Adaptive Observer-based Fault-tolerant Control for Actuator fault in quadrotor UAV

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*Abstract*—This paper proposed a novel Fault Tolerant Control (FTC) approach based on fault estimation (FE) for quadrotor multiple actuator faults. First, a nonlinear dynamic model of the quadcopter was presented tacking in to account high-order non-holonomic constraints as well as different physical phenomena that can influence the dynamics of the structure. Secondly, an adaptive observer is used to estimate the actuator fault magnitudes, then, control laws have been developed based on backstepping approach to compensate the fault effect in the system. Finally, different simulations have been carried out to show the performance and effectiveness of the proposed method.

Keywords—Active fault tolerant control, quadrotor unmanned aerial vehicles, nonlinear dynamical model, actuator faults, adaptive observer, backstepping approach.

# Introduction

Automatic dynamic systems sometimes might suffer from faults (malfunctions), e.g., offsets of actuators/sensors, deviations of component parameter, loss of actuator effectiveness, etc. These faults may degrade system performance or even cause safety problems.

The last decade quadrotors as unmanned aerial vehicles (UAV) have exhibited immense attention especially in civilian and military applications which require increasing safety.

The quadrotors have been studied lately by certain writers like in [1] and [2]. Many actuator faults tolerant control has been proposed. The work in [3] propose a FTC for attitude tracking based on the Disturbance Observer and a control allocation algorithm. An adaptive sliding mode FTC scheme based on prescribed performance control and neural networks is developed for an UAV quadrotor in [4]. In [5], a finite-time FTC based on a multivariable integral terminal sliding mode control (TSMC) and a finite-time exact observer (FEO) is proposed to separately accommodate the parametric uncertainties and actuator faults. The work [6] presents a new composite adaptive disturbance observer-based decentralized fractional-order FTC scheme based on nonlinear disturbance observers and robust controllers. An active FTC scheme based on fixed-time linear active disturbance rejection control is proposed in [7] using the fixed-time extended state observer (ESO) and a continuous output feedback controller against actuator fault and external disturbance. Other strategies are proposed in [8], [9], [10], [11].

In the field of active fault-tolerant control (AFTC), The FE-based FTC for Lipschitz non-linear systems has attracted great attention in the past decade. Its advantage is that it can estimate the faults shape (the magnitude with respect to time) without going through the residual generation phase. Significant literature on the subject of FE design methods for Lipschitz non-linear FTC systems has been established, mainly based on sliding-mode observers, observers for singular systems, and adaptive observers [12]. When faults are modelled in terms of parameter changes, adaptive observers can be used to estimate these faults.

This paper presents a new active FTC technique on a quadrotor in the presence of actuator faults. It is based on a joint use of an adaptive observer for fault reconstruction and estimation (FRE) and a backstepping approach for system control. Compared to previous work on the active FTC of a quadcopter UAV, the main contributions of this paper are:

(i) in our work we have not neglected the non-linearity of the dynamic model of the quadcopter and the high-order non-holonomic constraints; (ii) Both the system state and actuator faults can be simultaneously estimated by the used adaptive observer. (iii) The proposed approach is based on the use of the adaptive observer proposed in [13] which does not necessitate that the system structure meets the required standard observer matching requirement for the traditional adaptive state observer and it is possible to estimate both additive and multiplicative faults regardless of the number of measured outputs.

The paper is organized as follows. In the first section, the dynamic modelling of the quadcopter is carried out. To detect defects, an adaptive observer was developed to estimate the size of faults in the second section. Then, in the third section, a robust control strategy with actuator faults is established based on the backstepping technique taking in to account the faults presence. Finally, in the last section, simulations on MATLAB were carried out to validate the synthesized control laws. The results were conclusive in the presence of faults in the actuators.

# Nonlinear Dynamical modeling of quadrotor

The quadrotor dynamical model can be derived using the Euler-Lagrange formalism. Let’s introduce two reference frames. Let E (O, X, Y, Z) designate an inertial frame, and B (o, x, y, z) designate a frame permanently coupled to the quadrotor, as illustrated in figure 1. Both of them are assumed to be at the centre of gravity of the quadrotor UAV.

The absolute position of the quadrotor is denoted by the three coordinates () and its attitude by the three Euler’s angles () respectively called Roll angle ( rotation around x-axis), Pitch angle ( rotation around y-axis) and Yaw angle ( rotation around z-axis).



