UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electronic and Computer Engineering

PROPORTIONAL INTEGRAL DERIVATIVE BASED CONTROL FOR AUTONOUMOUS VERTICAL TAKE OFF AND LANDING OF QUADCOPTER SYSTEM

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A thesis submitted
in fulfillment of the requirements for the degree of Master of Science in Electronic Engineering

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DECLARATION

I declare that this thesis entitle “Proportional Integral Derivative Based Control for Autonoumous Vertical Take Off and Landing of Quadcopter System” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :…………………………………………………...

Name :…………………………………………………...

Date :…………………………………………………...

APPROVAL

I hereby declare that I have read this report and in my opinion this report is sufficient in terms of scope and quality as a partial fulfillment of Master of Science in Electronic Engineering

Signature :……………...

Supervisor Name :……………………....................................

Date :……………………...

DEDICATION

To my beloved mother and father

ABSTRACT

Since 2009, research on unmanned aerial vehicle (UAV) especially quadcopter system has attracted a considerable attention from researchers in the field. The quadcopter system is actually a class of flying robot that has ability to take off and landing in a vertical condition. Moreover, it has the advantage of good mobility, simple mechanics, and the carriage load ability. Therefore, the thesis focuses on developing a controller for vertical take-off and landing of a less human interaction UAV quadcopter system. The thesis begins with the quadcopter mathematical model derivation. The model takes into account all the hardware constraints such as, maximum speed and torque of brushless direct current (BLDC) motor, total payload, size of popeller and the electronic speed controller specification. Therefore, several experiments were undertaken to obtain important parameters such as the lift force factor, drag factor, and moment of inertia which required in order to estimate the behavior of the system and to reach better accuracy when designing the control. According to the study of quadcopter mathematical model, it has a non-linear system characteristics, where the acceleration quadcopter for dynamic and kinematic of system not directly proportional to the speed of the rotating propeller. Hence, attitude and altitude control system must be designed to meet the autonomous control system. The automatic attitude controller of the quadcopter is about controlling the angle of quadcopter body frame to generate the movement acceleration. This system is designed by combining the proportional integral derivative (PID) attitude control on Quadcopter rigid body with PID acceleration control of Quadcopter movement. The results revealed that the propose combined the controller improved the acceleration control compared to single axis tilting quadcopter approach. Then, the controller was tested for the targeted of 100m distance and the simulation result showed that the quadcopter able to reach the distance in 25.95s. On the other hand, the automatic altitude controller of the quadcopter is responsible to control the thrust force of the motor to produce desired vertical acceleration of quadcopter. The altitude controller has been tested on the prototype model for 1m targeted height and the simulation result confirmed that the quadcopter system able to reach the targeted height in 2s. The second stage of the analysis is to design and evaluate the altitude controller for real time application. For this purpose, PCI-1711 data acquisition card is used as an interface for controller design which routes from Matlab-Simulink to hardware. The real time application result shown that the quadcopter system able to reach the targeted height in 2.3s and the efficiency of without overshooting is 80.4% compared to the simulation result. Thus, The results revealed that the proposed PID altitude control improved the solution of altitude control in comparison to PD and back-stepping controller approach.

