VERTICAL MOVEMENT CONTROL OF QUAD-THRUST AERIAL ROBOT

Design, Analysis and Experimental Validation

Roman Czyba and Grzegorz Szafranski
Department of Automatic Control and Robotics, Silesian University of Technology, Akademicka 16, Gliwice, Poland

Keywords: Attitude Control, Altitude Control, Infrared Rangefinder, Unmanned Aerial Vehicle, Quad-Thrust Aerial Robot.

Abstract: In this paper we focus on the problem of the vertical movement control and approach to control algorithm implementation for unmanned aerial vehicle (UAV), known as a quadrotor. The most important control subsystems for the VTOL (Vertical Take-Off and Landing) are the attitude stabilization and the altitude regulation. Both systems are presented in this paper. However, the vertical movement of the platform has been confined to precise operations such as taking-off and landing. These actions demand high reliability and they are very crucial for autonomous flights. The design, analysis and the validation tests have been undertaken on the experimental aerial platform.

1 INTRODUCTION

In recent years, there has been rapid development of unmanned aerial vehicles (UAVs) and micro aerial vehicles (MAVs). These have become known as ”robotic aircraft”, and their use has become very wide. They can be classified according to their application for military or civil use (Nonami, 2010).

The attitude controller is an important feature since it allows the vehicle to maintain a desired orientation and, hence, prevents the quadrotor from crashing when the pilot performs the desired manoeuvre. On the other hand altitude of flight depends directly on the general thrust of all four motors. Therefore, to relieve the operator from the throttle continuous operation, the altitude control system was applied to adjust the height of the flight.

The attitude and altitude control problem of a VTOL-UAVs has been investigated by several researchers and a wide class of controllers has been proposed (Castillo, 2005), (Tayebi, 2006), (Valavanis, 2007), (Bouabdallah, 2007), (Nonami, 2010).

The main aim of this research effort is to examine the effectiveness of a designed attitude stabilization and altitude regulation control system for quadrotor. The paper is organized as follows. First, an experimental platform with an indication of technical solutions is introduced. The second part includes a mathematical description of the nonlinear quadrotor model. The next section presents a general scheme of control system which consists of two subsystems: MIMO attitude stabilization and altitude regulation. Finally, the results of experiments in the HiL structure (Hardware in the Loop) are shown. The conclusions are briefly discussed in the last section.

2 THE QUADROTOR SYSTEM DESCRIPTION

The aerial vehicle consists of a rigid cross frame equipped with four rotors as shown in Figure 1.

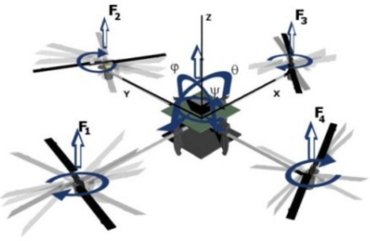

Figure 1: Quadrotor concept motion description.

Czyba R. and Szafranski G..
VERTICAL MOVEMENT CONTROL OF QUAD-THRUST AERIAL ROBOT - Design, Analysis and Experimental Validation.
DOI: 10.5220/0003460602870290
In *Proceedings of the 8th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2011), pages 287-290
ISBN: 978-989-8425-75-1

During experiments we use the setup which consists of: quadrotor airframe with propulsion system, AHRS, PC with I/O card and RC transmitter. The frame composed of carbon tubes attached to a plastic hub, and at the other ends with propulsion systems. Four propulsion systems, each one is composed of a brushed DC-motor driven by PWM signal. The miniature MTi Xsens AHRS estimates with a Kalman filter the 3D orientation data and gives the calibrated data of acceleration and angular velocity. The Matlab and Simulink software in combination with Real-Time Workshop and RT-CON allows an easy implementation of the control system in block diagram format via Simulink.

