DEVELOPMENT OF CONTROL ALGORITHM (PID-LQR) FOR POINT TO POINT MOVEMENT OF A NONLINEAR QUADROTOR UNMANNED AERIAL VEHICLE

by

Muhammad Kamran Joyo
1330610953

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School of Mechatronic Engineering
UNIVERSITI MALAYSIA PERLIS

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LIST OF ABBREVIATION

UAV	Unmanned Aerial Vehicle
PID	Proportional, Integral and Derivative
LQR	Linear Quadratic Regulator
RC	Remote Control
LQ	Linear Quadratic
GPS	Global Positioning System
EKF	Extended Kalman Filter
E-Frame	Earth Frame
B-Frame	Body Frame
H-Frame	Hybrid Frame
VTOL	Vertical Takeoff / Landing
DOF	Degree of Freedom
MATLAB	Matrix Laboratory
MEMS	Micro Electronic Mechanical Sensors

LIST OF SYMBOLS

m	Quadrotor mass (kg)
J_{Θ}	Generalized matrix
O_B	Gyroscopic propeller matrix WRT B-frame
O_H	Gyroscopic propeller matrix WRT H-frame
R_{Θ}	Rotation matrix (roll-pitch-yaw)
$S(.)$	Skew-symmetric operator
T_{Θ}	Transfer matrix
U_1	Vertical thrust respect to the body frame (N)
U_2	Roll torque respect to the body frame (Nm)
U_3	Pitch torque respect to the body frame (Nm)
U_4	Yaw torque respect to the body frame (Nm)
X	Quadrotor linear position along xe WRT E-frame (m)
$\dot{X}$	Quadrotor linear velocity along xe WRT E-frame (m s^{-2})
$\ddot{X}$	Quadrotor linear acceleration along xe WRT E-frame (m s^{-2})
Y	Quadrotor linear position along ye WRT E-frame (m)
$\dot{Y}$	Quadrotor linear velocity along ye WRT E-frame (m s^{-2})
$\ddot{Y}$	Quadrotor linear acceleration along ye WRT E-frame (m s^{-2})
Z	Quadrotor linear position along ze WRT E-frame (m)
$\dot{Z}$	Quadrotor linear velocity along ze WRT E-frame (m s^{-2})

$\ddot{Z}$	Quadrotor linear acceleration along ze WRT E-frame (m s^{-2})
ζ	Quadrotor generalized velocity vector WRT H-frame
$\dot{\zeta}$	Quadrotor generalized acceleration vector WRT H-frame
θ	Quadrotor angular position around y1 WRT E-frame (rad)
$\dot{\theta}$	Quadrotor angular velocity around y1 WRT E-frame (rad s^{-1})
$\ddot{\theta}$	Quadrotor angular acceleration around y1 WRT E-frame (rad s^{-2})
ϕ	Quadrotor angular position around x2 WRT E-frame (rad)
$\dot{\phi}$	Quadrotor angular velocity around x2 WRT E-frame (rad s^{-1})
$\ddot{\phi}$	Quadrotor angular acceleration around x2 WRT E-frame (rad s^{-2})
ψ	Quadrotor angular position around ze WRT E-frame (rad)
$\dot{\psi}$	Quadrotor angular velocity around ze WRT E-frame (rad s^{-1})
$\ddot{\psi}$	Quadrotor angular acceleration around ze WRT E (rad s^{-2})
ξ	Quadrotor generalized position vector WRT E-frame
$\dot{\xi}$	Quadrotor generalized velocity vector WRT E-frame
ω^B	Quadrotor angular velocity vector WRT B-frame (rad s^{-1})
$\dot{\omega}^B$	Quadrotor angular acceleration vector WRT B-frame (rad s^{-2})
Γ^E	Quadrotor linear position vector WRT E-frame (m)
F	Quadrotor forces vector WRT B-frame (N)
τ^B	Quadrotor torques vector WRT B-frame (Nm)
ν	Quadrotor generalized velocity vector WRT B-frame
Ω	Overall propeller speed (rad s^{-1})

