, or force bias caused by the electric regulator error of the motor

$$V_f = [u_f\tau_\phi\tau_\theta\tau_\psi]^T + \delta_a \tag{9}$$

where V_f is the faulty control input vector and δ_a is the unknown constant vector representing the actuator fault.

5) Hard over failure characterized by the actuator moving to its upper or lower saturation limits regardless of the commanded signal [56]:

$$F_i = F_{i_m} \mathrm{or} F_{i_M} \forall t \geq t_f \tag{10}$$

where F_{i_m} and F_{i_M} represent the minimum and the maximum values of the motor thrust, respectively, and t_f denotes the time of fault occurrence in the actuator.

6) Lock-in-place where the actuator states freeze at a particular value and will not respond to the subsequent commands [56]:

$$F_i = F_i(t_f)\forall t \geq t_f. \tag{11}$$

SENSOR FAULTS

Sensors faults affect the control strategy and the overall functioning of the system, which leads to a performance degradation [57]. Typical types of sensor faults are: drift, bias, calibration error, loss of accuracy, and sensor freezing [58]. Examples of sensors faults occurring on multirotor UAVs are height [59], [60], inertial measurement unit (IMU) sensors faults [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], and position sensors, such as the Global Positioning System (GPS) sensor [55], [73], [74], [75], [76], [77]. The loss of valid return from the altitude sensor can cause the vehicle to become unstable in vertical axis motions and can introduce the potential for loss-of-control. This mode can result from multiple causes: Flying above the maximum range of the sensor, flying over an obstacle, improper filtering, vibration from airframe, etc. The IMU fault results in a wrong or insufficient attitude information that could make the control impossible.

BEHAVIOR VERSUS TIME

Faults are classified according to this criterion into incipient, intermittent, and abrupt faults. Abrupt faults, such as actuator failure [78], [79], [80], sensor bias fault [61], [62], [81], etc., could result in equipment damage. They arise suddenly like a step change but are easy to detect. If the fault is persistent, the detection algorithm should estimate the fault occurrence time and the change in its magnitude. The intermittent faults profiles are modeled as repeated persistent faults that reset themselves after a random interval of time. This type of failure was rarely considered on multirotor UAVs [82]. The incipient faults [43] develop slowly and lead to a degradation in the equipment. For this type of faults, the detection algorithm needs to estimate the fault occurrence time and its slope. The incipient faults $f(t)$ considered in [43] were modeled as additive faults on the attitude subsystem as

$$f(t) = \beta(t - t_f)\zeta(X, t) \tag{12}$$

with

$$\beta(t - t_f) = \begin{cases} 0 & t \leq t_f \\ 1 - e^{-k(t-t_f)} & t > t_f \end{cases} \tag{13}$$

where t_f is the beginning time of the incipient fault, $\zeta(X, t)$ is a constant vector representing the upper limit value of the incipient fault, and k is a time constant. This type of faults did not attract much attention on multirotor UAVs when compared with abrupt faults although the incipient faults caused by the wear of motors and blades are inevitable in mechanical structures for a multirotor.

MATHEMATICAL MODELING

According to this criteria, faults are generally classified into additive and multiplicative faults. Additive faults are commonly modeled as additional constant or time-varying terms in the system's equations. These terms are often referred to as bias or offset terms and are added to the nominal values of the system states or measurements. In a physical sense, they appear as actuator [49], [50], [51], [52], [53], [54] or sensor offsets [73], [83], [84]. For example, in the case of a faulty sensor, the measured value may include an additive bias term that represents a constant offset from the true value as below:

$$y(t) = h(x(t)) + b + n(t) \tag{14}$$

where $y(t)$ is the measured value, $h(x(t))$ is the nominal output of the system, b is the bias term representing the fault, and $n(t)$ is the measurement noise. The bias term can be estimated and removed from the measurement to improve the accuracy of the estimation or control algorithm. Multiplicative faults are the types of faults in which the fault affects the system by scaling or multiplying the values of certain parameters or variables in the system's equations. They describe actuators [46], [47], [48] or sensors degradation and component faults as parameter changes within the process. For example, a sensor degradation can be modeled as

$$y(t) = \lambda h(x(t)) \tag{15}$$

where λ is a scaling factor that can be a function of time, state variables, inputs, or other parameters that affect the system. A more realistic classification should consider also the deterministic and stochastic models of the faults.

Based on this classification, we can notice that most of the multirotor faults considered in the literature are sensors or actuators faults, modeled as abrupt additive or multiplicative faults as will be detailed later. Table 2 summarizes some faults that could occur on the multirotor UAVs with the percentage of their occurrences according to [45], where failure modes were identified by keeping flight logs and data over all of the Michigan Autonomous Aerial Vehicles team's 1000+ indoor quadrotors flight tests in 2012. According to the authors, the frequencies of these failures demonstrate the likely frequency of failures during the development of a multirotor system and cannot be assumed to be representative of the probabilities that similar events will happen in real flights.

Table 2.

Frequency of Failure Modes [45]

Failure mode	Causes	Results	Occurrence
Navigation and stabilization algorithms	• Failure in position or attitude estimation • Absence of data received over the data channel • Bad control gains • Combination of linear control law with fast dynamical flight	• Unstable or loss of control • Crash	2.4%
Height sensor	• Flying above the maximum range of the sensor • Flying over an obstacle • Improper filtering • Vibration from the airframe vertical axis motions	• Loss of valid return from the altitude sensor • Instability in vertical axis motions	6.9%
Motor failure	• Progressive degradation • Prolonged use • particles in the motor housing • Electronic speed controller overheating • Overdraw on current • Hot environment	• High loss in system energy • Total loss of control	1.2%
Battery	• Connectors problems • Low voltage crash	• Crash	4.5%

A reliability analysis framework was proposed in [40] to identify and evaluate the criticality of failures in a multirotor UAV used for inspection by adopting the fault tree analysis and failure mode and effects analysis methodologies. According to this study based on the calculation of the Risk-Priority-Number and tested and verified on a quadrotor prototype, it was shown that the most critical component of the multirotor is the battery, followed by the motor/propeller system and then the GPS antenna.

CONTROLLABILITY ANALYSIS

The analysis of multirotor dynamic stabilization starts by establishing the sufficient and necessary conditions for the control reconfigurability. A multirotor with unidirectional propellers provides only a unidirectional lift [85]. Thus, classical controllability theory will have a major limitation if applied to a multirotor: the unilateral constraints do not pass the Kalman rank test [86], [87]. Some modified tests were proposed and applied in the literature on the multirotor UAVs to assess their controllability after actuators failures.

QUADROTOR

For a quadrotor UAV with unidirectional propellers, it was shown in [29] and [30] that a complete loss of a rotor results in a vehicle that is not fully controllable, however the vehicle's reduced attitude is controllable near some equilibrium solutions. This was done by exploiting the time invariant nature of the attitude equilibria and examining the rank of the controllability matrix. Based on this study, the proposed solution was to give up the control on the yaw and let the quadrotor spin around its vertical axis.

For a quadrotor with variable patch propellers, it was shown in [88] that the vehicle retains its controllability after one motor failure. This is due to the variable-pitch propeller that can adjust its pitch angle to generate either upward or downward thrust forces, which provides the quadrotor with strong maneuverability and high agility.

HEXAROTOR

The works in [86], [87], [89], and [90] considered the controllability problem of different configurations of hexarotor UAVs. The authors in [86] and [87] showed that a hexarotor with the standard arrangement of rotors [see Figure 3(a)] is not controllable if one motor fails. A new sufficient and necessary condition was proposed for controllability analysis of the multirotor-like systems using an Available Control Authority Index that evaluates the available control authority of the UAV after fault occurrence.

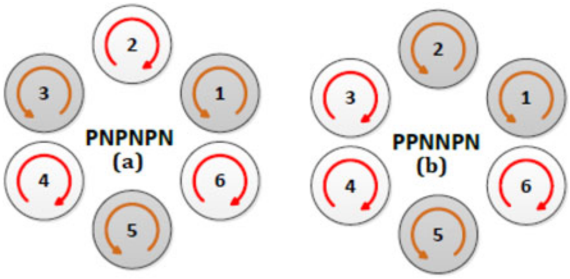


Figure 3.
(a) Traditional and (b) improved arrangement for fault tolerance.

