5. ANKARA INTERNATIONAL AEROSPACE CONFERENCE AIAC-2009-055
17-19 August 2009 - METU, Ankara TURKEY

THE EXPERIMENTAL SETUP FOR ALTITUDE CONTROL OF A QUADROTOR

Aydemir ARISOY[1], Mustafa ILARSLAN[2] and Serkan SAVRUK[3]
Air Force Academy, Istanbul, TURKEY

M.Kursat YALCIN[4]
Istanbul Technical University Istanbul, TURKEY

ABSTRACT

In this study, a novel mini "Vertical Take-Off and Landing (VTOL)" vehicle called Quadrotor is introduced. The design, construction and experimental setup for the altitude control of the Quadrotor is presented. Quadrotor is a helicopter with four rotors where the collective input (or throttle input) is the sum of the thrusts of each motor. The followed design approach has increased the stability and controllability of this mini unmanned air vehicle (UAV). Linear control methods are applied for the altitude control of this vehicle and experimentally tested in the laboratory environment. Experimental setup consists of a DSP based controller, an "Inertial Measurement Unit (IMU)", brushless DC motors and electronic speed controllers for the motors. In addition, CNY-70 sensors are used to measure the velocity of each motor. Quadrotor platform is constructed by using rigid carbon fibers and the test bed frame is composed of carbon fiber tubes attached with a plastic hub at their ends forming a plus shape. Lithium-polymer battery pack is chosen to supply energy to the Quadrotor. Additionally, a thrust test stand was developed to test motors and rotors individually in varying flight conditions. Thrust test stand measures the developing forces and torques using a load cell. The 6-DoF IMU unit was used to provide 3-dimensional sensing platform for the setup. The IMU unit is used for Quadrotor setup to feedback the gyro and tilt angle readings. The TMS320F28335 is used as Digital Signal Controller (DSC). This controller was the controller of the choice for the control of Quadrotor as it is highly integrated and provided high-performance solutions for such a demanding control application. Derived control algorithms are implemented by using the TMS320F28335. The obtained results in this laboratory environment using Quadrotor altitude control setup have motivated the authors to use an embedded controller for a free-flying Quadrotor.

INTRODUCTION

Unmanned Aerial Vehicles (UAV) are getting very popular at commercial, military and academic platforms. Military applications currently represent the biggest part of the UAV market, and this industrial sector is growing strongly. And also progresses in sensor technology, data processing, integrated actuators and energy storage devices made the development of miniature, autonomous flying systems possible. Amid to the availability of high-speed brushless motors, MEMS technology based inertial measurement units and high power to weight ratio Lithium-polymer batteries, unmanned air vehicles with better performance can now be designed and fabricated. On the other hand, their control is still a challenge [1,2].

In this study, designing, constructing and control of a Vertical Take-Off and Landing (VTOL) system called Quadrotor is presented. This study includes altitude stabilization, hovering control at any

[1] Dr. in a Dept. of Electronics Eng., Email: a.arisoy@hho.edu.tr
[2] Dr. in a Dept. of Electronics Eng., Email: m.ilarslan@hho.edu.tr
[3] Cadet, in a Dept. of Electronics Eng., Email: 4612savruk@harbiyeli.hho.edu.tr
[4] Research Asst., in an Electrical-Electronics Faculty, Email: mkyalcin@elk.itu.edu.tr

desired position and attitude control of Quadrotor. Classically PD controller derived and applied to this system. Being able to design a vertical takeoff and landing (VTOL)-UAV, which is highly maneuverable and extremely stable, is an important contribution to the field of aerial robotics since potential applications are tremendous (e.g., high buildings and constructions investigation, rescue missions, etc.).

Quadrotor control studies are increased during the last few years [8, 9]. Different control strategies have been studied by scientists in control area [7] and [5]. Quadrotor is the helicopter with four rotors. This design approach increased the stability and controllability of the mini unmanned air vehicle (UAV) [1]. Linear and nonlinear control methods applied to this novel UAV [3, 4] and experimentally tested in laboratory environment [6]. Experimental testing has been performed, with a frequency of 150 MHz, using a DSC TMS320F28235 controller board. The DSP Control Desk software in combination with MATLAB/Simulink, and Real-Time Workshop allows an easy implementation of the control algorithm in block diagram format via Simulink, with real-time adjustments of the control gains. The Algorithms are loaded to DSP by using the USB port of the computer and DSC.

This paper will be organized as follows: Section II is a presentation of the dynamic model of the Quadrotor. Section III is on the development of the control algorithm and introducing experimental setup. Simulation and experimental results are given in section IV. Finally, conclusion of this study is given at the last section.

