UNIVERSITI PUTRA MALAYSIA

# NUMERICAL STUDY ON ATTITUDE AND ALTITUDE CONTROL OF MULTI-ROTOR ROTORCRAFTS

LIM ANN

FK 2012 85

# NUMERICAL STUDY ON ATTITUDE AND ALTITUDE CONTROL OF MULTI-ROTOR ROTORCRAFTS

**LIM ANN**

**MASTER OF SCIENCE**

**UNIVERSITI PUTRA MALAYSIA**

**2012**

© COPYRIGHT UPM

# NUMERICAL STUDY ON ATTITUDE AND ALTITUDE CONTROL OF MULTI-ROTOR ROTORCRAFTS

**By**

**LIM ANN**

© COPYRIGHT UPM

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science**

**February 2012**

This thesis is dedicated to my family, with love

© COPYRIGHT UPM

Abstract of this thesis presented to the Senate of University Putra Malaysia as partial fulfillment of the requirement for the degree of Master of Science.

**NUMERICAL STUDY ON ATTITUDE AND ALTITUDE CONTROL OF MULTI-ROTOR ROTORCRAFTS**

**BY**

**LIM ANN**

**February 2012**

**Chairman: Abdul Aziz Bin Jaafar, Phd**

**Faculty: Engineering**

UAV is an acronym for Unmanned Aerial Vehicle, which is an aircraft with no pilot on board. UAVs can be remote controlled by a pilot at a ground control station, or it can fly autonomously based on pre-programmed flight plans or more complex dynamic automation systems. UAVs are widely used for a number of missions, including reconnaissance and attack roles. Motivation that drives UAVs research is due to its usefulness in many industries, such as agriculture, telecommunications, and military and also to overcome major challenges faced by designer especially in aspect of design and control strategy.

The research carried out is in this thesis is to design quadrotor and trirotor prototype for flight behavior study. The main mission profile for the rotorcrafts is to stabilize at certain altitude and attitude. There are two specific objectives for this study, first is to



© COPYRIGHT UPM

develop simulations which including dynamic for quadrotor and trirotor systems with given parameters; second is to stabilize the systems by applying controller on each subsystem and tune it to meet stability requirements. Stability is evaluated in aspect of rise time, settling time, overshoot and steady-state error.

The previous works of other researchers in multirotor rotorcraft are studied. Quadrotor and trirotor designed by other researchers are used as reference for developing simulation using Matlab Simulink. Control techniques are penetrated intensely for their applications, advantages and weakness. Equations of motion, actuator dynamics and controller equations are figured out and modified reasonably.

Controller tuning are carried out to obtain optimum gain which can compensate system error and perform multiple task action. Controller gain is then manipulated to examine behavior of the system. Comparisons with other researchers work are presented. Weaknesses of systems are identified and some suggestions are proposed to improve the system.

© COPYRIGHT UPM

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi sebahagian keperluan untuk Ijazah Master Sains.

**KAJIAN BERANGKA KAWALAN ORIENTASI DAN KETINGGIAN UNTUK PESAWAT ROTOR YANG BERBILANG ROTOR**

**Oleh**

**LIM ANN**

**Februari 2012**

**Pengerusi:** **Abdul Aziz Bin Jaafar, Phd**

**Fakulti:** **Kejuruteraan**

UAV adalah pesawat udara yang tiada juruterbang di atas kapal. UAV boleh dikawal oleh juruterbang di stesen bumi, atau diterbangkan secara autonomi berdasarkan pelan penerbangan, atau dikawal dengan sistem autonomasi yang dinamik lebih kompleks. UAV digunakan secara meluas untuk beberapa misi, termasuk peranan tinjauan dan serangan. Motivasi yang mendorong UAV penyelidikan adalah disebabkan kegunaannya dalam banyak industri, seperti pertanian, telekomunikasi, dan tentera dan juga untuk mengatasi cabaran-cabaran utama yang dihadapi oleh pereka terutama dalam aspek reka bentuk dan strategi kawalan.