Structural reconfigurability analysis was introduced in [89] and applied to a multirotor structural model. The study demonstrates that, a quadrotor is not able to hover with a failed actuator regarding its parameter values, while the reconfigurability of hexarotors depends on the arrangement of the rotors [clockwise (P) and counterclockwise (N)]. A set of new general algebraic conditions was provided in [90] to ensure static hover for any multirotor platform with any number of generically oriented rotors. The static controllability of a hexarotor UAV in any arbitrary fault configuration was described and assessed by evaluating its flight performance degradation. This is done by constructing the attainable control set (ACS) for the faulty and the nominal cases that has to be sufficiently large to allow a stable flight under disturbances.

OCTOROTOR

The works in [91] and [92] considered the controllability problem of different configurations of octorotor UAVs. In [91], the small time local controllability of the octorotor (star-shaped and coaxial) attitude dynamics was inspected by applying the nonlinear controllability theory with unilateral control inputs. The work in [92] studied the controllability of different configurations of star-shaped octorotors using the analysis of the static reconfiguration module and the ACS.

DISCUSSION

Standard hexarotors and octorotors are mistakenly assumed "by definition" to be failsafe platforms due to their redundant rotors. However, this is not true, in fact, a standard hexarotor or octorotor is not able to hover statically after actuators failures without a recovery mechanism. Figure 4 summarizes the fault-tolerance capability of the different arrangements of multirotor UAVs by building the ratios $\eta_i(\%)$ below using the ACS method, already adopted in [92] and [93]:

$$\eta_i(\%) = \frac{N_{f\text{cc}_i}}{N_{f\text{tot}_i}} * 100 i = 1, 2, 3, 4 \tag{16}$$

with $N_{f\text{cc}_i}$ and $N_{f\text{tot}_i}$ being the number of controllable i fault cases and the total number of faults combinations, respectively, and i represents the number of faulty motors. The ACS is a set of all possible independent controls, thrust u_f, roll τ_ϕ, pitch τ_θ, and yaw τ_ψ, that is generated by actuators within given constraints. It is obtained by mapping the boundary of the motors constraints set to a virtual control set by using the control effectiveness matrix B in (4). Based on the volume

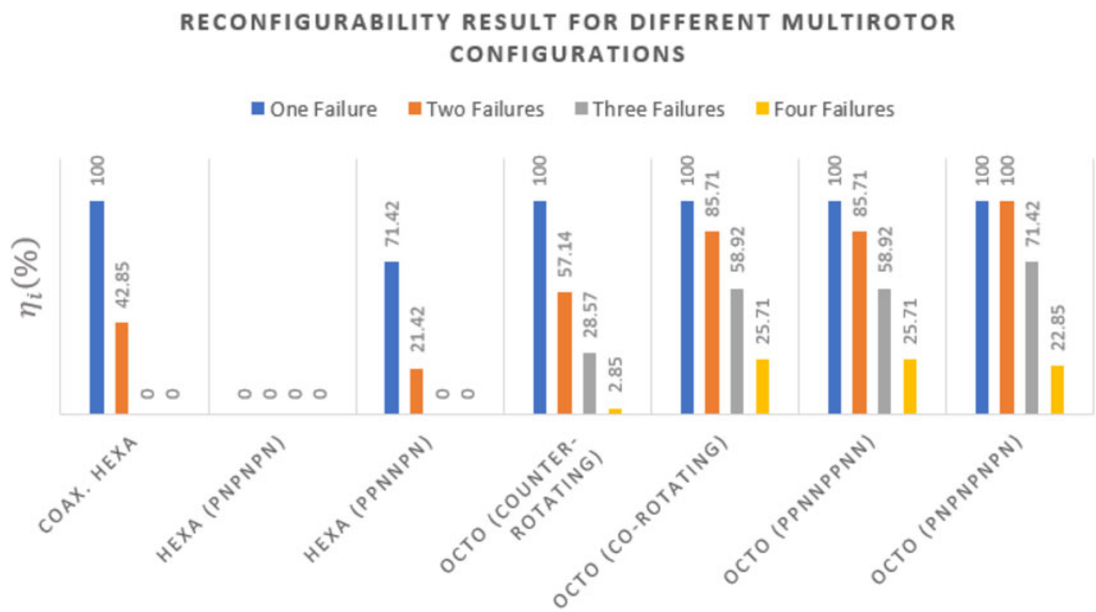


Figure 4.
Reconfigurability result for different multirotor configurations based on the $\eta_i(\%)$ values, where i refers to one, two, three, and four motors failures.

within the ACS, the control requirements could be investigated. To assess the controllability of the multirotor, the 4-D polytope obtained is cut at the nominal flying conditions $u_f = \mathrm{mg}$ and $\tau_\psi = 0$. If the origin of the roll–pitch plane is contained in the polygon, then the multirotor is controllable. According to the controllability results, it is clear that coaxial hexarotor and the star-shaped PNPNPNPN octorotor are the best configurations from a reliability point of view. However, the star-shaped PNPNPN hexarotor configuration is the most widespread configuration that can be found in any commercial flight controller even though its degree of reconfigurability is null. Different parameters other than the reliability intervene in the choice of the configuration, such as the endurance and the size. The overall size is considered as a major advantage of the coaxial multirotor. On the other hand, the coaxial rotors are less efficient than the isolated rotors where, at equal overall produced thrust, the isolated rotors absorb less power than the coaxial ones. This absorbed power is directly proportional to the drawn electric current, which is inversely proportional to the endurance.

RECENT PROGRESS IN MULTIROTOR FAULT DIAGNOSIS DESIGN

Fault diagnosis consists of identifying when a fault has been activated, and pinpointing the type of fault and its location. It is often carried out by a component that receives an Input/Output I/O sequence (information from sensors and actuators) from the targeted system and checks whether it is consistent with the behavior of this system. It is done in different steps [94]: fault detection, fault isolation, and fault identification. Fault detection is the most basic category, which gives only a yes/no information whether and when a fault (any fault) has occurred. Such an information is not enough for most critical systems, where more information about the fault is needed. In particular, its location and magnitude are required for a fault control strategy to be applied.

A commonly applicable technique to implement diagnosis relies on hardware redundancy, where multiple system components, sensors, and actuators are used for the same purpose. An error can be detected, and thus a fault is isolated, by checking the redundant part that performs differently from the others. This approach was applied in [95] for sensor fault detection in a quadrotor UAV, where three altitude sensors (MaxSonar EZ3 sonar, Maxbotix XL sensor, and Optitrack localization cameras mounted on the bottom of the quadrotor) generate three real-time measurements used in the residual generation algorithm. In [96], FDD based on hardware redundancy was considered where an approach for a hexarotor system using a redundant flight control architecture was proposed. This approach has many drawbacks since it introduces additional costs, maintenance, and extra weight. A different kind of redundancy, known as analytical redundancy [97], [98], can be adopted instead. It uses the relations that exist between the different system parts and the measured variables.

Different approaches for hardware redundancy free fault detection have been developed in the literature: model-based, processing-based, and knowledge-based approaches. A detailed classification of the existing fault diagnosis schemes on multirotor UAVs is shown in Figure 5.

Following discussions will be carried out according to the type of applied FDD scheme. Almost all FDD approaches applied on multirotor UAVs are focus on faults/failures of sensors or actuators.

MODEL-BASED APPROACHES

First, analytical/model-based approaches are discussed for actuators and sensors diagnosis.

STATE ESTIMATION

The first category includes state estimation techniques (observers-based and Kalman filters-based) and will be discussed first. The main types of observers used in the literature in this context are listed below.

Sliding-mode observer. The authors in [61], [62], and [81] proposed fault detection and isolation schemes for bias faults in gyroscope and accelerometer sensors of a quadrotor UAV. Using sliding-mode observer techniques, a robust attitude state estimation was obtained, then structured residuals were computed to detect and isolate simultaneous sensor faults. Using also the sliding-mode concept, an actuator fault reconstruction scheme was proposed in [99] for a quadrotor with inaccurate linear parameter varying (LPV) scheduling parameter knowledge. Liu et al. [43] proposed an associated adaptive and sliding-mode observer design to detect and estimate incipient actuator faults of a quadrotor while maintaining robustness against disturbances. Similar approach was presented in [100]. Sliding-mode observer was also considered in [78] and [79] to detect and isolate multiple successive total actuator failures in a coaxial octorotor. An estimation of the actuator loss of effectiveness in a coaxial octorotor was proposed in [46] using the super twisting sliding-mode observer. An approach for the estimation of both actuator and sensor faults based on a proportional multiple an integral sliding-mode observer was tested on an octorotor model in [101].

