THE DEVELOPMENT OF AUTOPILOT SYSTEM FOR AN UNMANNED AERIAL VEHICLE (UAV) HELICOPTER MODEL

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Dedication

This thesis is dedicated to:

My family for their patience and support during my study,
My friends for brightening my life with their friendship and showing me that life has no greater reward to offer than a true friend.

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In retrospect, this project did start humble but has grown to be a success as now. There are many happy times and many dispointing moments, but now I am very happy because all the hardship I had to go through mostly alone finally paid off.

ABSTRACT

The aim of this research project is to develop an autopilot system that enables the helicopter model to carry out autonomous hover maneuver using on-board intelligence computer. The main goal of this project is to provide a comprehensive design methodology, implementation and testing of an autopilot system developed for a rotorcraft-based unmanned aerial vehicles (UAV). The autopilot system was designed to demonstrate autonomous maneuvers such as take-off and hovering flight capabilities. For the controller design, the nonlinear dynamic model of the Remote Control (RC) helicopter was built by employing Lumped Parameter approach comprising of four different subsystems such as actuator dynamics, rotary wing dynamics, force and moment generation process and rigid body dynamics. The nonlinear helicopter mathematical model was then linearized using small perturbation theory for stability analysis and linear feedback control system design. The linear state feedback for the stabilization of the helicopter was derived using Pole Placement method. The overall system consists of the helicopter with an on-board computer and a second computer serving as a ground station. While flight control is done on-board, mission planning and human user interaction take place on ground. Sensors used for autonomous operation include acceleration, magnetic field, and rotation sensors (Attitude and Heading Reference System) and ultrasonic transducers. The hardware, software and system architecture used to autonomously pilot the helicopter were described in detailed in this thesis. Series of test flights were conducted to verify autopilot system performance. The proposed hovering controller has shown capable of stabilizing the helicopter attitude angles. The work done for this project gives solid bases and chances for fast evolution of Universiti Teknologi Malaysia autonomous helicopter research.

ABSTRAK

Hasrat utama projek penyelidikan ini adalah untuk membangunkan satu sistem pemanduan automatik bagi membolehkan model helikopter menjalankan misi berautonomi dengan hanya menggunakan keupayaan pengkomputeran pintar. Tesis ini disediakan adalah untuk menerangkan dengan terperinci kaedah rekabentuk, pelaksanaan dan pengujian sistem pemanduan automatik yang dibangunkan pada pesawat rotor tanpa juruterbang. Sistem pemanduan automatik direka bagi melakukan misi berautonomi seperti penerbangan berlepas dan apungan. Bagi rekabentuk pengawal, model dinamik tidak linear bagi helikopter kawalan jauh telah dibina menggunakan kaedah Pengumpulan Parameter melibatkan empat subsistem yang berbeza yang terdiri daripada dinamik badan tegar, aktuator, sayap berputar dan proses penghasilan daya dan momen. Model matematik helikopter tidak linear yang diperolehi akan dilinearkan menggunakan teori perubahan kecil untuk kegunaan analisis kestabilan dan rekabentuk suapbalik linear. Suapbalik keadaan linear untuk penstabilan helikopter dapat diperolehi menggunakan kaedah Penetapan Kutub. Sistem keseluruhan terdiri daripada sebuah komputer pada helikopter dan komputer kedua sebagai pengkalan bumi. Pengawalan helikopter dijalankan oleh komputer helikopter manakala operasi perancangan misi dan interaksi pengguna dilakukan di pengkalan bumi. Penderia yang digunakan untuk operasi berautonomi termasuklah penderia pecutan, medan magnet dan putaran serta penderia ultrasonik. Sistem perkakasan dan perisian yang digunakan untuk pemanduan berautonomi helikopter telah dibincangkan dengan lebih lanjut dalam tesis ini. Beberapa siri ujikaji penerbangan telah dijalankan bertujuan untuk mengesahkan prestasi sistem pemanduan automatik. Pengawal apungan yang direka didapati mampu untuk menstabilkan sudut gayalaku penerbangan helikopter. Kerja-kerja yang dijalankan untuk projek ini diharap dapat dijadikan asas dan peluang yang baik untuk memangkin penyelidikan helikopter berautonomi Universiti Teknologi Malaysia.

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LIST OF SYMBOLS

a_M	Main rotor blade lift curve slope
a_o	Lift curve slope
a_0	Rotor blade coning angle
a_{1s}	Longitudinal flapping with respect to a plane perpendicular to the shaft
b_{1s}	Lateral flapping
c_M	Main rotor chord
h_M	Main rotor hub height above CG
h_T	Tail rotor height above CG
l_H	Stabilizer location behind CG
l_T	Tail rotor hub location behind CG
m	Mass flow rate
n_{es}	Gear ratio of engine shaft to main rotor
n_T	Gear ratio of tail rotor to main rotor
p, q, r	Angular velocities about the x-, y- and z- axes
rpm	Rotation per minute
u, v, w	Translational velocities along the three orthogonal directions of the fuselage fixed axes system
u_a, v_a, w_a	Fuselage center of pressure velocities along *x, y* and *z* axis
u_w, v_w, w_w	Airmass (gust) velocity along *x, y* and *z* axis
v	Velocity at various stations in the stream tube
v_i	Inflow at the disc
v_a^V	Vertical stabilizer local *v*-velocity
w_a^F	Fuselage local *w*-velocity