DYNAMIC MODEL OF THE QUADROTOR

The physical setup is a complex structure and without simplifying assumptions it is cumbersome to derive the mathematical model based on Newton-Euler equations. The following are some assumptions that are used in developing the mathematical model of the Quadrotor. The carbon fiber structure is supposed to be rigid. The helicopter has a perfectly symmetrical structure so; the matrix of inertia will supposed to be diagonal. The bearing pressure and the trail of each engine are proportional to the square speed, which is an approximation very close to the aerodynamic behavior. Hovering condition is assumed. Ground effect was not implemented because the landing skids are long enough to keep the propellers out of ground effect even after touchdown. Then, dynamic equations of a Quadrotor can be written as below.

$$I_{xx}\ddot{\Phi} = \dot{\theta}\dot{\Psi}(I_{yy} - I_{zz}) + J_r\dot{\theta}\Omega_r + l(-T_2 + T_4) - h(\sum_{i=1}^{4} H_{yi}) + (-1)^{i+1}\sum_{i=1}^{4} R_{mxi}$$

$$I_{yy}\ddot{\theta} = \dot{\Phi}\dot{\Psi}(I_{zz} - I_{xx}) - J_r\dot{\Phi}\Omega_r + l(T_1 - T_3) + h(\sum_{i=1}^{4} H_{xi}) + (-1)^{i+1}\sum_{i=1}^{4} R_{myi}$$

$$I_{zz}\ddot{\Psi} = \dot{\theta}\dot{\Phi}(I_{xx} - I_{yy}) + J_r\dot{\Omega}_r + l(-H_{y1} + H_{y3}) + l(H_{x2} - H_{x4}) + (-1)^{i}\sum_{i=1}^{4} Q_i$$

$$m\ddot{x} = (\sin\Psi\sin\Phi + \cos\Psi\sin\theta\cos\Phi)\sum_{i=1}^{4} T_i - \sum_{i=1}^{4} H_{xi} - \frac{1}{2}C_x A_c \rho \dot{x}\left|\dot{x}\right|$$

$$m\ddot{y} = (-\cos\Psi\sin\Phi + \sin\Psi\sin\theta\cos\Phi)\sum_{i=1}^{4} T_i - \sum_{i=1}^{4} H_{yi} - \frac{1}{2}C_y A_c \rho \dot{y}\left|\dot{y}\right|$$

$$m\ddot{z} = mg - (\cos\Psi\cos\Phi)\sum_{i=1}^{4} T_i$$

Φ	:roll,	h	:distance to the frame origin,	l	:Quadrotor arm length,
θ	:pitch,	T_i	:thrust force,	g	:gravitational acceleration
Ψ	:yaw,	Q	:drug moment,	x, y, z	:positions
$I_{xx,yy,zz}$	:inertial moments	R_m	:rolling moment,	Ω_r	:total propellers' speeds
J_r	: rotor inertia,	H	:hub force,		

CONTROL METHOD

Quad-rotor rotorcraft, like the one shown in Figure 1, has some advantages over conventional helicopters. Given that the front and the rear motors rotate counter-clockwise while the other two rotate clockwise, gyroscopic effects and aerodynamic torques tend to cancel in trimmed flight. This type of counter-rotating rotor-pairs setup will cancel out the rotating force produced by the rotating rotor where the conventional helicopter is using the tail rotor to counter it. To increase the altitude of the flying robot, all the rotors' speed will be increased to produce more thrust. The front and back rotors are used to control the pitch of the flying robot. To fly forward, the front rotor's speed is decreased while the back rotor's speed is increased. The left and right rotors are used to control the roll of the flying robot. To fly to the right, the left rotor will rotate faster while the right rotor will rotate slower.

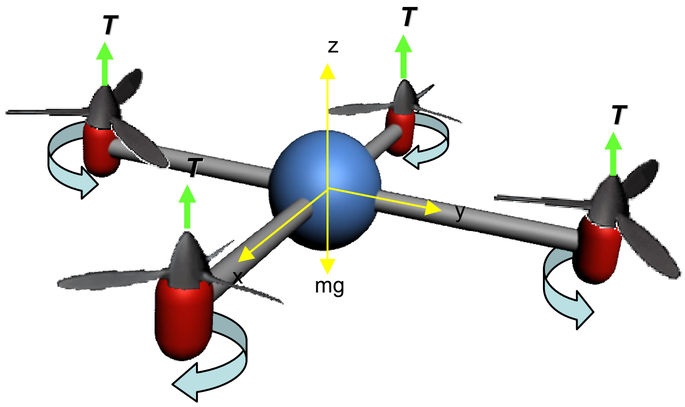

Figure 1: Quadrotor

$$u_1 = C_{p\Phi}(\Phi_d - \Phi) + C_{d\Phi}(\dot{\Phi}_d - \dot{\Phi})$$
$$u_2 = C_{p\theta}(\theta_d - \theta) + C_{d\theta}(\dot{\theta}_d - \dot{\theta})$$
$$u_2 = C_{p\Psi}(\Psi_d - \Psi) + C_{d\Psi}(\dot{\Psi}_d - \dot{\Psi})$$