The main advantage of sliding-mode observers resides in their robustness to unknown inputs, which could be a

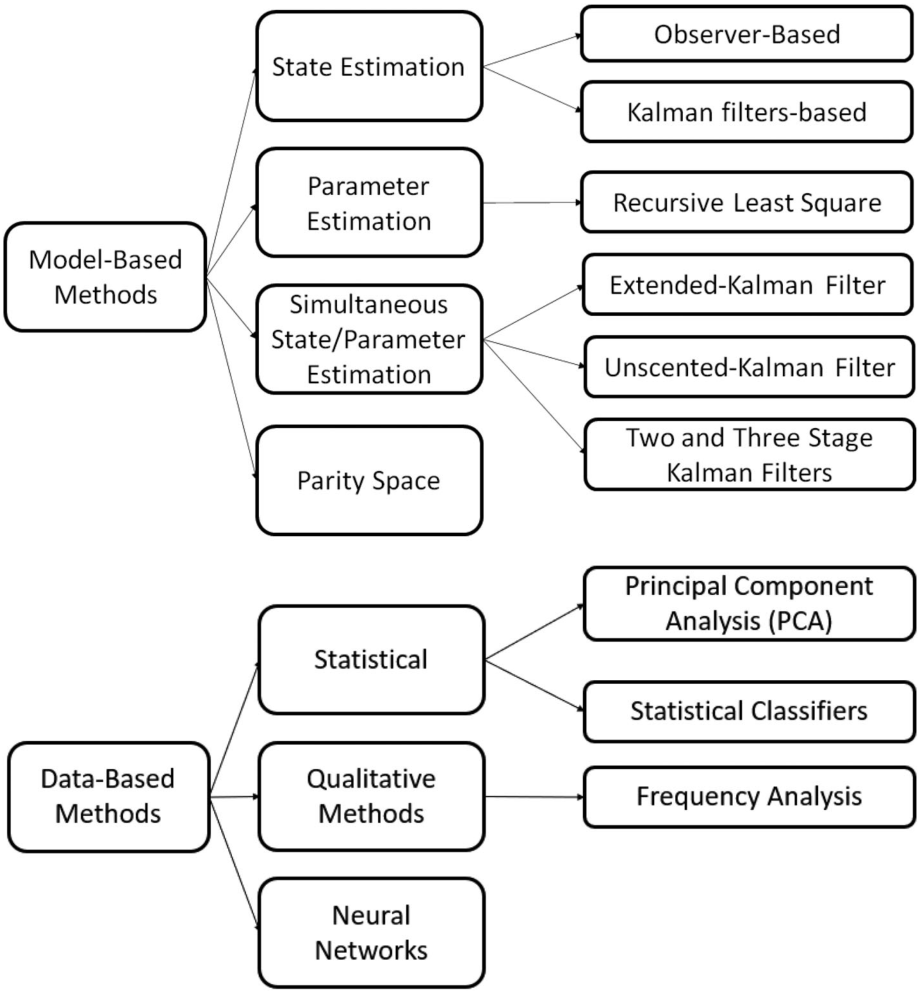


Figure 5.
Classification of FDD schemes applied on multirotor systems.

combination of nonlinearities, faults or system disturbances, and their ability to reconstruct them. However, their practical implementation for fault detection requires careful consideration of issues, such as measurement noise and fault threshold determination.

Thau observer. The work in [63] proposed a diagnostic Thau observer for IMU sensor fault diagnosis. The quadrotor model was shown to satisfy the necessary conditions to the application of the Thau–Lipschitz nonlinear observer when proper assumptions for the actuation forces are made. The authors in [64] have also used this observer for sensor fault diagnosis, where additive and incipient (ramp like) gyroscope failure types, which are very common failures in analog sensors, were considered. The authors in [51], [102], and [103] developed an adaptive Thau observer for state estimation of a quadrotor system and for computing a set of offset residuals to detect actuators faults. Noises, magnitude order unbalances, and modeling uncertainties were addressed. The adaptive Thau observer was considered also in [65] where the authors presented the real-time experimental evaluation of a nonlinear adaptive estimation scheme based on Thau observer to estimate the magnitude of simultaneous faults in the gyroscope and accelerometer sensors. Similarly, an adaptive Thau observer-based actuator fault estimation scheme was considered in [52] for taking off mode of a quadrotor where any actuator fault may cause catastrophic consequence and even crash, resulting in great loss. The Thau observer was also used in [47], [104], and [105] for actuators fault detection on a hexarotor system. The actuators faults are isolated by analyzing the orientation of the hexarotor after the fault occurrence in [47] and [105], and estimated using an eXogenous Kalman filter in [104]. The linear version of the Thau observer, the Luenberger observer, was also considered to design fault diagnosis units to detect and estimate sensor faults [83], [84] and actuators faults [106], [107].

The main challenge in implementing the Thau observer resides in the dependence of its performance on the UAV's dynamics and the characteristics of the fault.

H-infinity observer. A nonlinear robust H_∞ observer was designed in [53] for estimating states and actuator faults (proportional and time-varying faults) of a quadrotor UAV in the presence of nonlinear terms, parameter uncertainties, and external disturbances. The performance of the H_∞ observer was compared with that of a Kalman filter when dealing with the estimation of loss of control effectiveness of actuators in [54]. It was shown that it is much more robust than the Kalman filter for the wind disturbance, however, it requires significant expertise and experience to tune its parameters. The application of this observer to the sensor fault detection was presented in [108].

Unknown input observer. In active FDD approaches based on unknown input observers, unknown inputs could be decoupled from residuals. Xu et al. [48] combined this observer with the theory set approach to produce a mixed robust actuators faults diagnosis unit. It was shown that this proposed approach achieves robustness in diagnosis against modeling uncertainties, noises, and disturbances either by decoupling or by limiting their effect on the residuals. An unknown input observer combined with beard basic fault detection filters was used in [56] to compute directional residuals for actuators fault identification in a quadrotor UAV.

Kalman filters. The federal Kalman filter was considered in [66] to deal with the faults of both the z-axis gyro and the magnetic sensor. An interacting multiple model consisting of a bank of Kalman filters operating in parallel was validated by simulations in [59] for detection and isolation of both the loss of control effectiveness in motors and the bias faults in the altitude sensor. In [109], a Kalman-filter-based approach that detects unbalanced propellers was proposed using only the motor force commands and the accelerometer measurements. The Kalman filters were shown to be sensitive to the initial estimates of the state and parameter values, which can affect the accuracy of the fault detection mechanism.

Other types of observers were also implemented in the fault detection and diagnosis units on multirotor systems, such as disturbance observer [110], [111], [112], immersion and invariance observer [113], particle filter [114], nonlinear identity observer [73], generalized observer scheme based on adaptive estimators [115], high gain observer [55], adaptive extended state observer [116], polynomial observer [49], [50], intelligent output estimator [74], [117], LPV observer [118], [119], [120] and nonlinear geometric approach [67], [121].

PARAMETER ESTIMATION

Fault detection via parameter estimation is based on the principle that faults in a process could be associated with specific states and parameters of the mathematical model of the process [122]. This technique was considered in [123] to detect rotor faults that correspond to the deformation, damage, and wreckage of blades, which change the thrust and torque coefficients. The recursive least square estimators were used to estimate these coefficients and detect faults.

The implementation of this technique requires accurate models of the system, which may be difficult to obtain in practice, especially for such complex systems.

SIMULTANEOUS STATE/PARAMETER ESTIMATION

Online estimation of internal states and parameters is often required for fault diagnosis. Different works have considered the use of extended Kalman filter (EKF), unscented Kalman filter (UKF), two-stage Kalman filter (TSKF), and three-stage Kalman filter. A multiplicative EKF was employed in [124] for the state estimation and residual generation, and hypothesis testing was applied to detect bias and drift faults on the laser sensor.

A two-stage EKF was designed in [68] for detecting and identifying bias, drift, and oscillatory faults on the IMU. The TSKF was also considered in [75], [125], [126], [127], [128], and [129] for estimation of the loss of control effectiveness in the actuators. A three-stage Kalman filter was proposed in [130] to detect, isolate, and estimate the magnitudes of the actuator faults even if the quadrotor suffers from external disturbances. The augmented UKF was used in [69] to estimate the drift faults in the IMU and in [131] to develop an actuator fault diagnosis scheme using a parameter-estimation-based UKF. The zonotopic EKF was applied in [76] to the quadrotor model to detect sensors and actuators faults. An actuator diagnosis module was designed for a hexarotor UAV in [132] based on the adaptive eXogenous Kalman filter under model uncertainty and sensor noise and was validated offline using real data.

Fault diagnosis using simultaneous state and parameter estimation is computationally demanding. The accuracy of its estimates is affected by measurement noise and other disturbances, which can lead to false alarms or missed detections.

