MODELING AND CONTROL OF A CLASS OF AERIAL ROBOTIC SYSTEMS

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To my beloved mother and father

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ABSTRACT

The objectives of this thesis are to propose a new linear uncertain model with bounded uncertainties for an Unmanned Aerial Vehicle (UAV) helicopter system and to propose two new advanced nonlinear kernel controls for the UAV helicopter flight control system using the newly obtained linear uncertain model. The two new control algorithms are based on the Model Following Variable Structure Control (MFVSC) and the deterministic control. They are able to cope with system parameters variations due to the different flight conditions. The first proposed controller is the deterministic control approach augmented MFVSC. The second proposed controller is the deterministic control approach augmented MFVSC with nonlinear state feedback control. Two theorems have been derived based on the two newly developed control algorithms. The two theorems are stable in terms of the second method of Lyapunov provided that the assumptions for the proposed theorems are satisfied. Extensive simulations with different flight conditions and various controller design parameters have been carried out in this study to evaluate the performance and the robustness of the two new control techniques. The simulation results show that the two proposed control algorithms are capable of rendering the system state to track the desired state motion.

ABSTRAK

Tesis ini bertujuan untuk mencadangkan satu model linear baru yang tidak menentu bagi sistem helikopter Kenderaan Udara Tanpa Pemandu (UAV) dan mencadangkan dua kawalan kernel baru tak linear termaju bagi UAV helikopter tersebut dengan menggunakan model yang baru diperolehi. Kedua-dua algoritma bagi kawalan baru itu adalah berdasarkan kepada teori kawalan ikutan model struktur boleh ubah (MFVSC) dan teori kawalan berketentuan. Algoritma kawalan baru tersebut mampu untuk menampung variasi parameter sistem yang disebabkan oleh keadaan penerbangan yang berbeza. Pengawal pertama yang dicadangkan ialah kawalan pendekatan berketentuan kukuhan MFVSC. Pengawal kedua pula ialah kawalan pendekatan berketentuan kukuhan MFVSC dengan tambahan kawalan suap balik tak linear. Dua teorem diterbitkan berdasarkan dua algoritma kawalan yang baru dikemukakan. Kedua-dua teorem tersebut adalah stabil berdasarkan kaedah kedua Lyapunov dengan syarat andaian bagi teorem yang dicadangkan itu dipenuhi. Simulasi yang menyeluruh telah dibuat dengan keadaan penerbangan yang berbeza dan pelbagai parameter rekabentuk kawalan juga telah dilakukan dalam pengajian ini untuk menilai prestasi dan kemantapan kedua-dua teknik kawalan baru ini. Keputusan simulasi menunjukkan bahawa kedua-dua algoritma kawalan yang dicadangkan itu mampu untuk mengawal kedudukan sistem helikopter tersebut untuk menjejaki pergerakan yang dikehendaki dengan memuaskan.

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LIST OF SYMBOLS

V_x	-	Ground velocity in x direction
V_y	-	Ground velocity in y direction
ω_x	-	Roll angular rate
ω_y	-	Pitch angular rate
ϕ	-	Roll angle
θ	-	Pitch angle
V_z	-	Ground velocity in z direction
ω_z	-	Yaw angular rate
ω_{zf}	-	Built-in filter gain in the yaw channel
a_1	-	the first harmonics of longitudinal flapping angles of the main blade tip-path plane
b_1	-	the first harmonics of lateral flapping angles of the main blade tip-path plane

LIST OF ABBREVIATIONS

AI	-	Artificial Intelligent
AMFC	-	Adaptive Model Following Control System
CNF	-	Composite Nonlinear Feedback
LMFC	-	Linear Model Following Control System
LQR	-	Linear Quadratic Regulator
MFSMC	-	Model Following Sliding Mode Control
MFVSC	-	Model Following Variable Structure Control
NDP	-	Neural Dynamic Programming
NED	-	North-East-Down
RC	-	Radio Control
SISO	-	Single Input Single Output
UAV	-	Unmanned Aerial Vehicle
UGV	-	Unmanned Ground Vehicle
VSC	-	Variable Structure Control

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CHAPTER 1

INTRODUCTION

1.1 Unmanned Aerial Vehicle Helicopter System

Helicopters have a number of unique capabilities that other vehicles do not have, such as the ability to hover over one point on the ground, spin on its axis, to fly backwards and sideways, performing a pirouette and others. Similarly, an autonomous model helicopter potentially can accomplish the same flying capabilities to perform tasks which would not be possible with other vehicles. Thus, one can use the autonomous helicopter to survey, inspect or monitor difficult or hazardous areas, to perform the search-and-rescue operations and many others.

The technology of model helicopters has evolved significantly. Besides being a sophisticated piece of equipment for the hobbyists, it has become popular among the academic research communities as well, especially for the advanced nonlinear control theory and aerial robotics groups. The autonomous model helicopter is a kind of Unmanned Aerial Vehicle (UAV) system besides the usual fixed-wing aircraft system. In this thesis, it is also known as an UAV helicopter system for short.