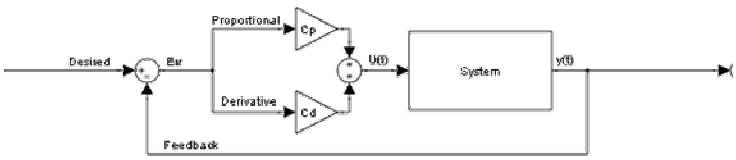

Figure 2: Control scheme

Control strategy has been developed for stabilizing the rotorcraft at hover. PD controller was derived from the equations and parameters given above as [1]. The system can be forced to the desired altitude with PD controller for velocity of each motor. PD control algorithm is given above (figure 2).

EXPERIMENTAL SETUP

Thrust and altitude control experiments have been made using different setup, thrust test setup and altitude control experiment setup.

Thrust Test Setup

Having calculated approximate payloads it is needed to choose the most appropriate propeller. Two types of propellers (two-bladed, tree-bladed) have been tested by using the thrust experiment setup (Figure 3). A thrust test stand was developed to test motors and rotors (propellers) individually in varying flight conditions. Because of these varying conditions, it is evaluated that trust produced by brushless DC motors is changing. Thrust test stand measures the forces and torques using a load cell. Two different propellers has been tested aspect from thrust producing. Two bladed and three bladed propellers have been tested to thrust producing, 200g and 450g measured via dynamometer per motor respectively. Having chosen propeller, they also were tested trusts of rotors for different DC inputs of speed controller. These inputs are produced by ePWM unit of DSP. The duties of inputs are varied from 1.10-1.78 ms.

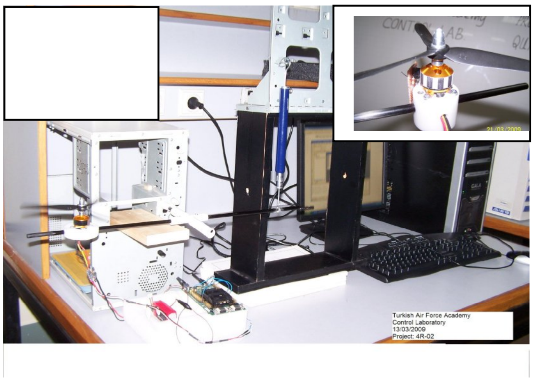

Figure 3: Thrust test setup, propellers and motor with speed feedback circuit

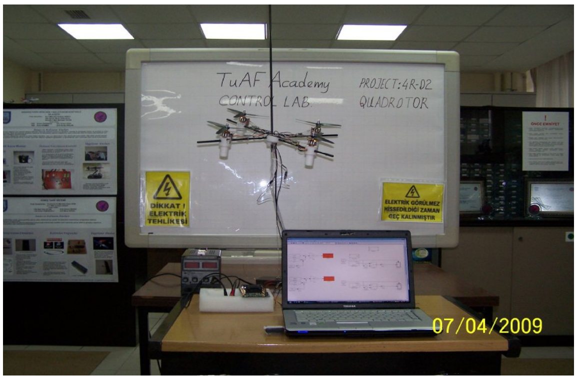

Figure 4: Experimental platform of altitude control for a Quadrotor

Altitude Control Experiment Setup

Experimental setup consists of DSP based controller, brushless DC motors driven by PWM signal and electronic speed controllers for motors. The TMS320F28335 is used as Digital Signal Controller (DSC). This controller is suitable to control application setup for Quadrotor. So it is highly integrated, high-performance solutions for demanding control applications. The TMS320F28335 have many features and includes high-performance 32-Bit CPU (TMS320C28x), Six Channel DMA controller (for ADC, McBSP, ePWM, XINTF, and SARAM), 32-bit external interface (XINTF), and enhanced control peripherals up to 16 PWM outputs. Motor rotation velocity feedback circuits, CNY70 sensors, were used to obtain the rotations of each rotor. This knowledge described as RPM were included in algorithm to cancel out the rotating force. That is to say the front and the rear motors' total rpm must be equal to other two motors' total rpm. inertial measurement unit (IMU). The IMU 6-DoF unit was used to provide 3 dimensional sensing platforms for setup. IMU unit includes the single IC triple axis accelerometer from free-scale MMa7260Q and combines it with three IMEMS gyroscopes. IMU unit is used for Quadrotor setup to feedback three gyro readings, three tilt readings. Test bed frame is composed of carbon fiber tubes attached with a plastic hub from their ends forming a plus shape. At the other ends of the carbon tubes motor-propeller assemblies are attached. Diameter of the carbon fiber tubes is 8 mm. They are used because of their light weight and high stiffness properties.