$\dot{\Omega}$	Propellers acceleration vector (rad s^{-2})
Ω_1	Front propeller speed (rad s^{-1})
Ω_2	Right propeller speed (rad s^{-1})
Ω_3	Rear propeller speed (rad s^{-1})
Ω_4	Left propeller speed (rad s^{-1})

Pembangunan kawalan algoritma untuk pergerakan titik ke titik sebuah kenderaan udara tanpa pemandu quadrotor non-linear

ABSTRAK

Dalam tahun-tahun kebelakangan ini, quadrotor UAV telah menarik perhatian para penyelidik untuk membangunkan bidang penyelidikan yang besar dalam bidang UAV. Quadrotor A mempunyai reka bentuk ringkas. Dikarenakan ianya mempunyai keunikan dalam bentuk dan reka bentuk yang ringkas ia memperolehi kesempatan dalam membawa pelbagai jenis isu-isu berkenaan dengan hal kawalan. Sistem quadrotor adalah tidak linear dalam alam, jadi ia memerlukan kawalan yang sesuai untuk memastikan kestabilan semasa penerbangan. Walau bagaimanapun, penyelidik telah dapat menyediakan beberapa penyelesaian kepada isu-isu mengenai kestabilan sudut, ketinggian, dan kawalan kedudukan quadrotor pada keadaan yang mencabar seperti pecah angin dan kebisingan tetapi masih belum berjaya diselesaikan. Dalam laporan tesis ini teknik reka bentuk kawalan moden dibincangkan dan penggunaan dalam isu-isu kawalan quadrotor adalah dibentangkan. Teknik-teknik kawalan dilaksanakan pada kawalan gerakan membujur pada quadrotor. Selepas mengenakan beberapa teknik kawalan terkenal pada sistem, dicadangkan bahawa sistem memerlukan suatu teknik kawalan inovatif untuk sistem quadrotor. Satu teknik kawalan inovatif adalah.

DEVELOPMENT OF CONTROL ALGORITHM (PID-LQR) FOR POINT TO POINT MOEMENT OF A NONLINEAR QUADROTOR UNMANNED AERIAL VEHICLE

ABSTRACT

In recent years the area of quadrotor UAV has drawn prominent attention of the researchers enabling to develop immense research area in the field of UAVs. A quadrotor has a simple architectural design due to which designing gets simple. Having advantage of uniqueness in shape and simple design it carries numerous kinds of issues regarding its controlling. A quadrotor system is nonlinear in nature, so it requires a suitable controller to ensure its stability during flight. However, researchers have been able to provide some solutions to the issues regarding angular stability, altitude and position control of quadrotor under the challenging conditions such as wind burst and noisy measurements but still they are not successfully resolved. In this thesis report modern control design techniques are discussed and their application in quadrotor control issues are presented. The control techniques are implemented on a longitudinal motion control of quadrotor i.e. issues related while maneuvering on horizontal plane. After imposing few renowned control techniques on the system it was observed that system requires to build a robust control technique for the quadrotor system. An innovative and more robust control technique is proposed for the position controlling quadrotor system. The controller is designed by fusing two distinct control techniques PID and LQR, which is named as PID-LQR. While flying quadrotor can experience two major issues; noises and external disturbance applied on the system. The nature of noises is the noise generated from GPS sensor and the system itself. The nature of disturbance is the disturbance applied externally on the system. The control technique works in such a way that PID is used for tackling a disturbance such as an external push or wind gust and LQR for rejecting noises of the sensor measurements. Furthermore the effectiveness of proposed control technique is also verified by comparing it with auto-tuned PID and optimized LQR techniques under disturbed and noisy conditions. The simulated results indicate that the proposed method yields a better response as compared to the conventional methods.