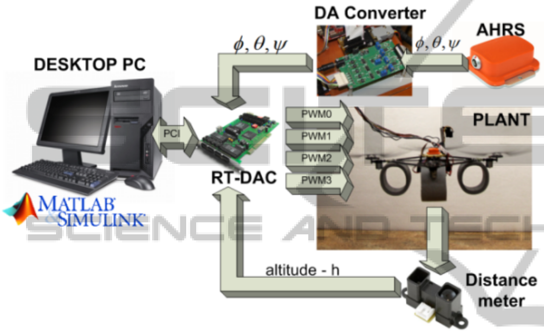

Figure 2: Quadrotor test bench.

This structure of experimental setup was used for a fast prototyping of designed control system, as well as the attitude and altitude control system concept, in the hardware in the loop system (Figure 2).

3 MATHEMATICAL MODEL OF THE QUADROTOR

The quadrotor is a six degrees of freedom system defined with twelve states. The following state and control vectors are adopted:

$$X = \left[\phi, \dot{\phi}, \theta, \dot{\theta}, \psi, \dot{\psi}, x, \dot{x}, y, \dot{y}, z, \dot{z}\right]^T \tag{1}$$

$$U = \left[u_1, u_2, u_3, u_4\right]^T \tag{2}$$

where: u_i – control input of motor, $\xi = [x, y, z]^T$ – position coordinates, $\eta = [\phi, \theta, \psi]^T$ – Euler angles,

The dynamic model is derived using Euler-Lagrange formalism (Bouabdallah, 2007), (Castillo, 2005), (Goel, 2009).

Finally the quadrotor dynamic model with x,y,z, motions as a consequence of a pitch, roll and yaw rotations is as follows:

$$\begin{gathered}\ddot{\theta} = \frac{1}{I_{xx}}\Big(-\dot{\phi}^2\left(I_{xx} - I_{zz}\right)s(\theta)c(\theta) + \\ -\dot{\phi}\dot{\psi}I_{zz}c(\theta) + T_\theta\Big)\end{gathered} \tag{3}$$

$$\begin{gathered}\ddot{\phi} = \frac{1}{I_{yy}\left(1 + s^2(\theta)\right)}\Big(-\ddot{\psi}I_{zz}s(\theta) - \dot{\theta}\dot{\phi}c(\theta)s(\theta)\cdot \\ \cdot\left(2I_{zz} - 2I_{yy}\right) - \dot{\theta}\dot{\psi}I_{zz}c(\theta) + T_\phi\Big)\end{gathered} \tag{4}$$

$$\ddot{\psi} = \frac{1}{I_{zz}}\left(-\ddot{\phi}I_{zz}s(\theta) + T_\psi\right) \tag{5}$$

$$\ddot{x} = \frac{f_g}{m}s(\theta) \tag{6}$$

$$\ddot{y} = -\frac{f_g}{m}c(\theta)s(\phi) \tag{7}$$

$$\ddot{z} = \frac{f_g}{m}c(\theta)c(\phi) - g \tag{8}$$

where: *s,c* abbreviations of ’*sin*’ and ’*cos*’, I_{xx}, I_{yy}, I_{zz} – inertia moments, f_g – total thrust, T_θ, T_ϕ, T_ψ – torques.

4 SCHEME OF CONTROL SYSTEM

A general scheme of control system (Figure 3) consists of two subsystems: attitude stabilization around hovering conditions and altitude regulation.

Both of control systems were designed based on the PID algorithm, but between them exists sufficient time-scale separation. It is achieved through proper selection of controller parameters. Applied fast prototyping methodology allows to tune the controller parameters through HiL (Hardware in the Loop) experiments.

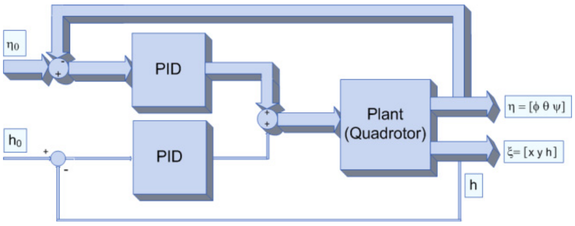

Figure 3: Block diagram of control system.