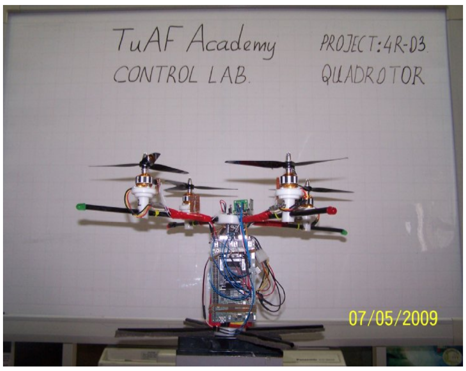

Figure 5: Quadrotor assembly

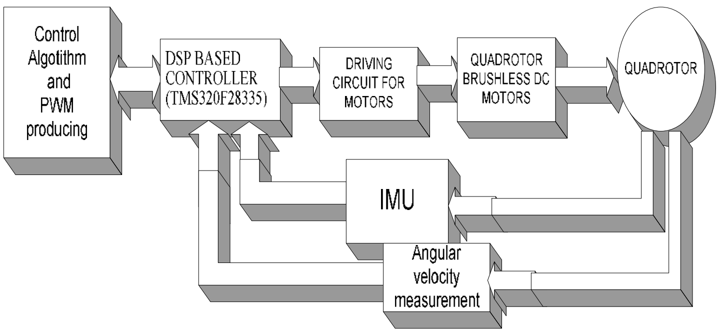

Figure 6: Quadrotor control test setup block diagram

Firstly, a strong metal stick was placed straightly from ground to ceiling and rotorcraft was hanged this stick from Quadrotor platforms' center. So rotorcraft was able to move from ground to ceiling safely. By this way, our control algorithms were experienced safely. Experimental setup and Quadrotor assembly are seen in photographs given figure 4 and figure 5 respectively. Quadrotor experimental test setup block diagram is given in Figure 6.

EXPERIMENTAL RESULTS

MATLAB/Simulink software environment is used to develop control algorithm and desired control signal produced via PWM signal. Required code is implemented into the DSC using RTW. Quadrotor platform payloads descriptions are given in Table 1. Computer simulation results for platform stabilization control with PD controller are shown in figure 7 and figure 8 without noise with noise respectively. Altitude test result based on rotor rotations is given in figure 9.

Table 1: Quadrotor assembly payloads

Weight of platform(not including motors and batteries)	350 g
4 x motor and 4 x speed controller	230 g
Batteries	300 g
DSP, IMU and CNY70 sensors with all cables	220 g
Total	1000 g

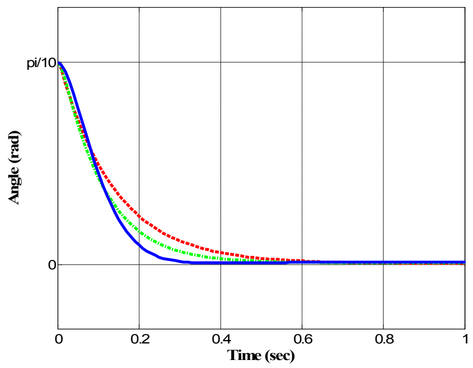

Figure 7: PD control results with initial conditions of π/10; without noise for platform stabilization.

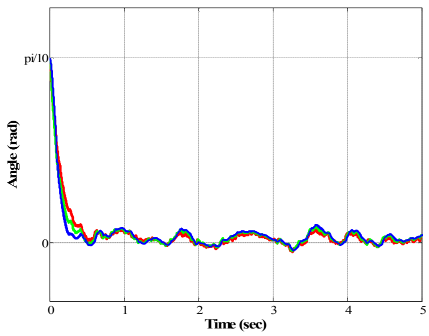

Figure 8: PD control results with initial conditions of π/10; with noise for platform stabilization.

