

Extended summary

Model-Based Diagnosis and Control

of Unmanned Aerial Vehicles:

Application to the Quadrotor System

Curriculum: Ingegneria Informatica, Gestionale e dell'Automazione

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Abstract.

Quadrotors are small aerial vehicles propelled by four rotors. They are commonly designed to be used as unmanned vehicles: vehicles that can accomplish a task without the aid of a human guide. In order to fly autonomously, the quadrotor must rely on: sensors that provide information about the external environment or the internal system states, actuators that physically realize the desired motion and a controller that drives the actuators according to the measurements and the task that need to be accomplished. Both sensors and actuators, however, may be subject to faults or failures and it is important that the vehicle can be also controlled if they occur. The thesis addresses two problems regarding the capability of the quadrotor vehicle to deal with faults: fault detection on sensors or actuators and the development of a stabilizing control law which can keep the vehicle flying even in case of actuator loss.

Fault detection on sensors or actuators is addressed developing a model-based diagnostic module, featuring a residual generator and a decision making block. The residual generator is built on a nonlinear observer (Thau observer) which compares its signals with the measurements provided by the sensors. The resulting signals are evaluated by the decision making block, according to an adaptive threshold policy. Because of the way it is built, the module can be applied to a wide class of unmanned vehicles satisfying certain conditions, and not to the quadrotor vehicle only.

The control law in case of actuator loss is developed using a double control loop architecture. The inner controller (based on feedback linearization) stabilizes the roll and pitch motion and regulates the altitude at a desired value. The outer controller manipulates the values of the desired roll and pitch angles in order to regulate the displacement along the horizontal plane. This is achieved sacrificing the controllability of the yaw angle, which does not compromise vehicle safety, but only limits the ability for the vehicle to point any visual sensor in a desired direction.

Keywords.

Fault diagnosis, nonlinear control, unmanned vehicles.



1 Problem statement and objectives

Unmanned Vehicles (UVs) can be defined as vehicles that can accomplish a task without the aid of a human guide. With an increasing availability of modern sensors and requirement for control systems to be more secure and reliable, fault diagnosis and tolerance in such systems is becoming more and more critical and significant [1,2,3,4]: in presence of undesirable effects, such as faults in the actuators or sensors, the vehicles control systems must be responsive and adaptive to such faults.

Among all the unmanned vehicles, Unmanned Aerial Vehicles (UAVs) are those which most profited of the advances in low-power embedded processors, miniature sensors and control theory. Low-power consumption allows to increase the flight autonomy; multiple miniature sensors can augment the set of available measurements and modern control algorithms can achieve attitude control, trajectory following and formation cooperation with performances which were unimaginable just few years ago [2].

The quadrotor vehicle, object of study of the thesis, represents one of the most promising architecture for unmanned vehicles [5]. Quadrotors, also called quadcopters, are small aerial vehicles propelled by four rotors. They present several advantages with respect to comparably scale rotary wing vehicles. First, the four rotors generate a greater vertical lift thrust which combined with the symmetrical geometry allows this kind of vehicles to be highly manoeuv-rable. Second, the use of four rotors allows each rotor to have a smaller diameter, thus reducing the possible damage caused by the blades in case of collision; moreover enclosing the rotors within a frame, the rotors can be protected during collisions, permitting flight indoor and in obstacle dense environments, with low risk of damaging the vehicle, its operators or its surroundings [6]. Third, quadrotors are based on fixed rotor blade pitch angles and vary their attitude changing the rotational speed of each rotor: this simplifies the design of the vehicle and reduces maintenance time and cost. High manoeuvrability, safety and simplicity have made them one of the most interesting aerial vehicles for indoor/outdoor navigation [7].

Despite different prototypes, control algorithms and approaches, all the quadrotor architectures share two things: they need the presence of several sensors in order to work properly and are more subject to motor problems, with respect to similar vehicles with a reduced number of motors. For these reasons the detection of faults on sensors or actuators and the capability of retaining control even when the vehicle is not perfectly working is of great importance [11], [12], [13]. Nevertheless in the case of the unmanned quadrotor vehicle only few researches have been devoted to the problem of fault detection and isolation and they are mostly useful for hover flight only. Moreover few Fault Tolerant Control (FTC) strategies have been proposed for the quadrotor vehicle and no control law has been proposed when one of the actuator is not working anymore.