1.2 Research on UAV Helicopter System: An Overview

Over the years, a lot of researchers have shown interests in model helicopter research, and they have had various degrees of successes (Cai *et al.*, 2005; Bortoff, 1999, Zhu and Nieuwstadt, 1996).

The BErkeley AeRobot (BEAR) project at UC Berkeley is a collective, interdisciplinary research effort that encompasses the disciplines of hybrid systems theory, navigation, control, computer vision, communication, and multi-agent coordination, since 1996. Currently, the team operates six fully instrumented helicopters. The research group has demonstrated a number of milestone achievements in the development of advanced autonomy for UAVs and UAV/UGV (Unmanned Ground Vehicle) platforms, such as the obstacle avoidance in urban environment, autonomous exploration in unknown urban environments (Shim *et al.*, 2005), perch-and-move of fully autonomous mission from take-off to land without any human assist, collision avoidance and others.

During the 1996 International Aerial Robotics Competition, MIT, Boston University and Draper Lab team was successful in building an autonomous model helicopter designed to hover, fly around, and recognize randomly placed drums (Johnson, 1996). The annual Aerial Robotics Competition, sponsored by the AUVS, has also generated a great deal of interest in autonomous robotics from many university teams. Thirteen out of the twenty officially-registered university teams from the United States and Canada has attended the past competition held on July 21st 2005 at the U.S. Army Soldier Battle Lab's Mckenna Urban Operations Site at Georgia. However, the competition has often depended more on the image recognition and sensing than on the helicopter control algorithms.

Sugeno (1994) has developed a control system based on the fuzzy control theory and had a considerable amount of success in flying a model helicopter for commercial purposes. The integrated control system can manage the low level basic flight modes to high level supervisory control and capable of taking a human voice as its input.

Other than the fuzzy logic control system, Russell Enns and Jennie Si (2000), from Arizona State University introduced a new neural learning control mechanism for helicopter flight control design, the neural dynamic programming (NDP). Their designs were tested using FLYRT, a sophisticated industry-scale nonlinear validated model of the Apache helicopter.

A group of researchers at Caltech performed an experiment consists of an electric model helicopter interfaced to and controlled by a personal computer (Zhu and Nieuwstadt, 1996). A state-space model for the angular position is identified from experimental data near hover, using the prediction error method. A Linear Quadratic Regulator (LQR) controller with integrators for set point tracking is designed for the system. The primary objective for the project is not to get a completely autonomous aerial vehicle but rather study the control issues and acts a testbed for advanced linear and nonlinear control methodologies.

At the University of Toronto, a Radio Control (RC) helicopter system is being built as part of the research into applied nonlinear control and visual servoing (Bortoff, 1999). The current research is working on the dynamic models and identification, however, the final goal towards stabilization of the helicopter in hover to autonomous execution of high-performance maneuvers such as inverted flight.

Helble and Cameron (2007) have commissioned the Oxford Aerial Tracking System (OATS), which consists of a commercial airframe and low-level flight controller, and assists with a camera on two-axis gimbal that enabling the system to visually track the ground targets. The system uses a commercial Automatic Flight Control System (AFCS) to achieve a steady flight and focuses the research on vision processing and high-level mission objectives.

Among the research communities as mentioned above, some are focusing on the control theory of the UAV helicopter system, some are focusing on developing an accurate model for the control purposes; while others are providing more autonomous capability for specific applications with additional of specific equipment or sensors.

A lot of the research focuses on adding extra autonomy to the helicopter, such as incorporating the imaging or visual sensing to perform a navigation task, especially in the aerial robotic fields (Tisse *et al., 2007*; Hamel and Mahony, 2007; Courbon *et al.,* 2010). However, not many are focusing in improving the maneuvering ability of the helicopter. Furthermore, most of the controllers are still based on the conventional linear control laws. Although there are some focusing on Artificial Intelligence (AI) techniques, such as the Fuzzy Logic or Neural Network controllers (Enns and Si, 2000), only a few are using more advanced nonlinear controllers, such as the multivariable adaptive control design (Krupadanam *et al.*, 2002), the LQR design (Zhu and Nieuwstadt, 1996), the H-infinity control (Cai *et al.*, 2011) and the Composite Nonlinear Control (Peng *et al.*, 2009).

This thesis is not focusing on providing extra autonomy to an existing system but rather on developing two advanced nonlinear control techniques for the UAV helicopter system. The new control techniques improve the system maneuvering ability and ensure that the UAV helicopter system closely follows the desired flight trajectory.

1.3 Problem Statement

A model helicopter is a dynamically fast and unstable system that requires a good autonomous flight control system in order to perform the prescribed tasks. The system parameters vary when the helicopter is hovering and when it is flying. Hence, most researchers design two or more controllers that switch back and forth to cover the different flight conditions. Cai *et al.* (2011) adopt a simple gain scheduling scheme to realize the full envelope flight. Besides, a linear interpolation is used to calculate the corresponding feedback gains for any intermediate status between any two adjacent flight conditions.

