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Quad-Rotor Unmanned Arial Vehicle – A Review

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Abstract

A review has been performed on modelling and control of Quad-Rotor unmanned arial vehicles (UAVs) based on earlier published works.This research develops a thorough understanding of the system's behaviour, whereas it can be used as case study, for experimenting with control techniques and other abilities developed. The main objective is to arrive at a complete and as realistic as possible conclusion, that too without unnecessary complexity, by using simulation model in Mat lab/Simulink, allowing further immediate use of the quad rotor in future studies.

1. Introduction

In the recent years, especially due to advances in Micro-Electromechanical Systems (MEMS), electrical energy accumulators, actuators and smaller integrated micro-controlled boards, the number of studies are growing in UAVs such as the quad-rotor and related autonomous aerial robots, not only by universities and research institutions for private civilian applications but also for military purposes. It is mainly due to the inherent characteristics of such aircraft, namely high maneuvering at low translational speeds and in small volumes while being able to carry significant payload, thus making them especially adequate for aerial surveillance and monitoring tasks.

The main advantage of rotating-wing over fixed-wing aircraft is the ability of hovering and omni-directional movement. A drawback is, however, relatively higher power consumption during the flight. Even inside the rotating-wing aircraft classification, a quad-rotor is much simpler and easier to build in comparison to a classical helicopter, since the rotors' rotational axis is fixed and there are no moving parts, like aerodynamic control surfaces. Nevertheless, the rotational speed of each rotor needs to be independently controlled in order to achieve the control goals of such a highly unstable open-loop system, which makes it a challenging control engineering problem.

2. Literature Review

An extensive literature review has been done for this study. Bouabdallah [2004a] presented a system model with DC motors and by using the Lyapunov Function's non-linear control technique approach for stabilizing the aircraft's orientation (Euler angles), compare the real system's behaviour with a respective simulation. Bouabdallah et al. [2004b] extended their work on the OS4 project as they compared classical PD and PID controllers for orientation stabilization with modern LQ adaptive optimal control, despite realizing that the latter one yielded only average results, due to modeling imperfections. Stepaniak [2008] made a detailed identification work of his built system and model derivation, besides discussing hardware implementation aspects. Despite not focusing on the control loops design, whereby classical control theory was used, his work turned out to be one of the main references hereby used.

Tayebi and McGilvray [2006], on the other hand, performed a thorough and advanced study on control techniques for attitude stabilization of a quadrotor. It was used quaternions for attitude representation, Lyapunov stability's criterion and a PD2 feedback structure, with which a model-independent PD controller was compared, achieving with both configurations global asymptotic stability and disturbance rejection in similar fashion. Their experimental results were obtained from a modified version of the Draganflyer III aircraft. Kim [2007] made an interesting performance comparison among four control techniques: LQR, LQR with gain scheduling, feedback linearization and sliding mode control. They experimentally verified that LQR with gain scheduling presented more robustness in light of modeling uncertainties whereas for an accurately modeled system a better performance was achieved with the sliding mode approach. A meticulous study of usually otherwise disregarded effects such as blade flapping and propeller modeling was done by Pounds [2004]. In fact, the theoretical model for the propeller thrust and torque discussed in their paper was employed in this present work. Later on, Pounds [2006] gave continuity to their work on the X-4 flyer Mark II quad-rotor implementation (Fig. 1.1a) by designing a discrete-time PID control law to their model including the very fast blade flapping dynamics. The closed-loop behavior, though, turned out to be poor at higher rotor angular speeds (! > 450 rad/s), approaching an unstable behavior, which was attributed to high-frequency noise from the rotors interfering with the accelerometer readings.

Hamel [2002] employed the non-linear Lyapunov functions and the back stepping approach allied to quaternion attitude representation for designing non-linear attitude stabilization controllers. Although presenting a minute theoretical study and proof-based mathematical derivations, their proposal unfortunately was not accompanied by experimental results. Castillo [2004] proposed a real-time non-linear nested saturation control scheme based on Lyapunov's stability criterion, where each system state is sequentially stabilized following a priority

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rule, hence allowing a wider stability region and therefore more aggressive manoeuvring while maintaining good disturbance rejection capability. Later on, Castillo et al. [2005] compared the performance of their non-linear control with a linear one such as LQR, which presents stability issues when the system is taken far away from its operation point used for the controller design. Martinez [2007] performed an extensive identification experimental study on a commercial Dragonfly XProquadrotor, including blade flapping and torsion investigations besides windtunnel tests to identify the aircraft's aerodynamic characteristics. Since his work didn't extend to the design of control loops, its use for this project was limited as another reference for cross-checking the basics aircraft modeling hereby dealt with.

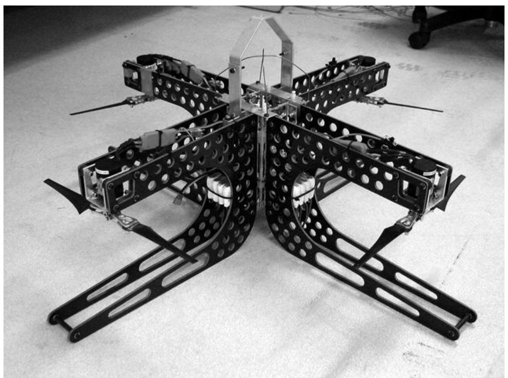

Fig: 1. STARMAC I

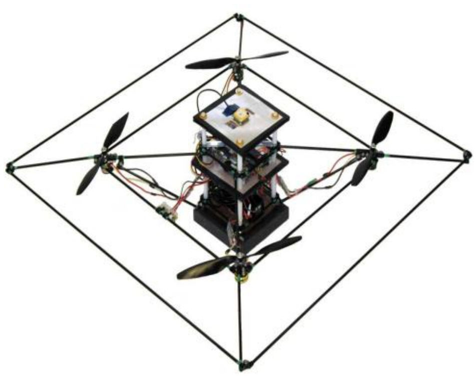

Fig: 2. X-4 Flyer Mark II

Voos [2009] applied feedback linearization in a nested control loop structure where theinner loop contains the attitude dynamics and the outer, the position one. Their experimental results were obtained also with a Dragon flyer real model. However, the dynamics of the DC motors used in the rotors was not considered in their work. *Hoffmann [2007]* focused their study on the aerodynamic effects on the quad-rotor's airframe when operating significantly far from the hover regime, at higher translational speeds, while also considering the very fast dynamics of blade flapping. Their theoretical results were experimented on the STARMAC II vehicle. *Rong Xu and ¨Umit ¨Ozg¨uner [2006]* presented a new design method for the flight control of an autonomous quadrotor helicopter based on sliding mode control. Due to the under-actuated property of a quadrotor helicopter, the controller can make the helicopter move three positions (x, y, z) and the yaw angle to their desired values and stabilize the pitch and roll angles. A sliding mode control is proposed to stabilize a class of cascaded under- actuated systems. The global stability analysis of the closed-loop system is presented. The advantage of sliding mode control is its insensitivity to the model errors, parametric uncertainties and other disturbances. Simulations show that the control law robustly stabilizes a quadrotor. A quadrotor is an under-actuated system with four independent inputs and six coordinate outputs. In this paper we present a new approach using sliding mode control to stabilize a quadrotor helicopter. A quadrotor system can be divided into a fully-actuated subsystem and an under-actuated subsystem.

Eduardo Rondon, Luis-Rodolfo Garcia-Carrillo and Isabelle Fantoni (2010) addressed the hover flight and speed regulation of a quad-rotor rotorcraft to perform autonomous navigation. For this purpose, a vision system was developed which estimates the altitude, the lateral position and the forward speed of the engine during flights. The visual information allows the construction of control strategies for different kinds of flying modes: hover flight, forward flight at constant speed. A hierarchical control strategy is developed and implemented. The local stabilization of the vehicle is proven. Experimental autonomous flight was successfully achieved which validates the visual algorithm and the control law. Image-based navigation arises as an attractive solution, small low cost cameras attached to the vehicle provide detailed information about the UAV motion and the environment structure. Due to this interaction between the sensor with its surroundings, new techniques can be developed permitting the vehicle to navigate within clustered environments. In recent years, vision has become an "ideally" to UAVs. The overall system consists of the rotorcraft, the down- ward looking camera attached to the vehicle, and the road model. The road zone is computed by a combination of line detection and color segmentation processes. Once the road information has been extracted, position and altitude estimates can be built. We consider the camera moving with respect to a rigid scene for pseudo speeds determination. *Samir Bouabdallah and Roland Siegwart* in their research came up with the conclusion that varying the rotor speeds, one can change the lift force and create motion. Thus, increasing or decreasing the four propeller's speeds together generates vertical motion. Changing the 2 and 4 propeller's speed conversely produces roll rotation coupled with lateral motion. Pitch rotation and the corresponding lateral motion result from 1 and 3 propeller's speed conversely modified as described in Fig. 1. Yaw rotation is more subtle, as it results from the difference in the counter-torque between each pair of propellers. In spite of the four actuators, the Quadrotor is still an underactuated and dynamically unstable system. It is well known that the VTOL systems are dynamically unstable and thus very hard to control the system natural response to an initial roll (or pitch) angular speed excitation. The system gains mechanical energy, starts to oscillate and tends to amplify rapidly these oscillations.

The research done by *Robbert van Ginkel, Iris Meerman and Timo Mulder [2005]* describes an autonomous landing procedure for the Parrot AR.Drone 2.0 quad- copter. An autonomous landing is defined as a landing with correct orientation on a predefined target marker without human intervention. The landing procedure should be initiated after first recognition of the specified landing location and until then manual control is assumed. The landing procedure can also be broken down into three steps: moving into horizontal position, orienting the direction the drone is facing and decreasing altitude while maintaining orientation and location until the surface has been reached. The first step in the process is that of colour segmentation. The target is red, therefore any object in the photo that is not red can be ex- cluded. To find the target in the image, contours are gen- erated of all red areas in the image. After all the contours in the image have been found, the contour that best matches the shape of the target marker is selected. After the image has been processed the actua- tion module, which is implemented as a movement function in our 'landing Platform' plugin, processes its results and generates the according movement.The review methods and technologies that have been applied in aerial robotics. The paper presents several unmanned aerial vehicle platforms. Then summarizes different control techniques including both control architectures and control methods. Furthermore, computer vision techniques for aerial robotics are briefly considered. Finally, the paper presents systems and projects involving multiple autonomous aerial and ground systems. In the last decades many autonomous and tele-operated vehicles for field robotics applications have been developed, including wheeled, tracked and legged vehicles. However, in many cases, ground vehicles have significant inherent limitations to access to the desired locations due to the characteristics of the terrain and the presence of obstacles that cannot be avoided. In these cases aerial vehicles is the natural way to approach the objective to get information or even to perform some actions such as the deployment of instrumentation. Then, aerial robotics seems a useful approach to perform tasks such as data and image acquisition of targets and affected areas, localization of targets, tracking, map building and others. Unmanned aerial vehicles (UAV) have been used for military applications but also are useful for many civilian applications such as terrain and utilities inspection, disaster monitoring, environmental surveillance, search and rescue, law enforcement, aerial mapping, traffic surveillance, and cinematography. In the last years UAVs improved their autonomy both in energy and information processing. However, the development of autonomous aerial robotic vehicles involves many problems related to limited payload, safety requirements, flight endurance and others. This paper reviews some significant developments in aerial robotics.