4.1 Attitude Stabilization

The quadrotor model described by equations (3)–(8), will be used to design the attitude control system that achieves the angular stabilization and regulation. The control task is stated as a tracking problem for the following variables:

$$\begin{aligned} &\lim_{t\to\infty}\left[\phi_0(t)-\phi(t)\right]=0 \\ &\lim_{t\to\infty}\left[\theta_0(t)-\theta(t)\right]=0 \\ &\lim_{t\to\infty}\left[\psi_0(t)-\psi(t)\right]=0 \end{aligned} \tag{9}$$

where $\phi_0(t), \theta_0(t), \psi_0(t)$ are the desired values of the considered variables (roll angle, pitch angle, yaw angle respectively).

4.2 Low Level Altitude Control

The main task of the altitude control system is to achieve and remain in a desired position calculated along the z-axis direction. The reference value can be either the constant level above the ground or a trajectory defined for take-off and landing manoeuvres. The height measurement is accomplished using an infrared rangefinder.

4.2.1 Distance Measurement

To provide altitude data for the unmanned aerial robots some different approaches are possible. One of the sensors that gives straight information about the distance or altitude are infrared rangefinders.

An infrared sensor is a distance measuring unit which consist of an integrated combination of PSD (position sensitive detector), IRED (infrared emitting diode) and signal processing circuit.

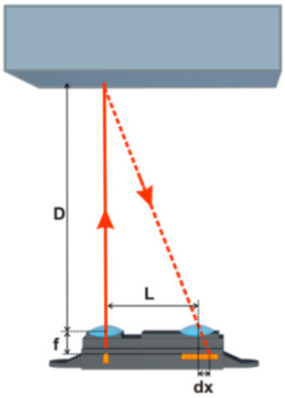

Figure 4: IR sensor theory of operation.

The principle of operation is based on the triangulation method, so sensor cannot be easily affected by the perturbations.

In theory the distance between object and sensor is calculated from the following formula:

$$D = \frac{L}{\frac{dx}{f} + \frac{1}{tg\alpha}} \tag{10}$$

where: D - measured distance, L - distance between transmitter and receiver, f - focal length, α – angle of transmitter, dx – position on PSD.

The main disadvantage is that the relationship between the measured distance and voltage is nonlinear.

4.2.2 Controller Design

The differential equation for z-axis movement (in the chapter 3) gives the basic information about the quadrotor dynamics. This equation (11) has been combined with the model of the propulsion system. On the basis of the dynamics comparison between the rigid body and motors, in our case the motor dynamics has been neglected. Only static relationship between generated thrust force and applied voltage to the motors is introduced (12). Such simplified model has been tested in Matlab/Simulink environment.

$$\ddot{h} = \frac{f_g}{m}\cos(\phi)\cos(\theta) - g \tag{11}$$

$$F_{Ti} = C_T \rho D^4 \cdot (k_n u)^2 \tag{12}$$

$$f_g = \sum_{i=1}^{4} F_{Ti} \tag{13}$$

The PID parameters have been obtained during the simulation experiments. The results are presented in the next chapter.

5 TESTS AND RESULTS

In this section, we present the results of experiments which were conducted on the quad-thrust aerial robot, to evaluate the performance of a designed attitude and altitude control system. At first, in order to obtain some basic knowledge about the dynamics of quadrotor, a simulation system was developed under Matlab/Simulink platform. The impact of the angular stabilization to the altitude control has been tested and verified during the simulation and experiments (Figure 5).

An autonomous start and landing of the quad-thrust aerial robot are presented in Figure 6.

The platform descends according to the ramp signal which ensures smooth landing and touching the ground. Results of attitude stabilization during the altitude control are presented in Figure 7.

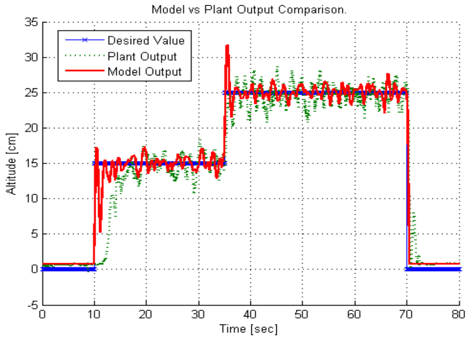

Figure 5: Altitude control. Model and plant comparison.