For this study, the UAV helicopter system under different flight conditions is described by a newly proposed linear uncertain model with bounded uncertainties. By combining the corresponding linearized models of different flight conditions together gives rise to a linear uncertain model with bounded uncertainties where a single robust nonlinear controller will be developed, proposed. In this thesis, two new nonlinear control algorithms are developed based on the variable structure control (VSC) theory.

1.4 Research Objectives

The objectives of the research are as follows:

I. To propose and formulate a linear uncertain model with bounded uncertainties for an UAV helicopter system from two linearized models corresponding to two different flight conditions; the hovering condition and the condition with forward flight speed of 6m/s.

II. To propose a new advanced nonlinear control technique for the kernel control of the UAV helicopter system based on the newly proposed linear uncertain model with bounded uncertainties.

III. To propose a second advanced nonlinear control technique for the kernel control of the UAV helicopter system with the consideration of the system input saturation.

IV. To simulate the UAV helicopter system using a few different flight conditions with the corresponding linearized models to evaluate the performance of the two newly proposed controllers.

1.5 Research Contributions

In this research, a new linear uncertain model with bounded uncertainties of an UAV helicopter system is proposed and derived. The new linear uncertain model is obtained from two linearized models identified using two different flight conditions; the hovering condition and a forward flight condition with a flight speed of 6m/s.

Two new control techniques/algorithms for the kernel control of the UAV helicopter system are proposed. The two newly proposed control algorithms are shown capable of controlling the UAV helicopter system under different flight conditions. The derivation of the two new control algorithms is detailed in the study. Besides, two theorems associated with each new control algorithm are proposed and the proof of stability using the Second method of Lyapunov is given.

Extensive simulations with different flight conditions are carried out with Simulink library of Matlab program. Linearized model corresponds to the flight condition will be used in the simulations to evaluate the controller performance under different flight conditions. Besides, various controller design parameters are also tested in the simulations. Performance analysis and conclusions of the simulation results are given.

1.6 Structure and Layout of the Thesis

Chapter 2 discusses the modeling of the UAV helicopter system. An uncertain model with bounded uncertainties is proposed to represent the nonlinear UAV helicopter system. The derivation of the uncertain model with bounded uncertainties is shown. It is derived from two linearized models with different flight conditions, namely the hovering and the slow forward flight conditions.

Chapter 3 discusses the design of the autonomous flight control system in detail. The flight control system is a hierarchical design consists of three control layers. This chapter also discusses the design of a reduced-order observer that is used to estimate the un-measurable state variables of the UAV helicopter system to enable a full state feedback controller design.

Chapter 4 gives a general review of the variable structure control. Some of the techniques revised in this chapter are being used for the synthesis of the new controllers. The chapter also discusses the switching surface design using the quadratic minimization technique, the equivalent control concept, the invariant property of the variable structure controller during the sliding motion, the regular form design, and the various discontinuous control design approaches. The chattering problem associated with the discontinuous control of the sliding mode control and techniques to reduce and eliminate it are also briefly discussed.

Chapter 5 presents the design of the unit vector approach model following sliding mode control (MFSMC). At the end of the chapter, a unit vector approach MFSMC controller is synthesized for the UAV helicopter system and it is being used throughout the thesis as a comparison controller to the two new proposed control techniques.

Chapter 6 presents a new control technique based on the variable structure control for the kernel control of the UAV helicopter system in detail. The system descriptions and assumptions of the new control algorithm are given. The new control algorithm uses the deterministic control approach for the design of the discontinuous control. Thus, a pseudo sliding mode is achieved instead of the ideal sliding mode. Auxiliary integrators of the controlled output states of the system are being augmented to the original system in the new control algorithm to reduce the steady state error. The augmented system also enables extra design flexibility to distribute the feedback control from the errors of the integrators of the controlled output states and the system states. A theorem and the mathematical proof of stability based on the second method of Lyapunov are provided. A kernel controller for the

UAV helicopter system based on the newly proposed control algorithm is developed at the end of the chapter and it is being used in the simulations in Chapter 8.

Chapter 7 presents another new control technique based on the technique described in the previous Chapter 6 by introducing an additional nonlinear state feedback control to the control law. System descriptions and assumptions of the new control algorithm are given. A theorem and mathematical proof of stability based on the second method of Lyapunov are provided as well. The nonlinear state feedback control depends on the error feedback from the integrators of the controlled output states of the system. The additional nonlinear state feedback control improves the response of the reaching mode of a variable structure controller. At the end of the chapter, a kernel controller for the UAV helicopter system based on the new control algorithm is developed and it is being used in the simulations in Chapter 8.

Chapter 8 shows the results of the extensive simulations of the three controllers developed on the previous chapters under different controller design parameter settings, system parameters and flight conditions. The three controllers are the unit-vector approach model-reference sliding mode control, the deterministic control approach augmented model-reference variable structure control, one without and another with the addition of the nonlinear state feedback control. The simulations are carried out extensively. Analysis, discussion and conclusions are also given based on the simulation results obtained.

Lastly, conclusion and suggestions for future research are given in Chapter 9.

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