Fig. 1. Quadrotor configuration

The dynamic model of the quadrotor is given as in [1] by:

|  |  |
| --- | --- |
|  | (1a) |
|  | (1b) |
|  | (1c) |
|  | (1d) |
|  | (1e) |
|  | (1f) |

Where:

* C and S indicate the trigonometrical functions cosines and sines respectively.
* is the total mass of the quadrotor.
* and are lift and drag coefficients respectively.
* , and are the constants inertia.
* , and are the translation drag coefficients.
* , and are the aerodynamic friction coefficients around (x, y, z).
* is the distance between the quadrotor centre of mass and the rotation axis of propeller.
* is the rotor inertia.

, , and are the control inputs of the system which are written according to the angular velocities of the four rotors as follows:

|  |  |
| --- | --- |
|  | (2) |
|  | (3) |

Taking into account nonholonomic constraints for our system is of major importance as are in compliance with physical laws and define the coupling between various states of the system. From the equations (1d) to (1f) we can extract the expressions below:

|  |  |
| --- | --- |
|  | (4a) |
|  | (4b) |

# Nonlinear adaptive observer design

## State-space model

The complete model resulting by adding the actuator faults in the model (1) can be written in the state-space form:

|  |  |
| --- | --- |
|  | (5) |
|  |

With:

is the state vector of the system, such as:

|  |  |
| --- | --- |
|  | (6) |

, , and are known constant matrices of appropriate dimensions, is the resultant vector of actuator faults related to quadrotor motions, represent the actuator faults vector, with, is a known function matrix which may depend nonlinearly on , is the input control vector, is the output vector giving by and is known nonlinear function vector.

Throughout this article, the following assumptions are considered:

**Assumption 0**: The pair (, ) is observable;

**Assumption 1**: and satisfy the Lipschitz property with respect to there exist positive constants and such that:

|  |  |  |
| --- | --- | --- |
|  |  | (7) |
|  |  | (8) |

**Assumption 2**: The fault vector is piecewise constant and bounded in the following sense:

|  |  |
| --- | --- |
|  | (9) |

Where is a known constant vector and is a known positive constant.

**Assumption 3**: The resultant of actuator faults related to quadrotor motions are slowly varying in time as follows:

|  |  |
| --- | --- |
|  | (10) |

**Assumption 4**: The matrix is persistently exciting, i.e., there exist positive constants , and such that for all :

|  |  |
| --- | --- |
|  | (11) |

## The adaptive state observer

In , authors have proposed a new methodology for an adaptive observer-based FE design for a certain class of nonlinear systems. This observer employs the nonlinear system model described by equation (1).

For developing the considered adaptive observer, in addition to assumptions cited below, the system model (5) has to satisfy the following conditions:

**Assumption 5:** The matrices , , and satisfy

|  |  |
| --- | --- |
|  | (12) |
|  | (13) |
|  | (14) |

**Assumption 6:** The first derivative in time of is continuous and bounded provided that is bounded.

Now, decompose C and E into bloc matrices as follows:

|  |  |
| --- | --- |
| and | (15) |

where and .

Without loss of generality, it can be assumed that the outputs of the system have been reordered so that the matrix is full rank. The state space correspondent to the model (1) is rearranged as follow:

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  | (16) |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |

With

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |

Define new coordinates as , where

|  |  |
| --- | --- |
|  | (17) |

Then, using (12) and (13), in the new coordinate system, the original system (1) has the following form:

|  |  |
| --- | --- |
|  | (18) |

Where

|  |  |  |
| --- | --- | --- |
|  | | *,* |
|  | |  |
|  |  | |
|  | |  |

Based on the transformed system (16), we propose the following adaptive observer:

|  |  |
| --- | --- |
|  | (19a) |
|  | (19b) |
|  | (19c) |

Where , , is the state estimate, is the fault vector estimate, is the observer gain matrix, is the learning rate matrix, and are matrices to be designed later, and is a switching leakage term defined as

|  |  |
| --- | --- |
|  | (20) |

which forces the estimated fault vector to remain within the region bounded by , with is a positive constant.

Let and respectively observation and the fault estimation error. Then, from (5), (10) and (19) we get

|  |  |
| --- | --- |
|  | (21) |
|  | (22) |

Where and .

Theorem 1 provides strategy adopted from [13] to design an adaptive observer using a LMI formulation.

**Theorem 1.** Under Assumptions 1, 2, 5 and 6, the observation error determined by (21) is asymptotically stable while the fault estimate error determined by (22) remains bounded, if there exist positive real numbers and and matrices , and such that:

|  |  |
| --- | --- |
|  | (23a) |
|  | (23b) |
|  | (23c) |

With: .