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DECLARATION OF THESIS

Author's full name : **MUHAMMAD KAMRAN JOYO**

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Title : **Development of Control Algorithm PID-LQR for Point to Point Movement of a Nonlinear Ouadrotor Unmanned Aerial Vehicle**

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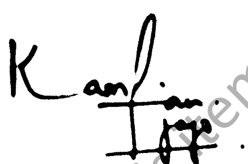

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CHAPTER 1

INTRODUCTION

1.1 Overview

UAVs have been a subject of interest to the researchers due to the rapid advancement in technology and demand as they are expected to become a major asset to aviation industry. The prospective of UAVs is endless due to their saturation in numerous areas. Generally their primary potential is used in military applications such as marine operations (S. Gray, 2003), battle damage assessment (A. Gerrard, 2004), border interdiction prevention and law enforcement (CC. Haddal, 2010). They have been able to penetrate in civil applications such as search and rescue missions (Bernard, 2011), wild fire surveillance (K. Alexis, 2009), monitoring over nuclear reactors (J.Han, 2013), power plants inspection (G. Caprari, 2012), agricultural services (J Mäkynen, 2012), mapping and photographing (NS. Board, 2005). UAVs are worthwhile in environments that are inappropriate for flight even by a skilled pilot. They have capabilites to perform the operations effectively and efficiently without compromising the pilot's life. These abilities makes them ideal for military purposes, so this has been the reason that their development has reflected the pace of technological advancement immensely.

There exist numerous types of UAVs; one of them is quad-rotor UAV which is prominent amongst the researchers. The cause of their prominence is due to their light weight, simple mechanical structure that makes its assembly trouble-free. Its capabilities to hover, VTOL and act sharply to the given commands identify their uniqueness in helicopter type UAVs. It has certain advantages over conventional helicopter such as the design of the conventional helicopter is massively complex therefore requires more efforts in maitennce making cost turns out to be huge. Quad-rotors can react more smarter and quicker than the conventional helicopters. The above mentioned qualities also marks them prominent over the fixed-wing UAVs.

As compared to the conventional helicopters quad-rotors configuration does not require a complex structural design. In general it consists of four rotors mounted at the four ends of a cross frame. A pair of motors (Q1 and Q3) rotates clockwise while other pair of motors (Q2 and Q4) rotates counter-clockwise direction. This combination of motor rotation counters the opposite torques produced by motors. The rotation of these propellers generate a vertical lifting force upwards which raises quad-rotor body in the air and it moves in pitch, roll, yaw, hover, takeoff and landing positions as each motor works independently .

1.2 Problem Statement

The quad-rotor system in general are distinctive in nature due to their unique design and operation. On the other hand this rotorcraft carries serious issues regarding its control. Quad-rotor UAV might look simple by design but is nonlinear in nature and has caused considerable annoyance to researchers in the past. The control for stabilization of the system for longitudinal motion under external disturbance such as air turbulence and noisy conditions is still a subject that is concerned to researchers and this matter requires a reasonable consideration.

1.3 Significance of the study

The quad-rotor system is inherently nonlinear and unsteady UAV system. In the real time applications these vehicles have to go through immensely harsh environment. The issues they face while maneuvering are external disturbances applied on the system such as an external push to the aircraft or air turbulence and false sensor measurements. In case of position controlling the sensor used to determine the position on a horizontal plane is GPS. These issues can affect the performance of quad-rotor during flight as they can drift the UAV from its original position. Hence, it requires an efficient robust position control design which is able to react quickly to the wind gusts and overcome the noisy measurements of the GPS sensor. This research work helps to resolve the issues faced by fully autonomous quad-rotor UAV during its longitudinal motion under uncertain conditions such as external disturbance and faulty sensor measurements.

1.4 Research Objectives

The purpose of the research is to develop an efficient robust control design for longitudinal motion of quad-rotor under various uncertainties acting on the system. The uncertainties that can effect the flight performance the UAV are external disturbances and noisy sensor measurements. PID and LQR control techniques are used to develop such control design that can collectively react efficiently to uncertainties acting on the system. Following are the objectives of this research:

i. To develop a mathematical model of quad-rotor UAV

Developing a mathematical model of quad-rotor is a demanding task. This research work includes development of a mathematical model. There are several methods to develop the mathematical model of quad-rotor. This research works follows Newton Euler method to extract the quad-rotor equations of motion.

ii. To develop and implement PID and LQR control algorithm for point to point movement of quad-rotor UAV

The quad-rotor UAV experiences several challenges while flying. With false sensor measurements, quad-rotor can become unsteady. While air turbulence can affect the flight of quad-rotor UAV by suddenly drifting from its desired position. The control algorithms PID and LQR are implemented to quad-rotor to analyze the response of quad-rotor under uncertain conditions that can act on quad-rotor in real time.

iii. To develop a robust control design for nonlinear quad-rotor UAV

On the basis of response of PID and LQR under air turbulence and false data measurements, a switching control technique PID-LQR is developed for an efficient response of longitudinal motion of quad-rotor.