w_a^H	Local horizontal stabilizer *w*-velocity
x	State vector
x_c	Control actuation sub-system state vector
x_f	Fuselage sub-system state vector
x_p	Engine sub-system state vector
x_r	Rotor sub-system state vector
A_1	Lateral cyclic pitch
A_d	Rotor disc area
AR_e	Effective aspect ratio
B_1	Longitudinal cyclic pitch
$C_{L\alpha}$	Lift curve slope from airfoil data
$C_{L\alpha}^H$	Horizontal tail lift curve slope
$C_{L\alpha}^V$	Vertical fin lift curve slope
C_{D_0}	Profile drag coefficient of the main rotor blade
C_D^F	Fuselage drag coefficient
C_{Do}^M	Main rotor blade zero lift drag coefficient
$C_{T\max}^M$	Main rotor max thrust coefficient
C_{Do}^T	Tail rotor blade zero lift drag coefficient
$C_{T\max}^T$	Tail rotor max thrust coefficient
C_Q	Torque coefficient
CG	Center gravity
I_{xx}	Rolling moment of inertia
I_{yy}	Pitching moment of inertia
I_{zz}	Yawing moment of inertia
I_β	Main rotor blade flapping inertia
K_β	Hub torsional stiffness
l	Distance from the pivot to the body CG
I_o	Moment contribution of the supporting structure
P_{M+S}	Oscillating period

PWM	Pulse width modulation
Q_e	Engine torque
R, M, N	Moment terms in roll, pitch and yaw directions
R_M	Main rotor radius
R_T	Tail rotor radius
S_H	Effective horizontal fin area
S_V	Effective vertical fin area
S_x^F	Frontal fuselage drag area
S_y^F	Side fuselage drag area
S_z^F	Vertical fuselage drag area
S_β	Stiffness number
T	Rotor thrust
V_c	Climb velocity
V_d	Rotor descent velocity
W	Weight of the UAV's model
X, Y, Z	Forces term in x, y, z directions
X_{uu}^F , Y_{vv}^F , X_{ww}^F	Fuselage effective flat plat drag in the *x, y* and *z* axis
Y_{uu}^V	Vertical stabilizer's aerodynamic chamber effect
Y_{uv}^V	Vertical stabilizer's parameter for lift slope effect
$Z_{\min}^H$	Horizontal stabilizer's parameter for stall effect
Z_{uu}^H	Horizontal stabilizer's aerodynamic chamber effect
Z_{uw}^H	Horizontal stabilizer's parameters for lift slope effect
δ_r^{trim}	Tail rotor pitch trim offset
λ_0 , λ_{1c} , λ_{1s}	Rotor uniform and first harmonic inflow velocities in hub/shaft axes
λ_i	Inflow ratio at rotor disc
λ_β	Flapping frequency ratio
δ_{col} , δ_{lon} , δ_{lat} , δ_{ped}	Main rotor collective pitch, longitudinal cyclic, lateral cyclic and tail rotor collective

γ	Lock number
γ_{fb}	Stabilizer bar Lock number
ρ	Atmosphere density
μ	Advance ratio
θ, ϕ, Ψ	Euler angles defining the orientation of the body axes relative to the earth
θ_0	Local blade pitch
θ_1	Blade twist angle
ψ	Rotor blade azimuth angle
Ω	Main rotor speed
Ω_{nom}	Nominal main rotor speed

Subscript

M, T, F, H, V	Representation for main rotor, tail rotor, fuselage, horizontal stabilizer and vertical stabilizer

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CHAPTER 1

INTRODUCTION

1.1 Background of the Research

Agile and precise maneuverability of helicopters makes them useful for many critical tasks ranging from rescue and law enforcement task to inspection and monitoring operations. Helicopters are indispensable air vehicles for finding and rescuing stranded individuals or transporting accident victims. Police departments use them to find and pursue criminals. Fire fighters use helicopters for precise delivery of fire extinguishing chemicals to forest fires. More and more electric power companies are using helicopters to inspect towers and transmission lines for corrosion and other defects and to subsequently make repairs. All of these applications demand dangerous close proximity flight patterns, risking human pilot safety. An unmanned autonomous helicopter will eliminate such risks and will increase the helicopter’s effectiveness. The first major step in developing unmanned autonomous helicopter is the design of autopilot control system for the craft itself. The work presented in this thesis is to develop an autopilot control system for a helicopter model in autonomous hovering.

An unmanned aerial vehicle (UAV) indicates an airframe that is capable of performing given missions autonomously through the use of onboard sensors and manipulation systems. Any type of aircraft may serve as the base airframe for a UAV application. Traditionally, the fixed-wing aircrafts have been favored as the platforms simply because their simple structures, efficient and easy to build and maintain. The autopilot design is easier for fixed-wing aircrafts than for rotary-wing aircrafts because the fixed-wing aircrafts have relatively simple, symmetric, and decoupled dynamics.

However, rotorcraft-based UAVs have been desirable for certain applications where the unique flight capability of the rotorcraft is required. The rotorcraft can take off and land within limited space and they can also hover, and cruise at very low speed. The agile maneuverability of model scaled helicopter or remote control (RC) helicopter sold in commercial market can be useful for an unmanned surveillance helicopter in a hard to reach or inaccessible environment such as city and mountain valley. Unmanned surveillance helicopter offers a lot benefits in search and rescue operations, remote inspections, aerial mapping and offer an alternative option for saving human pilot from dangerous flight conditions (Amidi, 1996).

Beside these advantages, helicopters are well known to be unstable and have a faster and responsive dynamics due to their small size. