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

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*Abstract*— This paper deals with the design of a novel Active Fault Tolerant Control (AFTC) algorithm for an under-actuated quadrotor UAV system in the presence of actuator faults. A robust control strategy based on the backstepping technique is used to compensate for the fault effect in the system. In order to estimate the system state and the fault magnitude, an adaptive observer is developed based on a nonlinear dynamic model of the quadcopter. This dynamic model, considering high-order non-holonomic constraints as well as various physical phenomena that can influence its dynamics, is briefly presented. Lyapunov-based stability analysis shows that the proposed control strategy design maintains the stability of the closed-loop dynamics of quadrotor aircraft even in the presence of actuator faults. Numerical simulation results are provided to show the good tracking performance of the proposed control laws.

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

# Introduction

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

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

The quadrotors have been studied lately by certain writers, as in [1] and [2]. Many actuator-fault-tolerant control strategies have been proposed. The work in [3] proposes 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], and [11].

The fault estimation (FE)-based FTC for non-linear systems has attracted great attention in the past decade. Significant literature on design methods for Lipschitz non-linear FTC systems has been established, especially observer-based methods. These methods are mainly based on sliding-mode observers, observers for singular systems, and adaptive observers [12]. When faults are modeled in terms of parameter changes, adaptive observers can be used to estimate these faults.

The proposed FTC technique uses the backstepping technique to synthesize the control laws, taking into account the real-time faults given by the adaptive observer. The main contributions of this paper are: (i) high-order non-holonomic constraints as well as various physical phenomena, which can influence its dynamics, are taken in to account in the modelling stage; (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 structure which does not necessitate that the system structure meets the required standard observer matching requirement for the traditional adaptive state observer and it can estimate both additive and multiplicative faults regardless of the number of measured outputs; (iv) the design procedure has been formulated into an LMI optimization problem.

In this study, a new FTC strategy for a quadrotor UAV system in the presence of actuator faults is presented. A nonlinear dynamic model of the considered system is briefly discussed, taking into account the drag forces along (X,Y,Z) axes, aerodynamic friction torques, torques due to gyroscopic effects, and high-order non-holonomic constraints. Then, after a coordinate change in the original system, a nonlinear adaptive observer was developed in order to estimate the size of faults. In the third part, a robust control strategy based on a backstepping strategy is used to handle the fault effect in the system. Finally, FTC laws are verified using MATLAB simulations, which gave pretty good results despite the occurrence of actuator faults.

# Quadrotor Nonlinear Dynamical modeling

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 center of gravity of the quadrotor UAV.

The absolute location of the quadrotor can be obtained by the three coordinates and its attitude by the three Euler’s angles, respectively: roll angle (rotation around the x-axis), pitch angle (rotation around the y-axis), and yaw angle (rotation around the z-axis).



Fig. 1. Quadrotor configuration

The dynamic model of the quadrotor, taking into account the drag forces along (X,Y,Z) axes, aerodynamic friction torques, and torques due to the gyroscopic effects, 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) |

Considering nonholonomic constraints for our system is of major importance, as they 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

After adding the actuator faults to the system model given by (1), the complete model can be written in state-space form:

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

Where the state vector of the system , is given by:

|  |  |
| --- | --- |
|  | (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 this part, we aim to extend the new methodology proposed in [2] for constructing an adaptive observer-based FE design for a nonlinear quadrotor system in the presence of an actuator fault. This observer employs the nonlinear system model described by equation (1).

For developing the considered adaptive observer, in addition to the 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 [2] 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.

# FTC Strategy of Quadrotor in presence of Actuator Faults

Based on the backstepping technique, an iterative algorithm is used to synthesize the control laws forcing the system to follow the desired path in the normal and the faulty case. 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 modeling system for convex optimization.

The quadrotor object of our study is the Draganfly IV, manufactured by Draganfly Innovations. Parameter identification is figured out in [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 Figures 2, 3, and 4. The state estimates in the faulty case are shown in Figure 2.



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

It can be seen from Figure 2 that the estimated states converge to the real ones accurately before and after the fault occurrence, which clearly illustrates the good performance and robustness of the control strategy.

Figure 3 presents the true and estimated faults. According to this figure, there is a very excellent estimation of the actuator faults and the mean of the estimation error and of the order of Therefore, the proposed observer can give a fast and accurate fault estimation.



Fig. 3. Fault estimation

Figure 4 presents the 3D position of the quadrotor in the faulty case. It demonstrates excellent performance and resilience towards stability and tracking even after the occurrence of actuator defects, which illustrates the efficiency of the control approach proposed in this paper.



Fig. 4. Global trajectory of the quadrotor in 3D along the (x, y, z) axis

# Conclusion

In this paper, a new observer-based fault estimation and reconstruction (FRE) technique using an adaptive observer is presented. The developed FRE is coupled with a backstepping approach to construct a new fault-tolerant control approach for actuator faults in quadcopters.

In these papers, the dynamic model non-linearity of the quadcopter and the high-order non-holonomic constraints are not neglected. Then, both the system state and the actuator faults can be simultaneously estimated by the 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.

Taking into consideration several physics phenomena that might impact our system's navigation in space as well as the high-order non-holonomic constraints, a complete nonlinear dynamical model of the quadrotor is briefly presented. Then, after a coordinate change in the original system, a nonlinear adaptive observer was developed in order to estimate the fault magnitudes. Finally, we presented stabilizing control laws based on the backstepping technique and taking into account the dynamic of the actuator faults. The design procedure has been formulated into an LMI optimization problem.

To evaluate the performance of the proposed strategy with defected actuators, a set of simulations is conducted in MATLAB. The simulation results have shown the high efficiency of this control strategy. It made it possible to precisely estimate the faults and ensure stability and trajectory tracking.

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