Penyelidikan yang dijalankan dalam tesis ini adalah untuk membina prototaip quadrotor dan trirotor untuk kajian kelakuan penerbangan. Profil misi utama untuk pesawat berbilang rotor tersebut adalah untuk mencapai kestabilan pada ketinggian

© COPYRIGHT UPM

tertentu dan orientasi .Terdapat dua objektif khusus bagi kajian ini, pertama ialah untuk membangunkan simulasi untuk dinamik quadrotor dan trirotor dengan parameter yang diberikan; kedua ialah menstabilkan sistem dengan mengaplikasikan pengawal dalam setiap subsistem dan menalanya untuk memenuhi keperluan kestabilan. Kestabilan sistem dinilai dalam aspek masa peningkatan, masa menetap, keterlanjakan dan ralat dalam keadaan mantap.

Kerja-kerja penyelidik lain dalam bidang pesawat rotor berbilang rotor dikaji. Quadrotor dan trirotor direka oleh penyelidik lain telah digunakan sebagai rujukan bagi membangunkan simulasi dengan menggunakan Matlab Simulink. Teknik kawalan dikaji dalam aspek aplikasi, kebaikan dan kelemahan. Persamaan gerakan, dinamik penggerak dan persamaan pengawal dicapai dan diubahsuai dengan munasabah. Penalaan pengawal dijalankan untuk mendapatkan pemalar yang optimum yang boleh membaiki ralat sistem dan melaksanakan beberapa tugas. Pemalar Pengawal kemudiannya dimanipulasikan untuk mengkaji ciri-ciri sistem. Perbandingan dengan kerja penyelidik lain dibentangkan. Kelemahan sistem dikenal pasti dan beberapa cadangan dikemukakan untuk memperbaiki sistem.

© COPYRIGHT UPM

## ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest thanks and appreciation to my supervisor, Dr. Abdul Aziz Jaafar, and co-supervisor Dr. Fairuz Izzuddin Romli for their advise, guidance and encouragement throughout my thesis writing. They help me greatly by giving suggestion for my experiment method and offering insightful comments, which make this thesis a reality.

I would like to thank Mr. Azizul and Mr Lee J.S. from Aerospace Engineering who have helped me to prepare the apparatus for my thesis experiment. I am appreciate for their patience on describe the function and using method of the apparatus. They also give me some useful advises on the experiment method.

Besides, I would like to express my heartful thanks to my dearest family for their constant support, love and encouragement throughout my study period. I thank in particular my dear soul mate, Mr. Dan J.X., who share my burden constantly and continuously give encouragement and full support to me in completing my study and thesis.

Once again, I would like to thank for all UPM staff, their cooperation and services that contribute to success in this thesis. Last but not least, I am sincerely appreciate for who have ever given help, advise, guiding and support to me.

© COPYRIGHT UPM

I certify that a Thesis Examination Committee has met on 28th February 2012 to conduct the final examination of Lim Ann on his thesis entitled "Numerical Study on Attitude and Altitude Control of Multi-rotor Rotorcraft" in accordance with the Universities and University College Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The committee recommends that the student be awarded the degree of Master of Science.

Member of the Thesis Examination Committee were as follows:

**Mohad. Ramly Mohd. Ajir, PhD**
Associate Professor LT. COL. (R)
Department of Aerospace Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

**Mohamed Tarmizi Ahmad**
Associate Professor LT. COL. (R)
Department of Aerospace Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

**Faizal Mustapa, PhD**
Associate Professor
Department of Aerospace Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

**Nukman Bin Yusoff, PhD**
Associate Professor
Department of Engineering Design and Manufacturing
Universiti of Malaya
(External Examiner)

_____
**NORITAH OMAR, PhD**
Associate Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:



© COPYRIGHT UPM

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

**Abdul Aziz Jaafar, PhD**
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

**Fairuz Izzuddin Romli, PhD**
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

© COPYRIGHT UPM

**BUJANG BIN KIM HUAT, Phd**
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

## DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously and is not concurrently, submitted for any other degree at University Putra Malaysia or at any other institution.