ABSTRAK

Semenjak tahun 2009, kajian ke atas sistem pesawat udara tanpa pemandu (UAV) terutamanya kuadkopter telah menarik perhatian para penyelidik dalam bidang ini. Kuadkopter adalah pesawat yang mempunyai keupayaan untuk berlepas dan mendarat dalam keadaan menegak. Selain itu, ia juga mempunyai kelebihan dalam penerbangan yang seimbang, mekanikal yang ringkas, dan keupayaan menampung beban. Oleh itu, tesis ini memberi tumpuan kepada membangunkan sistem kawalan untuk berlepas dan mendarat dalam keadaan menegak untuk mengurangkan keperluan kawalan dari manusia. Tesis ini dimulakan dengan penghuraian model matematik bagi kuadkopter. Pemodelan kuadkopter ini mengambil kira semua faktor peranti yang terlibat, antaranya adalah seperti; kelajuan maksimum dan tork yang dihasilkan motor (BLDC), jumlah muatan, saiz kipas dan spesifikasi pengawal kelajuan elektronik. Oleh itu, beberapa ujikaji telah dilaksanakan untuk mendapatkan nilai parameter-parameter penting seperti faktor daya angkat, faktor daya heretan, dan daya inersia yang diperlukan untuk menganggarkan tindak balas sistem dan untuk mencapai ketepatan yang lebih baik apabila mereka bentuk kawalan. Menurut kajian terhadap model matematik bagi kuadkopter, ia mempunyai ciri-ciri sistem bukan linear, di mana pecutan untuk kinematik dan dinamik sistem kuadkopter tidak berkadar terus dengan kelajuan kipas yang berputar. Oleh itu, kawalan pergerakan dan ketinggian perlu direka bagi melengkapkan keperluan sistem kawalan automatik. Kawalan sistem pergerakan automatik kuadkopter adalah adalah sistem yang mengawal sudut kerangka badan kuadkopter dan ia menjana pecutan pergerakan. Sistem ini direka dengan menggabungkan sistem kawalan proporsional integral derivatif (PID) pergerakan pada kerangka tetap kuadkopter dengan kawalan PID pecutan pergerakan linear kuadkopter. Melalui hasil kajian yang diperoleh, menunjukkan bahawa gabungan sistem kawalan ini dapat meningkatkan prestasi tindak balas pecutan berbanding dengan pendekatan sistem kawal sudut setiap motor. Sistem kawalan telah diuji untuk sasaran jarak pergerakan sejauh 100m dan hasil simulasi menunjukkan bahawa sistem kawalan ini dapat mencapai jarak sasaran dalam tempoh 25.95s. Selain daripada itu, sistem kawalan ketinggian automatik kuadkopter adalah sistem yang mengawal daya tujah yang dihasilkan motor untuk menghasilkan pecutan keatas mengikut kehendak sistem. System kawalan ketinggian ini telah diuji pada model prototaip untuk sasaran ketinggian 1m dan keputusan simulasi mengesahkan bahawa sistem kawalan quadcopter ini dapat mencapai ketinggian sasaran dalam tempoh 2s. Peringkat kedua adalah untuk menghasilkan sistem kawalan dan menilai pengawal ketinggian untuk aplikasi masa sebenar. Untuk tujuan ini, kad perolehan data PCI-1711 digunakan sebagai antara muka sistem kawalan yang menghubungkan antara unit perisian Matlab Simulink-kepada perkakasan keluaran. Keputusan dalam uji kaji yang dijalankan menunjukkan bahawa sistem quadcopter ini dapat mencapai ketinggian yang disasarkan dalam tempoh 2.3s dan kecekapan yang direkodkan adalah 80.4% berbanding dengan hasil keputusan simulasi. Oleh kerana itu, dapat dirumuskan bahawa hasil kajian menunjukkan PID kawalan ketinggian yang

dicadangkan dapat meningkatkan kawalan ketinggian berbanding pendekatan menggunakan pengawal jenis PD dan ‘back-stepping’.

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LIST OF ABBREVIATION

UAV	- Unmanned Aerial Vehicle
VTOL	- Vertical Take-Off And Landing
DAQ	- Data Acquisition Card
RTWT	- Real Time Windows Target
ESC	- Electronic Speed Controller
DC	- Direct Current
BLDC	- Brushless Direct Current Motor
DOF	- Degree Of Freedom
PID	- Proportional-Integral-Derivative Controller
LTA	- Lighter Than Air
HTA	- Heavier Than Air
PD	- Proportional Derivative Controller
ISE	- Integral Square Error
IAE	- Integrated Absolute Value Of The Error
COM	- Centre Of The Mass
COG	- Centre Of Gravity
LQR	- Linear Quadratic Regulator Controller
E-frame	- Earth Inertial Frame
B-frame	- Body Fixed Frame
IMU	- Inertial Measurement Unit
MIMO	- Multiple Input Multiple Output

SISO	- Single Input Single Output
RTAI	- Real Time Application Interface
COMEDI	- Control And Measurement Device Interface
CW	- Clock Wise
CCW	- Counter Clock Wise
3D	- Three Dimension
PWM	- Pulse Width Modulation
RPM	- Round Per Minute
Li-Po	- Lithium Polymer Battery
PCI	- Peripheral Component Interconnect
A/D	- Analogue To Digital
D/A	- Digital To Analogue
SRAM	- Static Random-Access Memory

LIST OF PUBLICATIONS

The research papers produced and published during the course of this research are as follows:

1. **Zaki Mustapa**, Shakir Saat, Husin S. H. and Norafizah Abas, 2015. Altitude Controller Design for Quadcopter UAV. *Jurnal Teknologi, Science and Engineering*, 74(1), pp. 181–188. (Scopus Indexed)
2. **Zaki Mustapa** and Shakir Saat, 2015. Autonomous Attitude Control of a Quadcopter Unmanned Aerial Vehicle (UAV) System. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC),* 7(2), pp. 153-160. (Scopus Indexed)
3. **Zaki Mustapa**, Shakir Saat, S. H. Husin, Norafizah Abas, 2014. Altitude controller design for multi-copter UAV. *International Conference on Computer, Communications, and Control Technology (I4CT)*, pp. 382 – 387. (Scopus Indexed)
4. **Zaki Mustapa**, Shakir Saat, S. H. Husin, Norafizah Abas, 2014. Quadcopter Physical Parameter Identification and Altitude System Analysis. *IEEE Symposium on Industrial Electronics & Applications ISIEA*. Presented: 28 September 2014.
5. **Zaki Mustapa**, Shakir Saat, and Norafizah Abas, 2016. Experimental Validation of an Altitude Control for Quadcopter. *ARPN Journal of Engineering and Applied Sciences,*11(6),pp.3789-3795. (Scopus Indexed)

CHAPTER 1

INTRODUCTION

1.1 Background of Thesis

Precision agriculture (PA) is an innovative, integrated and internationally standardized approach aiming to increase the efficiency of resource use and to reduce the uncertainty of decisions required to control variation on farms. It has attracted considerable attention from researchers around the globe because the agriculture industry can be strengthened through this precision farming approach. However, one of the main obstacles in this PA is the lack of monitoring technologies that could supply the real-time information consistently. Currently, the unmanned aerial vehicle (UAV) system is used to perform this task. However, the current UAVs are remotely controlled by a human; hence the information gathered stills restrictive.

There are two types of UAV systems, which are fixed wing and rotary wing. There are many designs of the UAV system that have been developed to fulfil the global requirement of UAV technology see (Naoharu Yoshitani et. al., 2009). Vertical take-off and landing (VTOL) structure, such as helicopter, blimp, tandem helicopter and quadcopter is one of the UAV systems that is getting attention among several academic researchers. However, each UAV VTOL structure designed has its own advantages and drawbacks. Due to the nature of the targeted applications, i.e. surveillance and monitoring robot, balance in stationary flight, simple mechanical system and slow speed flight abilities are highly required for UAV VTOL. Thus, the quadcopter system a class of UAV is more suitable to be used for UAV VTOL as surveillance and monitoring task.

This thesis is aimed at the study of controlling vertical take-off and landing (VTOL) for the unmanned aerial vehicle (UAV) of a quadcopter system. The quadcopter's architecture has been chosen for this research because it has good mobility, simple mechanics, and its ability on load capacity. On top of that, the quadcopter system is a nonlinear system, in which the speed of the motor varies the torque and force onto the rigid body of the quadcopter. Thus, the system requires a reliable altitude and attitude control strategy in order to develop an autonomous UAV VTOL quadcopter system. Hence, this research utilizes the mathematical model of the quadcopter system to design the appropriate controller to stabilize such system. For this thesis, the requirement of this study excludes the automatic navigation of the system. However, the study will describe the characteristics of the altitude and attitude control for vertical take-off and landing of the UAV system. The good performance of an automatic vertical take-off system indicates how fast the UAV system achieves its desired altitude and attitude.

1.2 Motivation

Flying machine technology has time and again led a great attraction on men inspiring all kinds of exploration and improvement. This research started in 2014, a time at which the UAV robotics community was continuing interest in autonomous UAV development. It was described that the scientific challenge in autonomous UAV design and the control in the lack of valuable solutions and cluttered condition were very motivating. Besides that, the demand of applications in both civilian markets and military inspired the funding of UAV development projects and it shows that the development of UAV has an interest in the world. Meanwhile, the ground-based autonomous robot development had already acquired great achievement with excellent results. Among these achievements include the ability of localization, navigation, obstacle avoidance etc. However, the ground-based robots have a limitation in uneven ground surface application and this causes the development of other alternative robot concepts. It includes the development of autonomous UAV systems in which one could follow and apply the autonomous ground-based robot techniques.

