NMPC-PID BASED NEW CONTROL STRUCTURE DESIGN FOR ALTITUDE AND ATTITUDE STABILIZATION OF NON-LINEAR QUAD-ROTOR TYPE UNMANNED AERIAL VEHICLES (UAV)

by

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LIST OF ABBREVIATION

UAV	Unmanned Aerial Vehicle
PID	Proportional, Integral and Derivative
NMPC	Nonlinear Model Predictive Control
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

LIST OF SYMBOLS

θ	Roll angle
ϕ	Pitch angle
φ	Yaw angle
Ω	Motor rotor angular velocity
ρ_a	Air density
m	Motor mass
I_{xx}	Rotor Inertia X-axis
I_{yy}	Rotor Inertia Y-axis
I_{zz}	Rotor Inertia Z-axis
K_e	Constant of motor
f	Figure of merit of propeller
η	Efficiency of motor
V	Voltage input of motor
A	Cross sectional area of rotor disc
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 xeWRT E-frame (m)
$\dot{X}$	Quadrotor linear velocity along xeWRT E-frame (m s^{-2})
$\ddot{X}$	Quadrotor linear acceleration along xeWRT E-frame (m s^{-2})
Y	Quadrotor linear position along yeWRT E-frame (m)
$\dot{Y}$	Quadrotor linear velocity along yeWRT E-frame (m s^{-2})
$\ddot{Y}$	Quadrotor linear acceleration along yeWRT E-frame (m s^{-2})
Z	Quadrotor linear position along zeWRT E-frame (m)
$\dot{Z}$	Quadrotor linear velocity along zeWRT E-frame (m s^{-2})
$\ddot{Z}$	Quadrotor linear acceleration along zeWRT 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 zeWRT E-frame (rad)
$\dot{\psi}$	Quadrotor angular velocity around zeWRT E-frame(rad s^{-1})
$\ddot{\psi}$	Quadrotor angular acceleration around zeWRT E(rad s^{-2})
ξ	Quadrotor generalized position vector WRTE-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})

Rekabentuk struktur kawalan baru berasaskan NMPC-PID untuk penstabilan pada ketinggian dan posisi pada kenderaan udara tanpa pemandu jenis empat rotor (UAV) yang tidak linear

ABSTRAK

Kenderaan udara tanpa pemandu jenis empat rotor (UAV) adalah helikopter yang mempunyai empat kipas. Untuk menjana daya angkat, dua kipas berputar mengikut arah jam dan dua kipas lagi berputar arah melawan jam dan oleh kerana kaedah kawalannya yang kompleks, helikopter ini adalah tidak linear dalam alam semula jadi secara keseluruhannya. Lantas ia mewujudkan pelbagai masalah semasa terbang dan menjadi sangat sukar untuk terbang stabil di bawah pelbagai ketidaktentuan. Objektif kajian ini adalah untuk membangunkan satu algoritma kawalan yang stabil dan mantap untuk penstabilan sikap dan ketinggian Quad-rotor. Untuk menyelesaikan masalah kestabilan, peranan penting ini telah dilakukan oleh maklum balas daripada sistem kawalan. Penstabilan sistem UAV bukan linear di bawah pelbagai ketidaktentuan seperti pecah angin, sistem dan sensor keadaan bunyi telah menjadi bidang utama penyelidikan mencabar di kalangan penyelidik dan banyak kerja-kerja penyelidikan yang dilakukan dalam lingkungan ini, tetapi masih terdapat banyak ruang yang terdapat di bidang ini. Dalam tesis ini, formalisme Newton-Euler telah digunakan untuk model dinamik sistem Quad-rotor dan kemudian dipertingkatkan lagi dengan kawalan yang lebih tepat untuk penstabilan sistem UAV tidak linear. Algoritma kawalan yang dicadangkan berfungsi dengan cekap dalam menstabilkan sikap dan kawalan ketinggian Quad-rotor, di mana ia mempunyai potensi untuk mengelak dan mengatasi pelbagai ketidaktentuan. Teknik kawalan yang dicadangkan dibahagikan kepada dua sub- sistem (iaitu: NMPC, PID). Untuk mengesahkan operasi penolakan gangguan, pengawal Berkadar, Integral dan Derivatif (PID) yang mantap dihasilkan daripada fasa pertama sistem yang dicadangkan. Kemudian untuk penyingkiran sensor dan sistem bunyi yang tidak diingini, algoritma kawalan Model Ramalan Kawalan Tidak Linear (NMPC) digunakan pada teknik pengoptimuman di mana ia mampu meminimumkan fungsi kos kriteria. Ia menunjukkan bahawa cadangan teknik kawalan NMPC-PID menghasilkan sistem kawalan stabil yang lebih mantap dan untuk mengesahkan keberkesanan teknik yang dicadangkan pada sistem UAV, maka simulasi dilakukan menggunakan MATLAB-Simulink bertujuan untuk mengesahkan dan memastikan peningkatan dalam kualiti dan keberkesanan kaedah cadangan.