Knowledge Based Control Methods: As far as the research in control methods is concerned different approaches can be used. Thus, fuzzy logic has been applied to control the Yamaha's helicopter at the Tokyo Institute of Technology, which demonstrated autonomous capabilities and also person–machine interfaces including voice command (Sugeno, Griffin, & Bastian, 1993). Fuzzy logic with rules generated by the observation of ahuman pilot and consultation with helicopter experts is the approach used in Cavalcante and coworkers (1995). In Montgomery, Fagg, and Bekey (1995) the behaviours of the control architecture proposed in the USC architecture are implemented as PD control loops with gains tuned by trial and error. In Montgomery and Bekey (1998), the ''teaching by showing'' approach is presented. In this work the controller is generated by using training data gathered while a human teacher controls a system until the synthesized controller can also control the system to meet predefined performance criteria. In Buskey, Wyeth, and Roberts (2001) learning is based on the direct mapping of sensor inputs to actuator control via an artificial neural network. Then, the neural network controller was used for the helicopter hovering. The analysis of the pilot's execution of aggressive manoeuvres from flight test data is the base of the method presented in Gavrilets, Frazzoli, Mettler, Piedmonte, and Feron (2001) to develop a full non-linear dynamic model of a helicopter. This model will be used in the design of new control systems for autonomous helicopters.

Learning Based Control Methods: On the other hand, several methods have been applied for model-based control of UAVs. Modelling the UAV dynamics is a main issue. The full model of a helicopter involving the flexibility of the rotors and fuselage and the dynamics of the actuators and the combustion engine is very complex. Then, in most cases, the helicopter is considered as a rigid body with inputs forces and torques applied to the centre of mass and outputs the position and linear velocities of the centre of mass, as well as the rotation angles and angular velocities. Furthermore, the relations between the control inputs of the helicopter and the above mentioned forces and torques should be considered in the model. In general, these relations involve the consideration of the aerodynamics of the fuselage and the effect of stabilizers. However, at low speeds these effects can be ignored (Koo &Sastry, 1998). In Kim and Tilbury (2004) a mathematical model and experimental identification of a model helicopter is presented. The model of the interactions between the stabilizer flybar and the main rotor blade is also included showing its effects in the stability of the model helicopter. The identification of the parameters is performed on a SISO basis using a specially built stands to restrict the motion of the helicopter to one degree of freedom. It should be noted that the identification from input–output data, collected when a human pilot is controlling the vehicle, is difficult because it is not possible to study the individual effect of each control input (the pilot has to apply more than one input to maintain the stability).

Commercially Available Quadrotors: Quadrotor implementations and studies do not limit themselves to the academic environment. Especially in the last decade, several commercially available models have appeared in the market, with a variety of models stretching from mere entertainment up to serious applications. For example, the German company Microdrones GmbH was established in 2005 and since then has been developing such UAVs for tasks such as aerial surveillance by police forces, inspection services of power lines, monitoring of nature protection areas, photogrammetry, and archaeology research, among others. A picture of the quadrotor is illustrated below. Another manufacturer of such aircraft is the Canadian Draganfly Innovations. Their quadrotor models portfolio stretches from the Draganyer X4, with 250 g of payload capacity up to the Draganflyer X8, illustrated in Fig. 1.3 (b), featuring a 8-rotor design, with payload capacity of 1000 g and GPS position hold function. Still another relevant manufacturer of quadrotors, among other products, is the

French company Parrot. Their A R. Drone model, pictures in Fig. 1.3(c) with a surrounding protective frame, is comparable in size to the md4-200 of Microdrone, however it can fly only for approximately 12 minutes, reaching a top speed of 18 km/h. It was designed for entertainment purposes, including video-gaming and augmented reality, and can be remote-controlled by an iPhone remotely through a Wi-Fi network.

(a) md 4- 20

(b) Dragon flyer X8

(c) The AR Drone

Fig: 3. Commercially Available Quad-rotors

3. Conclusion

The review performed on modeling and control of Quad-Rotor unmanned areal vehicles (UAVs) based on earlier published workshas been found useful to arrive at a complete and as realistic as possible conclusion, that too without unnecessary complexity, by using simulation model in Matlab / Simulink, allowing further immediate use of the quadrotor in future studies. The research studies have shown successfully how various components work and interact so that the resulting system is completely autonomous. This research develops a thorough understanding of the system's behaviour, whereas it can be used as case study, for experimenting with control techniques and other abilities developed.

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