PARITY SPACE

The main concept of parity space based methods is to generate auxiliary signals that are independent of system inputs under nominal operating conditions while carrying fault information [133]. This approach was considered in [70] and [134] for sensor fault detection in a quadrotor UAV and in [135] for detection of additive faults on the state vector. It uses nonlinear analytical redundancy relations based on geometric approach to generate structured residuals and isolate the fault. This approach was also considered in [136] for actuator fault detection in a hexarotor UAV. Another type of analytical redundancy relations based on the differential flatness property of the hexarotor UAV model was considered in [137] for sensors and actuators diagnosis.

DATA-BASED APPROACHES

Data-based approaches are classified as statistical methods, qualitative methods, and neural networks. Currently, investigations on these approaches for multirotor UAV systems are shown in literature.

STATISTICAL METHODS

The multivariate statistical methods, which utilize input and output information of the system, are very popular nowadays for the purpose of fault diagnosis due to their ability to tackle large number of highly correlated variables. In [138], principal component analysis (PCA) was adopted for online fault detection. The faults considered are a motor fault and a broken rotor fault. The main advantage of the PCA is that it reveals good information about the faults by focusing on the variation of correlation structure among system measurements. Statistical classification techniques, such as discriminant analysis, canonical variate analysis, partial least squares regression, fisher discriminant analysis, PCA, and multi-PCA were compared in [139]. Among these approaches, partial least squares regression shows the best performance for isolating a quadrotor actuator fault. Fault detection and isolation methods based on recursive least squares and weighted linear least squares were detailed in [140] and [141] to diagnose propulsion system faults of an octorotor UAV. An FDD scheme based on support vector machine was considered in [142] and [143] for motors and propellers diagnosis.

QUALITATIVE METHODS

Faults could be diagnosed using signal analysis techniques. Since some fault signals are time dependent or nonstationary, time–frequency signal analysis is critical for fault diagnosis. Common time–frequency signal analysis techniques are discrete wavelet transform and Fourier transform that were used in [144] to detect unbalanced propellers by means of audio signals, and in [145] to detect the number of shorted turns in a motor current signature analysis. In [146], a motor/propeller fault detection scheme based on the analysis of the vibration spectrum measured by the accelerometer was proposed, using the discrete Fourier transformation. Fuzzy logic techniques belong also to the qualitative data-based diagnosis techniques. An adaptive interval type-2 fuzzy logic was proposed in [147] as an actuator fault observer of a modified quadrotor UAV, which can effectively estimate the lumped faults without the knowledge of their bounds.

NEURAL NETWORK

Artificial neural networks were shown to be particularly very attractive when designing fault diagnosis schemes. Artificial neural networks can be effectively applied to both modeling and decision making. In [148], fuzzy adaptive resonance neural network was employed to detect whether motors are operating in normal or faulty condition. In [71], the neural network was used as an observer for faults in the quadrotor sensors. In [149], a parallel bank of recurrent neural networks was designed to precisely estimate the severity of actuator faults. An actuator fault detection method based on extreme learning machine was proposed in [150]. It was shown that this technique is computational acceptable to very small-scale microprocessors. Similar works were also considered in [60], [72], [77], [151], [152], and [153] on a quadrotor UAV, in [154] and [155] on a hexarotor UAV, and in [156] on an octorotor UAV.

DISCUSSION

The reported faults on multirotor UAVs with their corresponding FDD techniques are summarized in Table 3 with their advantages and drawbacks. Different from the quadrotor, for which multiple studies have been proposed for actuator fault diagnosis purposes, only few studies about fault tolerance of hexarotor and octorotor UAVs investigated the fault diagnosis problem, as others usually assume that the faults are perfectly diagnosed. However, this is not a realistic assumption since diagnosis in these systems is a very challenging topic due to the redundant actuators.

Based on this summary, one can notice the following.

1) Actuator and sensor faults have been widely investigated so far, however, structural faults are rarely considered. Structural faults in these systems, such as rotors and blades damages [138], [148], [151], [155] could lead to a partial or total loss of the actuators and can, therefore, seriously deteriorate flight performance, even lead to disastrous accidents.

2) The majority of diagnosis techniques (around 82%) are purely model-based while the measurement data that carry significant information on incipient faults and system behaviors are not fully used.

Table 3.

FDD Techniques Applied on Multirotor UAVs

Methods	Faults	Advantages	Drawbacks
Sliding-mode observer	• Bias in IMU [61], [62], [81] • Additive fault on motor speed [99] • Incipient physical structure aging [43] • Actuator loss of effectiveness [46], [100] • Total actuator loss [78], [79]	• Fault estimation and reconstruction • Quick convergence • Nonlinearity handled effectively • Estimation of some disturbances • Robustness to disturbances • Robustness to parameter variations	• Computational burden • Difficult tuning
Thau observer	• Additive and incipient fault on AHRS [63] • Additive and incipient fault on gyroscope [64] • Actuator loss of effectiveness [47], [51], [104], [105] • Offset in throttle input [102], [103]	• Low calculation complexity • Nonlinearities taken into account • Fault severity estimation	• Difficulty of distinguishing faults from unmodeled disturbances
Luenberger observer	• Offset on x velocity sensor [83], [84] • Total actuator failure [106], [107]	• Short detection delay • Easy implementation	• Difficult to distinguish faults from unmodeled disturbances • High sensitivity to noise
Adaptive estimator	• Bias in gyroscope and accelerometer [65] • Additive actuator fault [52] • Actuator loss of effectiveness [115], [116]	• Estimate simultaneous faults • Accurate parameter estimation	• Calculation complexity • Long detection delay
H-infinity observer	• Proportional and time varying actuator faults [53] • Actuator loss of effectiveness [54] • Sensor faults [108]	• Accurate estimation of time varying faults • Robustness and disturbance attenuation • Correct time response for fault detection	• Computation complexity
Unknown input observer	• Actuator loss of effectiveness [48], [56] • Actuator lock-in-place, float, hard over [56]	• Decouple the plant disturbance from the state estimation process	• Computational Complexity
Kalman filters	• Bias on z-axis gyro and magnetic sensor [66] • Actuator loss of effectiveness [59], [132] • Bias on altitude sensor [59] • Propellers damage [109]	• State perturbations and Gaussian measurement noise taken into account • Short detection delay	• Well-established for linear or linearized systems only • Gaussian assumptions not always valid

Table 3. (Continued)

Methods	Faults	Advantages	Drawbacks
Disturbance observer	• Actuator loss of effectiveness [110], [111], [112]	• Estimation of additive disturbances • Estimation of multiplicative faults magnitude	• Limitation of bandwidth of disturbance estimation
Immersion and invariance observer	• Actuator loss of effectiveness [113]	• Estimation of delayed unmeasured states	• Design complexity
Particle filter	• Actuator loss of effectiveness [114]	• Dealing with non-Gaussian noise	• Knowledge of statistical distribution of noise required • Huge computational cost
Nonlinear identity observer	• Offset on x sensor, drift on roll sensor [73]	• Robustness to uncertainties	• Difficult tuning • Computational burden
High-gain observer	• Bias in motor torque [55] • Bias in position sensor [55]	• Fast detection • Robustness to modeling uncertainty • Robustness to external disturbances • Simple to design	• Sensitive to measurement noise • Peaking phenomenon
Polynomial observer	• Additive fault on motor thrust [49], [50]	• Estimation of simultaneous faults • Identification of faults of small magnitudes	• High sensitivity to noise
Intelligent output estimator	• Bias on y position sensor [74] • Actuator loss of effectiveness [117]	• Fault magnitude estimation	• Noise due to the updating nature of the ultra-local model • Delay in fault detection
LPV observer	• Actuator loss of effectiveness [118], [119] • Bias on x, y, and z sensors [120]	• Low noise sensitivity	• Calculation complexity
Nonlinear geometric approach	• Step faults on accelerometer sensor [67] • Step fault on actuator [121]	• Robustness to large disturbances	• Computational cost
Moving horizon estimation	• Motor degradation [157]	• Fast convergence	• Online computation time
Parameter estimation (least square method)	• Blade deformation and damage [123] • Actuator loss of effectiveness [140], [141]	• Computational simplicity • Suitable for practical implementation	• Weak robustness to external disturbances • Time consuming
Simultaneous state/parameter estimation (EKF, TSKF, UKF)	• Bias in IMU [68], [69] • Actuator loss of effectiveness [125], [126], [127], [128], [129], [130], [131] • Bias on x, y, z sensors [75], [76] • Bias and drift on laser sensor [124]	• Immunity to external noise	• Low robustness to parameter variations • High computation burden • Performance depending on the initialization step

Table 3. (Continued)