Once the above conditions are satisfied, the observer gain L is chosen as

|  |  |
| --- | --- |
|  | (24) |

Moreover, if the persistency excitation condition in Assumption 4 holds, then the vector converges to zero.

# Control Strategy of Quadrotor in presence of Actuator Faults

In the proposed method, an adaptive observer is used as a monitoring module and the recovery module is based on the Backstepping approach.

Based on the backstepping approach, an iterative algorithm is used to synthesize the control laws forcing the system to follow the desired path in presence of actuator failures, we summarize all stages of calculation concerning the tracking errors and Lyapunov functions in the following way:

|  |  |
| --- | --- |
|  | (25) |
|  |  |

Where is the desired state of .

The related Lyapunov functions are provided by:

|  |  |  |
| --- | --- | --- |
|  |  | (26) |
|  |

Where .

The synthesized stabilizing control laws are as described in the following:

|  |  |
| --- | --- |
|  | (27a) |
|  | (27b) |
|  | (27c) |
|  | (27d) |
|  | (27e) |
|  | (27f) |

***Proof.*** Let’s demonstrate the expression of given by (27a)

The expression of the command can be find out using the following Lyapunov function

|  |  |  |
| --- | --- | --- |
|  |  | (28) |

Where and can be find using (25) and (26).

Using (21), (22), (25) and (26) after deriving (29), we get

|  |  |  |
| --- | --- | --- |
|  |  | (29) |

Where Q is given by (23b) and ( is the minimum eigenvalue of ) and .

The stabilization of (, ) can be obtained by introducing the input control :

|  |  |
| --- | --- |
|  | (30) |

Finally, the inequality (29) becomes

|  |  |
| --- | --- |
|  | (31) |

The same steps are followed to extract , , , and .

# Simulation Results

In order to evaluate the performance and effectiveness of the proposed approach, we executed simulations in MATLAB/SIMULINK® environment. The LMIs were solved using CVX, a MATLAB-based modelling system for convex optimization.

The quadrotor object of our study is Draganfly IV manufactured by Draganfly Innovations. Parameter identification is figured out [2] and resumed below.

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  | | |
|  | | |
|  | | |
|  | | |
|  | | |
|  | | |

In this simulation test, four actuator faults related to roll, pitch, yaw and altitude (, , , ) are introduced. The simulation results are presented in Figure 2, 3 and 4. The state estimates in faulty case are shown in Figure 2.



Fig. 2. Trajectories along roll (𝜑), pitch (θ), yaw angle (ψ), and altitude z

From this simulation (Figure 2), it can be seen that the desired and the true state are matched perfectly even in the presence of fault, which clearly illustrates the good performance and robustness of the control strategy.

The figure 3 present the true and the estimated faults.

According to Figure 3, there is very excellent estimation of the actuator faults. The estimates of and converges rapidly to the real values. The mean of the estimation error of and of the order of . Therefore, the proposed observer can give a fast and accurate fault estimation.



Fig. 3. Fault estimation

Figure 4 illustrate the 3D trajectory of the quadrotor aircraft throughout the flight. The simulation results indicate high performances and resilience towards stability and tracking even after the occurrence of actuator faults, which shows the efficacy of the control method suggested in this work.



Fig. 4. Global trajectory of the quadrotor in 3D along the (X, Y, Z) axis

# Conclusion

This paper introduces a new fault-tolerant control (FTC) strategy for diagnosing actuator faults in the quadcopter. This is the first time that this methodology proposed in [13] is used in the field of active FTC for a quadrotor. It is based on the observer-based fault estimation and reconstruction (FRE) technique using an adaptive observer.

In our work we have not neglected the non-linearity of the dynamic model of the quadcopter and the high-order non-holonomic constraints. Then, both the system state and the actuator faults can be simultaneously estimated by the used adaptive observer proposed in [13]. The used observer does not necessitate that the system structure meets the required standard observer matching requirement for the traditional adaptive state observer and it is possible to estimate both additive and multiplicative faults regardless of the number of measured outputs.

Firstly, we introduced a complete nonlinear dynamical model of the quadrotor, taking into consideration several physics phenomena that might impact our system's navigation in space. Secondly, an adaptive observer has been developed to estimate simultaneously the system state used in feedback control and actuator faults used in the FDI task. Thirdly we presented a stabilizing control law, in the presence of actuator faults, based on backstepping technique.

Several simulations in MATLAB were run to evaluate the performance of the proposed strategy with a defective system at the roll, pitch, yaw and altitude actuators. The results of the simulation clearly illustrate the good performance of the adopted strategy. It made it possible to precisely estimate the faults and to ensure stability and the trajectory tracking.

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