The present thesis aims to develop a module for detecting faults on sensors or actuators which equip the quadrotor vehicle [14], and a control law capable of stabilizing the quadrotor vehicle in case of loss of one of the actuators [15].



2 Research planning and activities

2.1 The Mathematical Model

In order to provide the mentioned solutions, the first planned activity was that of developing a mathematical model of the quadrotor vehicle (see figure 1 for a schematic representation of the vehicle), which could be later used to implement model-based techniques or as a substitute of the real system in simulated scenarios. The activity has been carried out with the aid of models already available in literature, such as [8], [9], on which modifications were made in order to adapt them to the case of study of the thesis. The resulting model is based on the rigid body dynamics approximation of the quadrotor vehicle, on which different forces and moments are considered. The dynamics has been initially formulated in terms of the body frame coordinates (i.e. the frame which is fixed to the center of mass of the vehicle) and then expressed in terms of the earth frame coordinates (i.e. the inertial frame) using kinematics transformations.



Figure 1: the quadrotor vehicle scheme used to derive the mathematical model

The resulting equation set is made of 12 first order differential equations, whose solutions describe the linear and angular motion of the vehicle in the inertial frame.



2.2 Fault Detection System

With a mathematical model available, it has been then possible to investigate the problem of detecting faults on sensors or actuators which equip the quadrotor vehicle. This has been done developing a Fault Detection (FD) module for the quadrotor vehicle according to a model-based approach.

Since unmanned vehicles are usually approximated as rigid bodies subject to actuation and gravity forces, the idea was that of studying the mathematical formulation of the rigid body subject to such forces and evaluate under which assumptions it could be written as a state-space observable system satisfying local Lipschitz conditions.

When proper assumptions are satisfied, that is to say

- the body frame origin can be placed at the center of mass of the rigid body
- the body frame axes are the principal inertia axes of the rigid body
- the contribution of the small body forces (Euler, centrifugal and Coriolis) to the translational dynamics is neglectable
- actuation forces are "smooth"

it is possible to adopt a nonlinear Lipschitz observer, namely the Thau observer, in order to build residual signals (i.e. signals calculated as the difference between the actual measurements and the observer outputs, thus carrying information about the presence of faults on the system – see figure 2).



Figure 2: the scheme adopted for the FD module

Once the residuals are available they can be used for diagnosis purposes adopting a decision making block, in which each residual is compared to a threshold which is a linear combination of a constant value, mean value and variance of the residual, multiplied by proper weights which must be chosen according to the application scenario and calculated on a moving window. When a residual exceeds the assigned threshold, then the fault is detected and the system is assumed to be faulty.



Finally the module has been used to detect faults on sensors or actuators of the quadrotor vehicle in a simulated scenario, in which the mathematical model previously derived was adopted.

2.3 Control Laws in Case of Actuator Loss

Once a FDI system was available, the focus has been moved on control strategies in case of actuator loss.

When one of the rotor fails, the quadrotor looses the ability to control independently the three torques necessary to fully control the attitude of the vehicle. Furthermore this rotor failure implies the loss of controllability of one variable from roll, pitch, yaw and altitude. From a physical point of view, the most important variables to control are roll, pitch and altitude. The roll and pitch angles are of vital importance because a small change in their values may affect the stability of the vehicle and reflects in a big change in the longitudinal/lateral displacement in the earth frame. On the other hand altitude must always be kept above a positive threshold in order to avoid collision with the ground. The impossibility to control yaw displacement when a rotor failure occurs, instead, implies loosing the heading of the vehicle, which is important whenever the vehicle must accomplish tasks that require directional sensors, but may be considered of minor importance when dealing with a safe landing procedure. For these reasons a control law was developed which sacrificed the controllability of the yaw state.

The control structure was realized using a double loop architecture as described in figure 3. An inner and faster controller has the task to regulate the roll and pitch angles and the altitude of the vehicle. An outer and slower controller has instead the aim of modifying the desired values of roll and pitch by small angles in order to perform trajectory following.