NMPC-PID based new control structure design for altitude and attitude stabilization of non-linear Quad-rotor type unmanned aerial vehicles (UAV)

ABSTRACT

Quad-rotor typed unmanned aerial vehicles (UAV) are rotorcraft that has four propellers. In this design there are two arms and each arm has two propellers at their end.. It has complex controlling structure, that is why this rotorcraft is overall non-linear in nature. Hence, it creates a lot of difficulties during flying and become very difficult to make it fly stabilize under different sort of uncertainties. Therefore, stabilization of non-linear UAV system under various uncertainties like wind burst, system and sensor noise conditions has been a challenging research domain among the researchers and many of research work has been done in this domain, but still there is a lot of room available in this area. The objective of this research is to develop a stable control algorithm for Quad-rotor attitude and altitude stabilization. To solve its stability problem, the important role is done by making a control algorithm which satisfies its control system requirements. In this thesis, the Newton-Euler formalism was used to model the dynamic of Quad-rotor system and then a robust with more accurate control for stabilization of non-linear UAV system is intended. The proposed control technique is divided into two sub-systems. In order to validate the disturbance rejection operation, a robust Proportional, Integral and Derivative (PID) controller is derived in first phase of proposed system. Then for the removal of unwanted sensor and system noises, Non-Linear Model Predictive Control (NMPC) control algorithm is used which works on the technique of minimizing the cost criterion function. It is shown that proposed NMPC-PID based control technique results in a more robust stable control system and to verify the effectiveness of proposed technique on UAV system, it is simulated on MATLAB-Simulink environment which confirms and verify improvements in quality and effectiveness of the proposed method.

CHAPTER 1

INTRODUCTION

1.1 Overview

The desire of flying has been one of the biggest challenges for mankind and has generated centuries of failures and thousands of dangerous attempts (J.Ansorge, 2012). The helicopter history is short in comparison with fixed-wing aircraft (TA Weisshaar, 2013). In recent years, usage of unmanned air vehicles (UAV) increased noticeably (A. Ayele, 2013). UAVs can be classified into two main groups, namely, fixed wings and rotary wings. Rotary wing air vehicles have an advantage, which is vertical takeoff and landing capability, compared to fixed-wings UAVs (P. Fahlstrom, 2012). There are different types of rotary wing air vehicles such as single rotor, twin rotors, tri-rotors, and quad rotors and so on. Usage area of a Quad-rotor can be separated into three major parts such as: military operations (R. Schneiderman, 2012), public applications (B.S.Hsu, 2013), and civil applications (R.L. Finn, 2012).

A quad-rotor UAV has exceptional advantages with its size, weight and its simple mechanical arrangement (Keun Uk Lee, 2011). This is the main reason that, nowadays these UAVs are wide used in various applications at minimal cost and without endangering any risk to human life (A. Burkle, 2011). UAVs are inherently suitable for military applications such as border patrolling, security intelligence, cartography, surveillance, cost guards, acquisition of targets (CK Hsu, 2010) and (HY. Chao, 2010). UAVs have also penetrated in civilian applications such as search & rescue missions (Krerngkamjornkit, 2013), explorations (Caldeira, 2013), security & surveying of oil pipe lines (Zhang, 2013), forests on fire (Ferrell, 2013), agricultural applications (Vanzeler, 2013) and power & nuclear plants inspection (Ćosić, 2013), (A. Rango, 2010), (A. S. Laliberte, 2010) and (EP. de Freitas, 2010). As a result the research community has seen substantial improvements in the design of controllers for these types of vehicles (J Stowers, 2011). The extensive consideration towards quad-rotor UAVs is due to its ability to complete the tasks efficiently and autonomously (L. Geng, 2013). It is a distinctive type of UAV because of its unique shape and functioning. With its inimitability, several technical & typical issues are associated to quad-rotor that opened a way to a gigantic research work .

The cause of Quad-rotor UAV prominence in this era is due to 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 quickly than the conventional helicopters. These qualities of Quad-rotors are also marks them prominent over the fixed-wing UAV.

As per controlling of Quad-rotor is concern, the performance of desired control law is dependent upon the accuracy of mathematical model which ensures the actual system. A control system is the interconnection of components forming a system configuration providing a desired response. Once the desired response is known, then error can be calculated which is the difference between desired and actual signal. A quad-rotor system is a simple structure but nonlinear in nature which make its control very difficult and complicated (TS Kang, 2013). Researchers have been facing issues with overall controlling and tackling to the air disturbances while flying which is the major concern in this proposal.