CONCLUSION

This study has been focused on setting up a real-time experimental environment for altitude stabilization control of the Quadrotor. A dynamic model based on Newton-Euler equations has been used for simulation and control of the system. This study includes altitude stabilization, hovering control at any desired position and altitude control of Quadrotor. A PD-controller was derived and applied to the system. The proposed linear control method has been implemented by using computer simulations and tested by using the experimental setup that included a DSP based microcontroller in the laboratory environment. The experimental setup consists of a DSP based controller, an “Inertial Measurement Unit (IMU)”, brushless DC motors and electronic speed controllers for the motors. Additionally, CNY-70 sensors are used to measure the velocity of each motor. This experimental study and obtained results in the laboratory environment using the Quadrotor altitude control setup have motivated the authors to use an embedded controller for a free-flying Quadrotor.

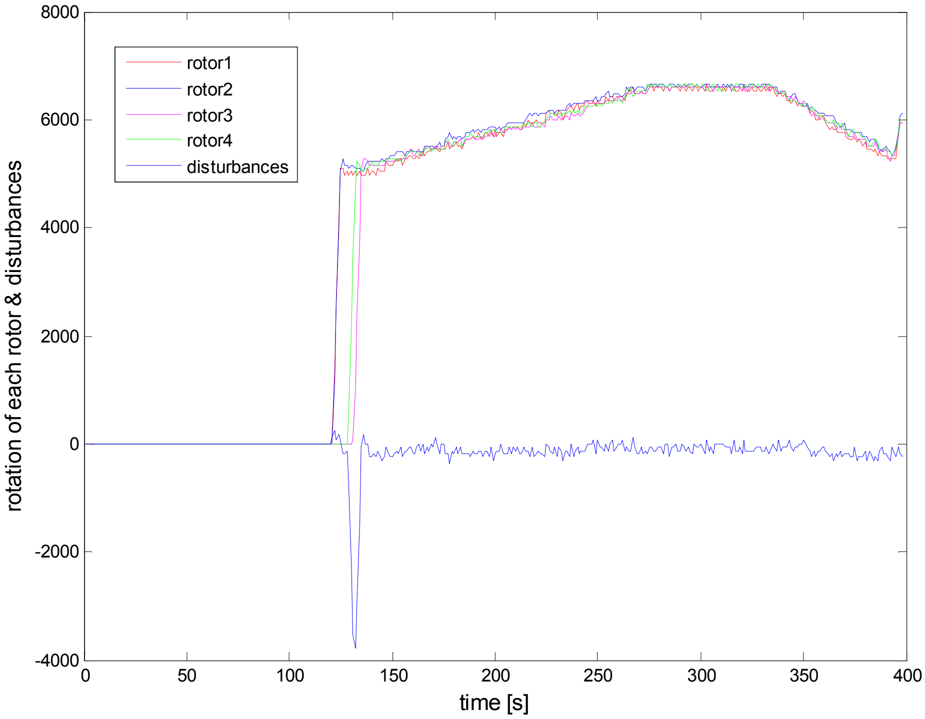

Figure 9: Altitude test result based on rotor rotations.

References

[1] Dikmen, I. C.; Arisoy, A.; Temeltas, H.; *Attitude control of a Quadrotor*, Recent Advances in Space Technologies, 2009. RAST '09. 4th International Conference on, Page(s):722 – 727,11-13 June 2009.

[2] Homan, G., Huang, H., Tomlin, C. J., Waslander, S. L., *Quadrotor Helicopter Flight Dynamics and Control: Theory and Experiment*. In Proceedings of the AIAA Guidance, Navigation, and Control Conference, Hilton Head, SC, August 2007.

[3] Andrew, N., *Linear and non-linear control of a quadrotor UAV* , M.S.Thesis, Clemson University, 2007.

[4] Rosas, A., Angel, E., *Path tracking control for an autonomous four rotor mini-helicopter*, M.Sc. Thesis., University of Calgary (Canada), 2007.

[5] Tayebi, A. and McGilvray, S., *Attitude stabilization of a VTOL quadrotor aircraft*, IEEE transactions on control systems technology*,* vol. 14, no. May 2006.

[6] Amrutbhai, P.C., *Building a testbed for mini quadrotor unmanned aerial vehicle with protective shroud.*, M.S.Thesis, Wichita State University, 2006.

[7] Castillo, P., Lozano, R. and Dzul, A., *Stabilization of a Mini Rotorcraft with Four Rotors*, IEEE Control Systems Magazine, 2005.

[8] Boubdallah, S., *Design and Control of an Indoor Micro Quadrotor,* ICRA 2004, New Orleans (USA), April 2004.

[9] Gilvray, M. Stephen J., *Attitude stabilization of a quadrotor aircraft*, M.Sc.Thesis, Lakehead University (Canada), 2004.