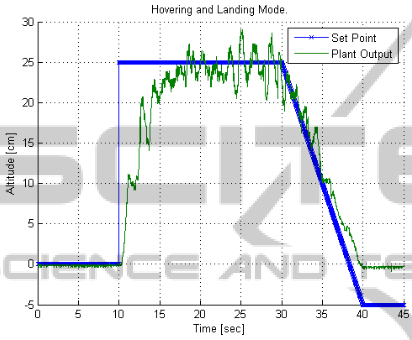

Figure 6: Autonomous take-off and landing.

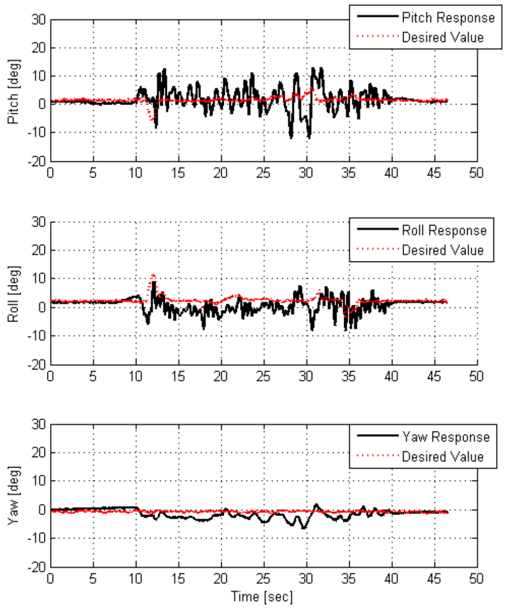

Figure 7: Angular stabilization during the altitude control.

6 CONCLUSIONS

The quad-thrust aerial robot can make possible plenty of potential applications for unmanned aerial vehicles. In this paper we have presented the quadrotor dynamics. Designed control system consists of the angular stabilization and altitude regulation of the platform. In case of attitude stabilization the problem of different dimensions between inputs and outputs was solved by the MIMO PID controller and output block which allows the control algorithm to be accomplished. In case of altitude control some model simplification has been made in order to achieve the controller parameters. Taking into consideration the limitations of the IR sensor, the altitude control works surprisingly well. Presented solution can be applied in both the indoor and outdoor environment as well. The achieved results are satisfactory. The main disadvantage is the limitation in the height measurement but it is allowed to perform precise manoeuvres, such as taking-off and landing.

ACKNOWLEDGEMENTS

This work has been granted from funds for science in 2010-2012 as a development project No. OR00011811.

REFERENCES

S. Bouabdallah, 2007. *Design and Control of Quadrotors with Application to Autonomous Flying.* Ph.D. dissertation, School of Computer and Communication Sciences, Lausanne.

P. Castillo, R. Lozano, and A. E. Dzul, 2005. *Modelling and Control of Mini-flying Machines.* Springer-Verlag, 2005, ch. 3.

R. Czyba, 2010. *Attitude Stabilization of an Indoor Quadrotor*. Proc. Of European Micro Aerial Vehicle Conference and Competition, EMAV.

A. Tayebi and S. McGilvray, 2006. *Attitude stabilization of a VTOL quadrotor aircraft.* IEEE Trans. on Control Systems Technology, vol. 14, no. 3, 2006, pp. 562-571.

K. P. Valavanis, 2007. *Advances in Unmanned Aerial Vehicles.* Springer-Verlag, 2007.

K. Nonami, F. Kendoul, S. Suzuki, W. Wang, D. Nakzawa, 2010. *Autonomous Flying Robots.* Spirnger, 1st edition.

R. Goel, S. M. Shah, N. K. Gupta, N. Ananthkrishnan, 2009. *Modeling, Simulation and Flight of an Autonomous Quadrotor.* Proceedings of ICEAE.