1.2 Problem of Statement

Stability and control has been one of the major problem and always a challenging domain for designer and researchers. The disappointment of many aircraft projects in the past can be directly accredited with insufficient solutions to the stability and control problems. Stabilization of non-linear unmanned aerial vehicle system under various uncertainties like wind burst and system & sensor noise conditions has been a challenging research domain among the researchers. To, overcome this problem a new robust NMPC-PID based controller for stabilization of non-linear unmanned aerial vehicle systems is proposed, which will make system altitude and attitude stabilize more accurately and efficiently.

1.3 Significance of the study

The Quad-rotor system is inherently nonlinear and unsteady UAV system. The issues UAV system are facing while maneuvering, hover or VTOL are air turbulence and false sensor measurements. These issues can affect the performance of Quad-rotor during flight, as they can drift the UAV and it can create a problem for UAV to achieve its desired position. Hence it requires an efficient altitude and attitude control design which will be able to react quickly to the wind gusts and overcome the noisy measurements of the sensors. The research work will help to resolve the issues faced by fully autonomous quadrotor UAV during its longitudinal motion such as air turbulence and false sensor measurements.

1.4 Research Objectives

The main objectives are as described below:

- To determine Kinematics and Dynamics of Quad-rotor UAV.
- To develop suitable control algorithms for Quad-rotor's altitude and attitude stabilization under uncertainty condition.
- To innovate switching based control technique based on NMPC and PID controller for attitude and altitude stabilization of Quad-rotor.

1.5 Thesis Organization

This thesis explores the topic of development of new NMPC-PID altitude and attitude stabilization control algorithm for non-linear quad-rotor type unmanned aerial vehicles (UAV). Chapter 1 (current chapter) provides the introduction of this research with significance, objective and an overview on how the dissertation is organized. Chapter 2 describes the history of UAV aircraft from its construction beginning till it become so popular. Also discuss about the control methods of this system and finally Quad-rotor altitude and attitude taken into account for survey. Chapter 3 describes the mathematical modeling of Quad-rotor UAV with complete kinematics and dynamics and further presents the methodology of implementing PID and NMPC based controller. Chapter 4 describes the effectiveness of both controllers separately by putting the analysis validation into account of attitude and altitude of Quad-rotor UAV and presents the development of new control algorithm and the results obtained for the developed system and also discuss about the results for the different feature extraction methods. Chapter 5 gives the conclusion of the project. Further, this chapter summarizes the contribution made in this research and suggestions for future research works are discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Significance amount of research and development has been done on unmanned aerial vehicle (UAV) systems, yet modest endeavor has been going into exploratory of UAVs. This chapter begins with the discussions on a various UAV systems developed in the past and some existing designs are also presented in this section with their specific general objective. Further the applicability of PID and NMPC controller to this application is also discussed. Finally, at the end of this chapter a summary is presented.

2.2 Quad-rotor UAV Design

In the past years the popularity in designing of Quad-rotor has been increased tremendously. Due to rapid advancement in electronics and aviability of miniaturized sensor, high power batteries and high speed dc motors, Quad-rotor has attracted a lot of research effort.

Quad-rotor idea start builing 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, 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).

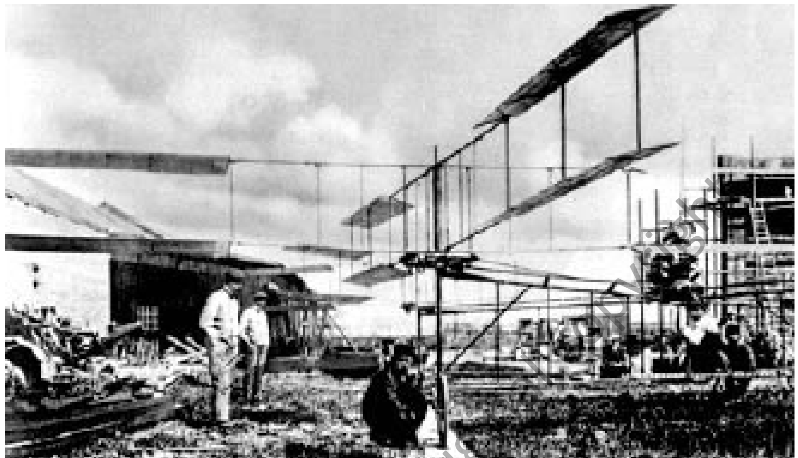

Figure 2.1: Breguet-Richet Gyroplane.

De Bothezat we the first person who designed Remote Control (RC) based Quad-rotor 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.