Methods	Faults	Advantages	Drawbacks
Parity space	• Additive faults on IMU [70], [134] • Additive fault on the actuator [135] • Actuator loss of effectiveness [136]	• Fast response	• Very sensitive to measurement noise and system disturbances.
Data-driven approaches (statistical)	• Rotor breakage [138], [143] • Motor failure [139], [142]	• Dynamical model not required	• Limited to known fault classes • System dependent
Data-driven approaches (qualitative methods)	• Rotor damage [144], [146] • Motor short circuit [145]	• Fast implementation • Effective in detecting transients • Dynamical model not required	• Limited time a frequency resolution
Neural networks	• Rotor damage [148], [151], [155], [150], [152], [153] • Bias, Drift in Gyroscope [71], [72] • Actuator loss of effectiveness [149], [156] • GPS fault [77] • Rotor failure [154] • Barometer fault [60]	• Dynamical model not required • Ability to learn by themselves	• Learning convergence not guaranteed • Large training time • Need of large amount of data

3) Around 48% of the works presented experimental validation of the results: online validation during real free flights [55], [60], [62], [65], [72], [74], [78], [79], [81], [83], [84], [105], [106], [109], [114], [115], [117], [125], [131], [132], [142], [149], online validation when the UAV is fixed on a testbed [51], [100], [103], [113] or offline validation using recorded real data [46], [61], [66], [112], [124], [129], [136], [137], [138], [139], [141], [143], [144], [145], [146], [148], [151], [154], [155]. Outdoor validations describing real flights in a real environment with sensors noise and external disturbances were performed in [60], [83], [84], [105], and [132].

4) Only few works have studied the fault detection, isolation, and estimation times in experimental validations and are summarized in Table 4. It was shown that the average detection and isolation times vary according to the fault magnitude, where faults with large magnitudes could be detected faster than faults with small magnitudes [72], [115]. Since the experiments in the works appearing in Table 4 were not performed with the same hardware and under the same failure cases and the same environmental conditions, a fair comparison of the detection times characterizing each technique would not be possible.

5) Actuators dynamics are rarely considered while detecting and estimating the faults [109], [114], [116], [123], [125], [126]. In practice, actuator dynamics are not fast enough to be neglected, which may deteriorate the overall performance of the system when they are not included in the diagnosis and recovery strategy.

6) One main challenge in multirotor fault diagnosis is the existence of multiple single faults that appear concurrently. Few works have considered the detection of simultaneous faults during real flights. The scenarios studied in this context are simultaneous faults on gyroscope and accelerometer [81], actuators loss of effectiveness in all motors of a quadrotor [125], [129], two propellers damage [146], total failure of two motors or more [105], [142], in addition to simultaneous actuators and sensors faults [55]. Fault detection and isolation of successive faults was also tested in [114] after the occurrence of successive actuators loss of effectiveness, and in [79] after successive complete failures of four motors of an octorotor. Some works have considered the use of Kalman filter-based methods for simultaneous faults estimation. However, their stability analysis when applied to nonlinear systems is challenging.

In addition, with limited measurements, the observability condition will be difficult to be satisfied due to the augmented state variables introduced to represent the fault parameters. Instead, other techniques based on structured residuals were proposed to solve this problem. The most reliable solution resides in adding extra sensors to monitor simultaneously the behavior of the different sensors and actuators, such as current sensors, for example [142]. However, this would add extra cost and weight on the multirotor.

7) The techniques developed in most of the cited works as well as the adopted models represent adequately the multirotor system and no noise or unexpected disturbances are present. These requirements are rather stringent, however, and are not met in real multirotor systems. A number of research works have focused on robust algorithms for fault detection. The robustness of a fault detection system means that it must be only sensitive to faults, even in the presence of model-reality differences, noise, and disturbances. The problem of robustness in fault detection in multirotor UAVs using observers has been treated in some works using the active approach, based on decoupling the effects of the uncertainty from the effects of the faults on the residual using eigenstructure assignment methods [56], unknown input observer method [48], robust parity equations [135], and H_∞ [53], [54], [108]. Other approaches called passive were also considered. They enhance the robustness of the fault detection system at the decision-making stage, mainly propagating the effect of the uncertainties to the residual that can be used as an adaptive threshold [62]. Robustness in fault estimation was also considered in some works using adaptive estimators [61], [65], [81], [115] and sliding-mode observers [43], [100].

RECENT PROGRESS IN MULTIROTOR FTC DESIGN

The recent studies on active and passive FTC systems applied to multirotor attitude and altitude will be reviewed in this section. Fault tolerance of a multirotor refers to its ability to continue its mission without interruption when one or more of its components fail. A commonly applicable technique to implement system recovery relies on hardware redundancy as in [158] where a hardware redundant solution for actuator failure in a quadrotor was proposed. The conventional configuration was modified to a coaxial-propelled configuration where upper and lower propellers rotate in opposite directions, thus canceling out any resultant torque during hover. A motor failure is then tackled by turning OFF the active motor opposite to the

Table 4.

Fault Detection and Isolation Times for Multirotor UAVs

UAV	Fault	Detection time t_d Isolation time t_I
Quadrotor	Bias in IMU [62], [81]	$t_d < 5$s $3\text{s} < t_I < 7\text{s}$
	Actuator loss of effectiveness [115] ($6\% < \text{LOE} < 10\%$)	$0.48\text{s} < t_d < 1.9\text{s}$ $0.45\text{s} < t_I < 1.4\text{s}$
	Bias in laser sensor [124] ($0.05\text{m} < \text{Bias} < 0.25\text{m}$)	$0.5\text{s} < t_d < 8.43\text{s}$
	Drift in laser sensor [124] ($0.001\text{m/s} < \text{Drift} < 0.020\text{m/s}$)	$4.02\text{s} < t_d < 37.88\text{s}$
	Actuator loss of effectiveness [131]	$t_I = 0.5$s (30%)
	Drift in gyroscope [72]	$0.5\text{s} < t_I < 3\text{s}$
	Bias on the y-position sensor [74]	$t_I = 265$ ms
Hexarotor	Total actuator failure [106]	$t_d = 0.145$s $t_I = 0.3$s
	Total actuator failure [137]	$t_I < 1$s
	Total actuator failure [154]	$t_I < 0.3$s
	Actuator loss of effectiveness [136]	$t_I = 0.2$s (30%)
Octorotor	Total actuator loss [78]	$t_I = 0.6$s
	Total actuator loss [79]	$t_I = 0.8$s
	Total actuator loss [141]	$t_d = 1.55$s
	Total actuator loss [142]	$t_I = 0.36\text{s} t_I = 0.4\text{s}$ (50%)
	Actuator loss of effectiveness [46]	

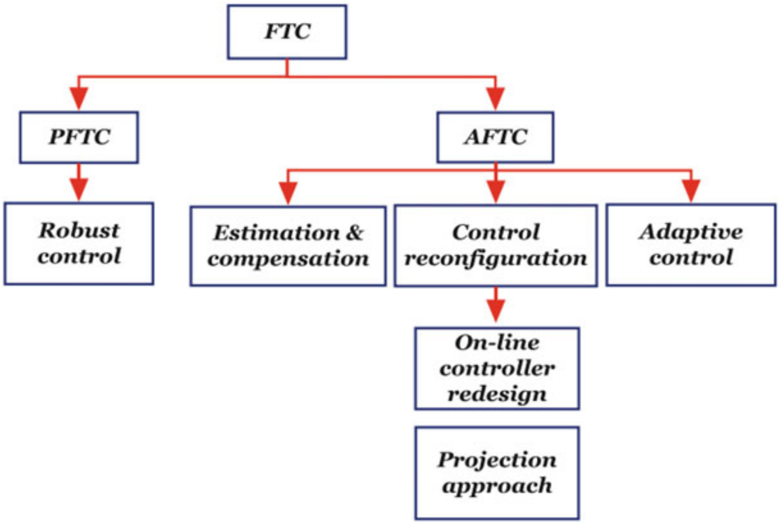


Figure 6.
General classification of FTC methods.

failed motor. Many other techniques were proposed under a complete actuator failure of a quadrotor without adding actuators redundancy. Their main concept is to sacrifice the controllability of the yaw state and to control the UAV position for safe landing. In [29] and [30], periodic solutions for a quadrotor maintaining a height around a position in space despite the loss of up to three propellers were presented. The proposed control strategy consists of the vehicle spinning about a primary axis and tilting this axis for translational control. Indoor and outdoor flights validated this strategy with the position feedback obtained by external sensors. Similar works but relying only on onboard sensors were presented in [80] and [159] where the position control of the quadrotor subjected to complete failure of one rotor was achieved through onboard vision-based state estimation and GPS module, respectively. The incremental nonlinear dynamic inversion approach was adopted in [160] and [161] to control the quadrotor and compensate for the unknown aerodynamic effects resulting from the complete loss of one or two opposing rotors. For validation, free flights were performed in a large-scale wind tunnel. A fault-tolerant controller able to recover a quadrotor from arbitrary initial orientations and angular velocities despite the complete failure of a rotor was developed in [162]. The approach validated in real flights consists of a cascaded control method and a control allocation method based on quadratic programming. In [163], severe actuators faults with motor saturation were tackled by sacrificing yaw motion. This results in a rapid rotation and divergence of position control that was resolved by a feed-forward control loop on the pitch and roll angles. The emergency fault-tolerant controller proposed in [164], [165], and [166] transforms the quadrotor suffering a total loss of one actuator into a trirotor UAV. Experimental results in [164] showed that the infected UAV was successful in maintaining its desired path despite the non-symmetric structure of the trirotor. Many other works that proposed and validated by simulation approaches tolerating complete loss of one or two motors can be found in [167], [168], [169], [170], [171], [172], [173], [174], [175], and [176].