Figure 3: double control loop adopted in case of actuator loss

The inner controller, based on feedback linearization [10], allows to write the roll, pitch and altitude nonlinear dynamics as a linear system in the Brunowski form (chain of integrators). The resulting linear system can then be controlled using a proper linear control law. The remaining dynamics, which describes the lateral and longitudinal motion of the vehicle, was used to develop the control law for the outer loop, under the assumption of small angles. Mod-



ulating the desired values of roll and pitch with a proper frequency, proportional to the angular velocity at which the vehicle is rotating, a desired position in the horizontal plane can be reached.

The developed control law has been tested in a simulated scenario, showing how it performs when the inner controller or both the inner and outer controllers are running.

An alternative version was also presented which took into account saturation constraints, thanks to the use of a robust feedback linearization approach together with loop-shaping techniques.

3 Analysis and discussion of main results

The diagnostic module has been tuned in a simulated environment in order to detect additive and slow varying (incipient) faults on sensors or actuators of the quadrotor vehicle. In figure 4 the residuals in case of fault at t=25s on the sensor measuring the roll angle.



Figure 4: residuals in case of fault on the sensor measuring the roll angle

As it can be seen in figure 4, both residuals 2 and 3 exceed the designed thresholds when the fault appears in the system: the decision logic can then trigger the faulty state status (similar behaviors can be seen for faults affecting the pitch measurement or for actuators fault).

The control law in case of loss of an actuator has been validated in a simulated scenario in which the initial states are far from the hover condition and the controllers have the task to



stabilize the system (roll and pitch angle must go to zero), to reach the origin position of the horizontal space and to land (z must go to zero) when that position is reached.



Figure 5: the linear and angular positions of the quadrotor vehicle when both inner and outer controllers are running

As it can be seen in figure 5 the roll and pitch angles are stabilized, but there are small oscillations due to the presence of the outer controller which tends to force the attitude angles to differ from zero. The yaw angle, whose controllability was sacrificed, does not reach instead a steady state value, but increases according to a linear law. The lateral and longitudinal positions reach the origin, while the altitude quickly assume the desired value of *10m* until the landing procedure.

4 Conclusions

The main contributions of the thesis are two.

The first contribution is the development of a fault diagnosis module, based on a nonlinear model and applicable to a wide class of unmanned vehicles. The nonlinear observer, even if simplified, can take into account a more comprehensive dynamics with respect to linear observers which are usually adopted in fault detection schemes for unmanned vehicles. Moreover, FD modules are typically developed as ad hoc solutions for a certain vehicle only, thus wide applicability represents an added value of the proposed approach.

Isolation capabilities of the proposed solution are at the moment limited even if they can be partially granted to particular cases of study. At the moment fault isolation is under investigation, by means of the development of a bank of observers which are all sensitive to faults in all sensors or actuators but one: in this way it could be possible to isolate where the fault is af-



fecting the system. The main challenge is to maintain, for each subsystem, the mathematical hypothesis which are needed to grant convergence of the Thau observer. Possible future works on the diagnostic module should be mainly focused on the improvement of fault isolation capabilities as described above and the validation on a real vehicle. The fault diagnosis module, moreover, could be exploited to derive diagnostic information to be integrated inside a prognosis module [17], capable of predicting, within a certain margin of uncertainty, possible wears of the quadrotor components which can affect both performances and stability.

The second contribution of the thesis is that of solving the problem of controllability of the quadrotor vehicle when only three rotors are working. Even if the proposed control law does not take robustness directly into account (since it is based on feedback linearization techniques), it represents a valid approach to understand the problem and lay down the nominal conceptual foundations for subsequent robust control designs in the presence of actuator failure. Moreover robust variations of the feedback linearization techniques are available in literature and preliminary results of their application to the quadrotor system has been presented as well.

The control system could be improved by extending the robust approach to the whole dynamics and fully analyzing the effects of parameter variations and/or actuator saturation in the closed-loop response. Both these aspects are currently under investigation. Possible future works mainly regard the validation of the control law on a real vehicle and the development of a high level control law, capable of managing cooperative tasks [18], [19] by properly setting the reference values of the low level controllers.

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