1.5 Thesis Organization

This thesis explores the area of quad-rotor helicopter type UAVs. A mathematical model is developed with few conventional algorithms implemented on it and on the basis of the system requirements a control design is developed by fusing two distinct techniques PID and LQR. The research works carried out are presented in five chapters of this thesis.

Chapter describes the introduction of this research work and an overview on thesis organization. The literature review on modelling of quad-rotor, discussion on the control techniques and its implementation on quad-rotor by previous researchers are presented in Chapter 2. The previous work on quad-rotor has been surveyed and discussed in this section. Chapter 3 solely relates to the modelling of quad-rotor and control design. The equations of motion for quad-rotor have been derived using Newton Euler method. All the parameters used for derivation are discussed comprehensively. It also presents the concepts of configuring a control design for longitudinal motion of quad-rotor. An inclusive discussion is done on PID, LQR and proposed algorithm based on PID-LQR. Chapter 4 presents the all the simulation results obtained from the developed position control system for quad-rotor UAV. Furthermore it also provides a brief comparison with other conventional techniques. Chapter 5 summarizes the contribution made in this research and suggestions for future research works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The concept of quad-rotor began in the very early years of 1900 century. Early products of quad-rotor were very huge, heavy and were unsuccessful. In 21st century, quad-rotor size was converted to very small dimensions and technological advancement made its structural design very simple. They have brought incredible evolution in the past years in rotorcraft and helicopter area. Researchers were able to design unmanned quad-rotor UAV that is able to execute missions with perfection in any situation. This chapter provides a detailed survey of quad-rotor UAVs that are recently developed and a review of control techniques developed in recent years.

2.2 Survey of Former Designed Quad-rotor UAVs

Quad-rotor idea start building in early 1900's, an experimental rotor craft was built by Breguet brothers which flew in the year 1907 for the very first time named Breguet-Richet Gyroplane (Leishman, 2006), shown in Fig. 2.1. Whole body is made up of steel that is why the weight of aircraft is around 500kg without the pilot, finally this aircraft did not flew well and was not controllable at all by any means (Nicol, 2011).

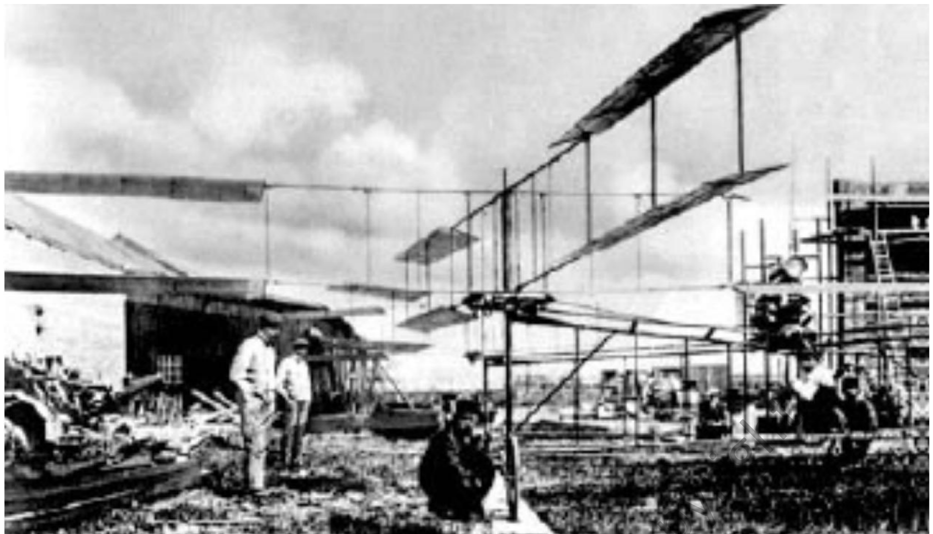

Figure 2.1: Breguet-Richet Gyroplane

De Bothezat the first person who designed Remote Control (RC) based quad-rotor (Leishman, 2006), shown in Fig. 2.2. This design has got capabilities to fly on low altitude and was very slow in moving to horizontal motion because it has no any control algorithm for avoiding uncertainities and therefore it affected by wind very gently (Orsag, 2010).