All the approaches discussed above in this section are based on active FTC architectures that requires the development of a fast and accurate FDD scheme. However, this aspect was not discussed in any of the experimentally validated works that focused on the recovery step while supposing that the failed motor is perfectly detected and isolated. Moreover, most the experimental validations made use of light weighted quadrotors (mass $m \leq 0.5$ kg, arm length $l \leq 0.1785$ m) and were not tested on heavier UAVs.

Another type of faults occurring on the propulsion system is the actuator loss of effectiveness. Adaptive control, robust control, estimation and compensation, and control reconfiguration (see Figure 6) are the most widely applied techniques to designing FTC laws to compensate these faults and are reviewed below.

In order to maintain complete control on the UAV in the case of one or more motor failures, the current existing solution is to consider some configurations of multirotors with redundant actuators, i.e., hexarotors and octorotors [31], [177].

The controllability study presented in section "Controllability Analysis" shows that a standard hexarotor (adjacent rotors spinning in opposite directions) is uncontrollable when one rotor fails. According to this, FTC strategies were proposed to control a degraded system, where the yaw states are ignored [86], [178]. To guarantee full state control after one motor failure, some researchers have proposed the design of tilted rotor hexarotor UAVs that keep the ability to reject disturbance torques in all directions while counteracting the effect of a motor failure, without requiring any in-flight mechanical reconfiguration of the vehicle or change of the motor rotation direction [179], [180], [181]. To avoid mechanical complexity following this approach, other researchers have proposed the use of an alternate hexarotor configuration (PPNNPN). In this configuration, recovery from the failure of two rotors is possible when applying FTC approaches. The most widely applied technique for FTC of redundant multirotor UAVs is the control allocation that is discussed below.

FTC ADAPTIVE CONTROL

Adaptive control techniques have been extensively used to handle parameters uncertainties. That is mainly due to their capability to estimate those parameters online. Exploiting this characteristic, many investigations on multirotors have considered the application of adaptive control to designing attitude FTC law. In [149], an active FTC strategy based on adaptive sliding-mode control (SMC) and recurrent neural networks was designed and validated in experiments on a quadrotor UAV system to tolerate actuator faults. Of particular interest to this article, model uncertainties were addressed in the design, however, without investigating issues of matched and mismatched external disturbances, which may affect the performance of the active FTC system.

The authors in [182] derived a reconfiguration FTC scheme based on adaptive control and quantum logic to ensure good tracking capability of the quadrotor under faults in propellers. The quantum logic was applied to achieve the quantization of the disturbances patterns. In recent works [183] and [184], passive nonlinear robust adaptive fault-tolerant altitude and attitude schemes based on backstepping and sliding-mode techniques, respectively, were designed and implemented on a quadrotor to accommodate actuator faults and compensate for parametric uncertainties and external disturbances. A dual adaptive FTC strategy based on adaptive SMC and adaptive boundary layer was presented in [185]. Within this adaptive strategy, both actuator faults and model uncertainties were compensated without the knowledge of the fault information and uncertainty bounds. For more recent development of FTC systems on quadrotor, hexarotor, and octorotor UAVs to accommodate actuators loss of effectiveness, blades damage, and sensor faults by using adaptive control technique, the studies in [186], [187], [188], [189], [190], [191], [192], [193], [194], [195], [196], [197], [198], [199], and [200] can be further referred.

Recently, deep reinforcement learning has been applied in few works to tolerate actuators faults [201], [202] and cyber-physical attacks [203] and to reject disturbances [204] on UAV systems. Reinforcement learning can adapt to changes in the environment, it does so through learning from experience rather than using a predefined model. Therefore, it can be considered a form of adaptive control, but it is a different approach from traditional adaptive control techniques. In overall, reinforcement learning has shown promise in FTC of multirotor UAVs, however, it is still a relatively new area of research with some significant challenges that need to be addressed.

ROBUST CONTROL-BASED PASSIVE FTC METHODOLOGIES

Among the different robust control schemes SMC has recently revealed high robustness to uncertainties when controlling systems with nonlinear and highly coupled dynamics. It is also characterized by its insensitivity to external disturbances and uncertain parameters and its rapid response. Thus different SMC algorithms have been developed in the literature and applied to quadrotor, hexarotor, and octorotor passive and active FTC design [52], [156], [205], [206], [207], [208], [209]. In [116], [210], [211], [212], [213], [214], and [215], continuous and nonsingular integral terminal sliding-mode controllers were proposed to accommodating actuator faults in quadrotor attitude system. It was shown that these controllers could achieve high-precision tracking and fast finite-time convergence performance in both reaching and sliding phases.

A comparative study of three SMC-based fault-tolerant controllers (conventional, integral, and integral terminal) for trajectory tracking of a quadrotor UAV subject to actuator faults was provided in [216]. Simulation results showed that the conventional SMC suffers from the chattering problem and presents low robustness to simultaneous faults. The integral terminal SMC outperforms the integral SMC for faults greater than 30%, and chattering is alleviated when these two controllers are employed.

The works in [217] and [218] discussed the implementation of an SMC scheme combined with control allocation on a quadrotor suffering from actuators failures and installed on a gimbal setup. The results show the robustness of the controller when compensating a loss of effectiveness up to 25%. In [219], SMC was introduced into the FTC design to improve the accuracy of a fuzzy adaptive nonlinear FTC scheme proposed for attitude dynamics of quadrotor UAV subjected to different sensor faults in Euler angle loop. In real flights, considering the attitude dynamics only is not sufficient and studying the entire dynamics is essential, which makes the development of the FTC system more challenging and more valuable. The use of other robust controllers, such as backstepping [111], [147], [220], [221], H-infinity [222], [223], [224], active disturbance rejection control [225], fuzzy state feedback controller [226], nonlinear dynamic inversion [227], and

PID structured optimal controller [228], was also investigated in the design of FTC systems.

In addition to the integer-order control techniques, some works exploited the robustness property of fractional-order controllers for the fault tolerance of UAV systems [229], [230], [231]. One advantage of this type of control is its ability to capture the memory effect and frequency dependence of the system, which can improve the system's robustness to faults and disturbances. Overall, fractional-order control shows promise for fault-tolerance applications in UAVs due to its ability to capture the complex dynamics of these systems and improve robustness to faults and disturbances. However, further research is needed to explore its effectiveness in different fault scenarios and its practical implementation.

ACTIVE FTC BASED ON ESTIMATION AND COMPENSATION

A widely studied active FTC technique is the estimation and compensation method where a compensation input is superimposed on the nominal control input. This approach was considered in [83] and [84] where the sensor fault estimation was solved by utilizing an augment variable observer, and an FTC law was developed by combining an existing proportional derivative (PD) control law and the results of fault estimation. In [115], the actuator fault estimation was elaborated according to the functional structure of the fault and was used to adjust the baseline controller output signal before sending it to the motor servo control system, while the baseline control algorithm remains unchanged. In [113], the immersion and invariance observer was utilized to estimate the actuator fault, which is combined with a sliding-mode controller to stabilize the attitude of the quadrotor. For more recent development of the FTC law design on quadrotor UAVs to estimate and compensate actuators loss of effectiveness, the works in [55], [75], [126], and [232] can be further referred.

ACTIVE FTC BASED ON CONTROL RECONFIGURATION

In this paradigm, a complete controller reconfiguration is performed after diagnosing the fault. Several reconfiguration strategies have been proposed for a quadrotor UAV for completely automatic reconfiguration and are reviewed below. The existing active reconfigurable control approaches belong to one of the following schemes: LPV/gain scheduling, control mixer/pseudoinverse, linear quadratic, model predictive control (MPC), dynamic inversion or feedback linearization, multiple-model, eigenstructure assignment, intelligent control using learning methodologies, fuzzy logic, neural networks, and expert systems.