1.3 Problem Statement

Currently, a major challenge of an autonomous UAV VTOL quadcopter system is to produce a good altitude and attitude control. The quadcopter system is a highly nonlinear system, in which the speed of the motor varies according to the torque and force applied to the rigid body of the quadcopter and it requires a much more reliable controller to achieve high performance of hovering. The quadcopter has six degrees of freedom (DOF) which consists of angular velocity and linear acceleration of the quadcopter. The angular velocity of the quadcopter will be determined by the linear acceleration. Whereas, the linear acceleration concerns with the linear movement. Thus, developing an autonomous UAV quadcopter has several procedures to ensure that the systems are reliable in order to be implemented in the real world application. The development begins with controlling the altitude, which is important to make sure the UAV system able to fly with less human interaction. The autonomous altitude control must have a closed loop feedback to let the controller respond on the current height of the system. The performance of the controller is measured on the period of self-take-off at a certain height and also measured on how smooth the system is in a stationary condition. Hence, the PID controller has been involved as a controller in this work. Besides that, the attitude of the quadcopter controller should be designed as well. The advantage of PID controller is its feasibility and easy to be implemented. The PID gains can be designed based on the system parameters, if they can be obtained or estimated precisely. Moreover, the respond of the PID control system is faster than other controllers. The attitude control system is designed to produce the desired acceleration of the attitude control autonomously. Both angles of roll, θ and pitch, ϕ would produce the torque to generate movement based on the E-frame, where each movement is either straightway fly or sideways fly. The acceleration controller of the quadcopter movement is a major part in the development of an autonomous quadcopter. The controller used to ensure the movement corresponds with a specified algorithm task.

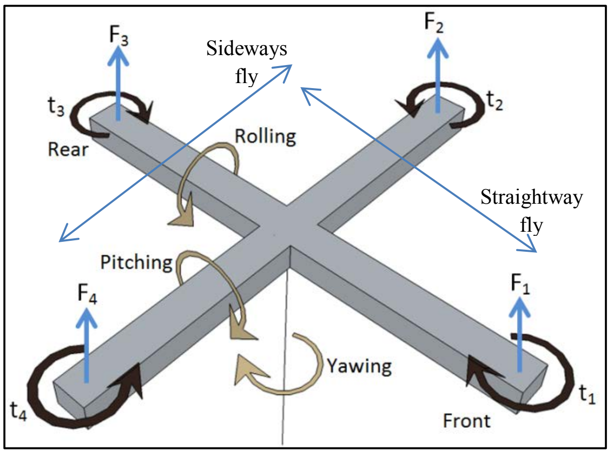

Figure 2.1 Illustration of quadcopter aerial vehicle concept

1.4 Objectives

The main objective of this research is to design and develop an autonomous UAV VTOL for a quadcopter control system. More specifically, the objectives of this research are as follows:

1. To investigate Quadcopter system based on mathematical model description
2. To develop the attitude and altitude control system based on PID controller approach.

3. To analyse the performance of the controller for altitude and attitude control system.
4. To implement a real-time application into designing a UAV controller. Real-Time Windows Target integrates the change of controller parameter from Matlab-Simulink.

1.5 Scope of Thesis

The main focus of this research is to utilize a PID controller at the altitude and attitude of the quadcopter system. The detailed scopes of this work are as follows:

1. The experiment is focused on a model quadcopter with a 0.8 kg payload weight and is 40 cm in length between the end of the cross quadcopter frame. The physical parameter is included into the final mathematical equation of the quadcopter model. In this part, control system design will take into account the parameters involved in the Quadcopter system.
2. The altitude control system is designed to enable the quadcopter system achieve the desired height. The motor speed cut-off in the system has been set to 600rad/s for the upper cut-off, and 200rad/s for the lower cut-off. The analysis is conducted to achieve a 1 meter height target within a 2s period. The control system also tested for the 20 meter height target to analyse the reliability of the controller in high altitude. The performance of the controller is evaluated by comparing the upgraded controller and the existing one through experiments.
3. The rolling and pitching control system is designed to produce a movement at the target rolling and pitching angle. This movement rate would generate a force to move to the right or to the left trajectory based on the E-frame. The design of the angular velocity of the quadcopter controller should be able to respond to achieve