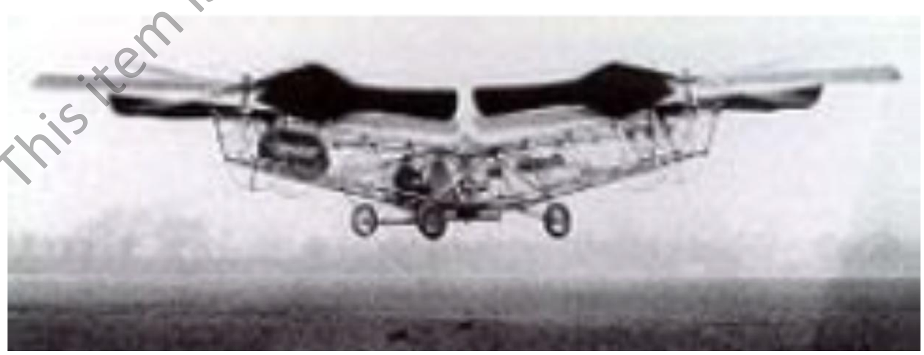

Figure 2.2: De Bothezat design

In the recent years quad-rotor have gained immense attention of researchers due its demands in military and civil applications. More complex and robust control techniques have been developed in order to provide detailed representation of quad-rotors in real life.

Advancement in sensor technology and processors have led to the development of small quad-rotor UAVs. The indoor micro quad-rotor UAV was developed and was named as OS4 (Bouabdallah, 2007a). Fig. 2.3 shows the diagram of the model. The mathematical design and modeling were presented and the quad-rotor was equipped with the sensors that could measure position, altitude and orientation (Bouabdallah, 2004a). The OS4 was equipped with control technique which are classical PID and LQ control techniques (Bouabdallah, 2004b). PID performed well as compared to LQ because for LQ controller discovering the suitable weight matrices to satisfy the stability of the control was difficult. Whereas PID provided simple method of tolerance for uncertainties acting on the system. Further researchers also developed and implemented a model to simulate the dynamics of OS4 quad-rotor UAV on MATLAB. This enabled them to rectify the control parameters for their control techniques and test obstacle avoidance techniques (Bouabdallah, 2007c). It also enabled them to test filters and sensors.

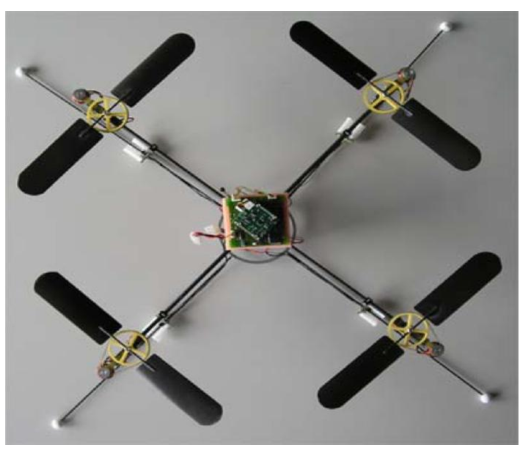

Figure 2.3: OS4 model

Research activities have increased with the improvements made in processors and MEMS technology. People have been working on designing testbeds for quad-rotor UAV in order to design autonomous flight controls and sensing. A quad-rotor known as Dragonflyer, is a commercially available quad-rotor and shown in Fig. 2.4. It is equipped with seven different sensors enabling the quad-rotor to be more stabilized during manual and autonomous flight. It also carries a payload such as high resolution camera for video transmission (Lacher, 2012).

Figure 2.4: Dragonflyer quad-rotor

Now in this era, many classical type of quad-rotor is being implemented like Starmac II (Hoffmann, 2007b), shown in Fig. 2.5. Composition of this quad-rotor is done by electronic interface board and several processors. This design divides its dynamics into two parts first attitude and altitude which control by a fast rate low level processor and secondly position is control by simply low level atmega 128 microprocessor (Hoffmann, 2011a).