ACTIVE FTC BASED ON PROJECTION APPROACH

The methods following the controller redesign by projection to known scenarios identify offline the controllers to be applied during the faulty operation, and the controller that is more adapted to the occurring fault case is selected online. This reconfiguration approach was considered on a quadrotor UAV in [233], [234], and [235] and on a hexarotor UAV in [236]. The work in [233] proposed a multiple model adaptive FTC scheme based on mixing of the outputs of multiple linear quadratic state feedback controllers designed considering closed-loop system performance for ranges of motors loss of effectiveness. Stability analysis was provided and verified via indoor real-time experiments. An adaptive optimal reconfiguration control scheme was proposed in [234] for a quadrotor with actuator faults via combined multiple models describing the failure system under different fault conditions. The reconfiguration ability was confirmed through simulation results. The authors in [235] designed an active FTC based on a bank of sliding-mode controllers, each one tuned to give the best performance for a specific actuator fault. No stability proof was presented in this work.

This reconfiguration paradigm is simple, however, it requires significant offline efforts for the design of the bank of controllers and online effort for the implementation of all these controllers especially during switching.

ACTIVE FTC BASED ON ONLINE CONTROLLER REDESIGN

We start first by MPC, which is capable of reconfiguring the controller by updating the internal plant model to reflect the faults. This approach was considered in [127] where the MPC was applied to the nonlinear model of the quadrotor through successive convexification algorithms. This architecture is capable of controlling partial loss of actuator effectiveness and complete loss of actuator without needing controller switching and by considering actuator saturation limit. The authors in [237] proposed an MPC-based trajectory tracking approach for a quadrotor UAV under actuator loss of effectiveness by controlling only its acceleration. This has led to less computational burden and faster closed-loop dynamics. The application of MPC in [238] showed that the time response of the controller is much better when using smaller predictive controller window as it gives much greater control effort to handle the actuator faults. The main advantages of MPC are its capability of disturbances rejection and insensitivity to parameters change and faults. However, its main drawbacks reside in the high computing power requirements that limit the applicability of this method in practice. This approach was considered in [239] on a hexarotor system.

The pseudoinverse is an active FTC approach that makes use of the concept of model-matching in explicit model following. Its concept is based on the requirement of the reference closed-loop system matrix to compute the new controller gain after a fault has occurred. This approach was considered in [117] to tolerate different loss of effectiveness actuator fault scenarios. Its main challenge resides in the guarantee of stability of the reconfigured closed-loop system in addition to the minimization of the time consumed to approach the acceptable matching.

The fault hiding approach using virtual actuator was proposed in [106] on a hexarotor UAV, and in [107] on an octorotor UAV. Its key idea is to insert a reconfiguration block between the nominal controller and the faulty plant to hide the fault from the controller. Using this approach, the fault-tolerance property can be added to an existing scheme, without affecting its performance already achieved by the controller under nominal conditions.

The design of reconfigurable FTC systems based on gain scheduling/LPV techniques was also considered on quadrotor UAVs and hexarotor UAVs [240]. Nguyen et al. [128] and [241] developed an FTC architecture based on self-gain scheduling where the scheduled gains were parameterized as polynomial functions of the loss of effectiveness of a quadrotor's actuators estimated by a TSKF and tuned offline. The main advantage of this smooth switching is that it avoids undesirable transient phenomenons during the reconfiguration process. On the other hand, LPV techniques provide a methodical design procedure to control uncertain, nonlinear, and highly coupled systems. The advantages of this technique include robust performance and guaranteed global stability. LPV control uses the $H-\infty$-robust control framework. This technique was studied in [118], [120], [242], and [243].

To take into account the degraded performance of the faulty actuators and avoid their potential saturation, a command/reference governor may be needed in addition to the reconfigurable controller to adjust the reference trajectory automatically, such as in [74], [131], and [244].

FTC DESIGN USING CONTROL ALLOCATION

Control allocation is defined as the problem of distributing control effort among multiple redundant actuators. The control allocation algorithms applied on multirotor UAVs assume a linear effector model in the form

$$V = Bu \tag{17}$$

where $B \in R^{m \times P}$ is the control effectiveness matrix presented in (4), that relates the control inputs u representing the real thrusts of the motors to the virtual control inputs $V = [u_f \tau_\phi \tau_\theta \tau_\psi]^T$ produced jointly by the effectors. According to the way of calculating the vector u, control allocation algorithms are classified into direct allocation, pseudoinverse, modified pseudoinverse, constrained optimization methods based on fixed point method, and quadratic or linear programming or their combination [20].

With application to hexarotor UAVs, in [245] and [246], the control allocation problem was stated using a parametric programming formulation and solved offline for an explicit solution that minimizes energy consumption during flight with a low computational load. The actuators constraints, such as the limits on the motors speeds, were taken into account while solving the optimization problem. This strategy was able to tolerate up to two motors failures with outdoor experimental validation. Similarly, in [105], once a fault was detected, the allocation matrix was modified correspondingly to adopt the new geometry of the hexarotor. A control allocation based on gain-scheduling control in the framework of structured H_∞ synthesis was designed in [247] for actuator loss of effectiveness compensation without solving any online optimization problem. A fault-tolerant adaptive control allocation after one motor failure was proposed in [248] and [249]. This control allocation problem solved using an online optimization was capable of exploiting the whole attainable virtual control set while avoiding actuator saturation whenever possible. The estimation of its computational effort leads to approximately 5000 multiplications and 4500 additions for the whole optimization.

In the case of an octorotor UAV, due to the increased number of redundant control effectors, the allocation of these controls to achieve the desired moments becomes nonunique. In [79], the objective of control reallocation after up to four motors failures is to recover the octorotor subject to saturation constraints while minimizing the energy consumption. Another common way to deal with the extra freedom in u calculation is to use pseudoinverses. The weighted pseudoinverse control allocation was considered in [142] while neglecting any saturation and rate constraints on the motors speeds. The redistributed pseudoinverse was applied in [141]. The first step of this technique is to solve the unconstrained control allocation problem and then project the optimal vector u onto the admissible set of inputs to satisfy the constraints. A combination of FTC adaptive SMC with control allocation schemes was presented in [250], [251], and [252]. In the case of the desired virtual control not being achieved by the control allocation, the online adaptive SMC can smoothly adjust the control gain to stabilize the overall system. The integral SMC [231], [253], LPV SMC [254], [255], Supertwisting SMC [256], and $\mathcal{L}1$ roust control [257] were also combined with control allocation for accommodating single and multiple actuators failures.

The control allocation technique was also considered on quadrotor systems in [110], [123], and [258].

DISCUSSION

Table 5 summarizes the advantages and shortcomings of each of the most used robust controllers in the passive

Table 5.

Advantages and Shortcomings of Various Robust Control Strategies for FTC of Multirotor UAVs

Robust controller	Advantages	Shortcomings
Conventional SMC	• Robust to exogenous disturbances and para-metric uncertainties • Simple structure • Disturbance rejection	• Chattering problem • Finite time con-vergence of the states not assured • Large energy consumption
Terminal SMC	• Finite time convergence • Robustness to parametric uncertainty without reco-ursing to high frequency switching control • High steady-state tracking precision	• Disturbance bound needs to be known • Becomes infinite if states crosses equilibrium • Chattering problem
Nonsingular terminal SMC	• Eliminates singularity • Finite time convergence • High-precision tracking performance	• Chattering problem
Integral terminal SMC	• Zero steady-state error for constant or eventually constant disturbances • Eliminates singularity • Fast convergence speed • Handles mismatched uncertainties • Chattering mitigation	• Additional tuning parameters • Increased computational load
Fractional-order control	• Improved robustness • Memory effect • Fewer parameters	• Complexity of fractional-order calculus • Complex design
Backstepping control	• Robust • Fast response • Precise tracking capability • Low computational resources	• Large control signals • Complete knowledge of the full state
H-infinity control	• Disturbance and uncertainties rejection • Accurate tracking performance	• High level of mathematical understanding needed
Nonlinear dynamic inversion	• Conceptually simple • Handles nonlinear systems without gain scheduling	• Requires an accurate knowledge of the nonlinear system dynamics

FTC strategies applied on multirotor UAVs. Table 6 summarizes the reviewed active FTC systems with their classification in addition to the main challenges related to their implementation.

Based on this summary, one can notice the following.