_____

**LIM ANN**

Date: 28th February 2012

© COPYRIGHT UPM

## TABLE OF CONTENT


| | | | Page |
|---|---|---|---|
| **DEDICATION** | | | I |
| **ABSTRACT** | | | II |
| **ABSTRAK** | | | IV |
| **ACKNOWLEDGEMENTS** | | | VI |
| **APPROVAL** | | | VII |
| **DECLARATION** | | | IX |
| **LIST OF TABLES** | | | XIV |
| **LIST OF FIGURES** | | | XV |
| **LIST OF SYMBOLS AND ABBREVIATIONS** | | | XVIII |
| **CHAPTER** | | | |
| 1 | **INTRODUCTION** | | 1 |
| | 1.1 | Introduction of UAV | 1 |
| | 1.2 | Research Activities of UAV | 3 |
| | 1.3 | Problem Statement | 4 |
| | 1.4 | Hypothesis | 4 |
| | 1.5 | General objective | 4 |
| | 1.6 | Objectives of Thesis | 4 |
| | 1.7 | Thesis Layout | 5 |
| 2 | **LITERATURE REVIEW** | | 6 |
| | 2.1 | Introduction | 6 |
| | 2.2 | Early History of Rotorcraft | 6 |
| | 2.3 | Modelling Mathematical model for Rotorcraft | 12 |
| | | 2.3.1 Equations of Motion for rotorcraft | 12 |
| | | I. Newton-Euler Method | 15 |
| | | II. Lagrangian Equation | 16 |
| | | 2.3.2 Control Input | 18 |
| | | 2.3.2.1 Control Input for Quadrotor | 18 |




© COPYRIGHT UPM

2.3.2.2 Control Input for Trirotor 20
2.3.3 Actuator Dynamic 21
2.4 Control Strategy 22
2.4.1 PID Control 23
2.4.1.1 Introduction of PID Control Theory 23
2.4.1.2 Tuning Method 24
2.4.1.3 Limitation of PID Control 27
2.4.1.4 Implementation of PID Control 28
2.4.2 LQR Optimal Control 31
I. State Dependent LQ Optimal Control 31
II. Classic LQR Optimal Control 32
2.4.3 Feedback Linearization 33
2.4.4 Backstepping Control 33
2.4.5 Sliding mode 34
2.4.6 Nested Saturation 34

3 **RESEARCH METHODOLOGY: DYNAMIC AND CONTROL OF QUADROTOR AND TRIROTOR** 37
3.1 Introduction 37
3.2 Vehicle Component and Simulation Block Diagram Construction 39
3.3 Parameter Selection 41
3.3.1 Quadrotor Model 41
3.3.2 Trirotor Model 43
3.4 Simulation Block Diagram Construction 44
3.5 Motor Dynamic and Voltage Combinations 46
3.5.1 Voltage Combination for Quadrotor 46
3.5.2 Voltage Combination for Trirotor 49
3.5.2.1 Trirotor (with tilting on tail rotor) 49
3.5.2.2 Trirotor (without tilting on tail rotor) 51
3.6 Decoupling of Voltage 54
3.6.1 Decoupling Voltage for Quadrotor 54
3.3.2 Decoupling Voltage for Trirotor 54



© COPYRIGHT UPM

(with /without tilting on tail rotor)
3.7 Dynamic Modelling by Mathematical Approach 56
3.7.1 Equation of Motion for Quadrotor 57
3.7.2 Equation of Motion for Trirotor 60
3.7.2.1 Trirotor (with tilting on tail rotor) 60
3.7.2.2 Trirotor (without tilting on tail rotor) 62
3.8 Controller Design 63
3.9 PID Controller Tuning Methodology 65
3.9.1 Heuristic Tuning Method 65

4 **RESULT AND ANALYSIS** 68
4.1 Quadrotor Simulation 68
4.1.1 Controller Tuning 69
I. Roll Angle 70
II. Pitch Angle 72
III. Yaw Angle 75
IV. Altitude Z 77
4.1.2 Result Analysis 80
4.2 Trirotor Simulation 83
4.2.1 Controller Tuning 86
I. Roll Angle 86
II. Pitch Angle 88
III. Yaw Angle 90
IV. Altitude Z 91
4.2.3 Result Analysis 94
4.3 Discussion 99
4.4 Comparison of Results 100
4.5 Closure 101

5 **CONCLUSION AND FUTURE PROSPECT** 102
5.1 Conclusion 102
5.2 Suggestion and Future Prospects 103

© COPYRIGHT UPM

**BIBLIOGRAPHY** 104
**APPENDIX** 108
**BIODATA OF STUDENT** 121

© COPYRIGHT UPM