1) Sensor faults are rarely considered as a major FTC problem [55], [74], [75], [83], [84], [120], [197], [219], [220]. Generally speaking, the controller redesign is not required when using data fusion for sensor masking. The switching concept is commonly adopted to switch from a faulty sensor to a healthy redundant one or to a reliable estimation of the faulty sensor outputs.

2) The overall performance of an active FTC system depends not only on the quality of the diagnosis and recovery components, but also on the interaction of them in a real-time environment. Only few works have discussed the integrated design and real validation of the fault diagnosis and reconfigurable control on multirotor UAVs [55], [74], [78], [79], [105], [106], [117], [131], [142], [163], [199], [232], [233], [248]. However, systematic design guidelines for issues, such as how to design the diagnosis scheme effectively for reconfigurable control of multirotor UAVs and what are the requirements on this scheme, still need to be further discussed and investigated.

3) The active FTC design schemes should be able to cope with the postfault modeling errors and diagnosis uncertainties. With respect to this, robust control techniques were exploited in few works [55], [105],

Table 6.

Reconfigurable Control Algorithms in Active FTC Systems Applied to Multirotor UAVs		
Classification criterion	**Reconfiguration or accommodation method**	**Challenges**
Mathematical design tools	• Estimation and compensation [83], [84], [55], [113], [115], [126], [75], [232]	• Performance highly affected by fault estimation accuracy and the presence of simultaneous faults
	• Adaptive control [149], [182], [183], [184], [185], [186]-[197], [198], [199], [207], [177], [200]	• Slow convergence • Not reliable in critical cases due to the absence of health monitoring
	• Reinforcement learning [201], [202], [203], [204]	• Lack of interpretability • Limited generalization
	• Intelligent control [156], [208], [226]	• Necessity of training information • Complexity of providing the correctness of knowledge processing
	• Multiple model [233]-[235], [236]	• Significant offline efforts for the design of the bank of controllers • Restricted to the finite number of faults that have been considered offline • Online effort for the implementation of controllers
	• Pseudoinverse [117]	• Stability of the reconfigured closed-loop system • Time consumed to approach the acceptable matching
	• Gain scheduling (GS) [128], [240], [241]	• Guarantee of closed-loop stability and performance only in a local sense
	• LPV [118], [120], [242], [243]	• Computational Complexity
	• MPC [127], [237], [238], [239]	• High online computational effort • Need of an accurate dynamic model • No guarantee for stability
	• Control allocation [110], [123], [258], [245], [246], [247], [248], [141], [142], [249], [105], [250], [251], [257], [231], [252], [253], [254], [255], [256]	• Actuator constraints not taken into consideration • Solving optimization problems online
	• Virtual actuator [106], [107]	• Performance highly dependent on fault diagnosis system
Design approaches	• Precomputed laws: LPV, gain scheduling, and multiple model,	
	• Online automatic redesign: MPC, pseudo-inverse, adaptive control, and virtual actuator	
Reconfiguration mechanisms	• Optimization: MPC • Switching: LPV, gain scheduling, and multiple model • Matching: pseudoinverse • Following: MPC • Compensation: adaptive control • Fault hiding: virtual actuator	

[248] for reconfigurable controller design in taking into account uncertainties and disturbances. The work in [106] deals explicitly with diagnosis uncertainties problem by proposing an evaluation method that guarantees that the diagnosis result is always unambiguous from the point of view of control reconfiguration.

4) An important number of existing FTC schemes are designed based on the assumption of fast linear actuator dynamics where the actuator generates an output similar to the input. However, this assumption is not satisfied in practice where actuators are subject to nonlinear dynamics, such as actuator saturation. As shown in [29], [30], [116], [116], [123], [126], and [187], the motors dynamics have a large influence on the system behavior.

OPEN PROBLEMS IN MULTIROTOR UAVS FTC

Despite the recent developments in multirotors FTC systems with faults, parameters uncertainties, and disturbances addressed, the problem of reliable FTC system is still not completely discussed. More specifically, the following issues should be solved further:

1) Proper modeling of the multirotor UAV under faults.
2) Energy consumption under faults.
3) FDD and FTC during takeoff and landing.
4) Generalization of FDD schemes.
5) Bidirectional rotor systems.
6) Fault tolerance in presence of faults and attacks.
7) Fault-tolerant cooperative control of multiple multirotor UAVs.

PROPER MODELING OF THE MULTIROTOR UAV UNDER FAULTS

One of the main challenges in model-based FDD and FTC systems of multirotor UAVs resides in the existence of models that do not reflect the properties of the UAV adequately under faults. For example, the time-varying disturbances resulting from the faults occurrence were never considered in the modeling phase. The behavior of the propellers with damaged blades when rotating was not modeled accurately [30]. This affects the diagnosis and recovery processes based on the model of the UAV.

ENERGY CONSUMPTION UNDER FAULTS

The problems related to energy consumption of multirotor UAVs and flight endurance maximization have been widely studied in the literature. However, they have been just tackled at path planning level and they focused to maximize the flight endurance by considering the minimization of energy consumption without taking into account the effect of fault actuators and its impact on battery discharge, during the mission development [259]. Once an actuator fault occurs, it was shown that the battery discharge rate increases due to the tracking controller trying to compensate the fault effects. This constraint should be explicitly considered in the FTC design. In some situations, it would be necessary to consider additional actions, such as reducing the flight speed of the UAV or reconfiguring the initial path by reducing the number of way points. In addition, it is necessary to determine at which state of charge levels it is possible to reconfigure the control efforts without reconfiguring the initial mission conditions.

FDD AND FTC DURING TAKEOFF AND LANDING

The multirotor must perform reliable maneuvers that encompass not only the normal flight conditions, such as hover or forward flight, but also the take-off and landing maneuvers, where interaction with the ground occurs. In the critical take-off phase, the autopilot controller must provide robustness to uncertainties in both the environment and the dynamical vehicle model and to faults. In most of the available literature, FDD and FTC techniques were tested during hovering or forward flight or during takeoff by using a simplified reduced model and neglecting the ground effect [52].

SCALABILITY OF FDD SCHEMES

Several methods have been used for fault diagnosis of multirotor UAVs and developed from different backgrounds and considerations. The majority of these methods handle one specific type of faults (sensor or actuator fault) and only the single faults case. The FDD method should be able to treat not only one type of fault or single fault but also different, multiple, and simultaneous faults as well. This is a challenging task to achieve because of the interactive effects of the multiple failed components.

BIDIRECTIONAL ROTOR SYSTEMS

The FTC performance of multirotor UAVs is constrained by the unidirectional rotors that rotate in one direction only. The bidirectional rotors can help to accommodate more patterns of actuator failures. A recent work proposing a new propeller blades design to meet desired aerodynamic performance was presented in [260] and still needs to be validated.

FAULT TOLERANCE IN PRESENCE OF ATTACKS

Attacks on UAVs can be categorized as physical attacks, such as jamming or spoofing of GPS signals, or cyberattacks, such as malicious software or network intrusions [261]. Ensuring the fault tolerance of UAVs in the presence of attacks is a complex and still an ongoing challenge. It requires a combination of redundancy, fault detection and isolation (FDI) techniques, and secure communication protocols to ensure the safety and reliability of these systems in the face of potential attacks.

FAULT-TOLERANT COOPERATIVE CONTROL OF MULTIPLE MULTIROTOR UAVS

In UAVs formation, the embedded transmitter and receiver devices are used to establish communication among neighboring UAVs within the network. However, due to the limited capacity, the communication ranges of these devices cannot be infinite. As a result, the FTC design for multi-UAVs must explicitly take into account the communication constraints and ranges of the transmitter and receiver devices to ensure practicality of the control strategies. In addition, communication time-delays and faults may severely degrade the FTC performance. Although earlier works have addressed communication time-delay issues in unmanned vehicles [262], very few results have been obtained on the FTC of multi-UAVs that consider these communication constraints.

CONCLUSION

As an active and emerging field of research in control systems, fault tolerance has recently attracted more attention. By thoroughly understanding the practical applications, the investigative scope of FTC systems design was presented. More specifically, a brief review of the recent developed works on multirotor UAVs FTC design was given from several different viewpoints. The existing approaches in fault diagnosis including model-based and data-driven-based schemes, and fault-tolerant controller design of multirotor UAVs were discussed in details. The review indicated that each existing FTC design approach has its own advantages and limitations, and having enough redundancy is a key solution to improve multirotor reliability. In the design process, the stochastic nature of the system, uncertainties, impreciseness, and time delay of diagnosis should all be taken into consideration. In addition, the capability of the controller to handle external disturbance and system uncertainties needs to be guaranteed.

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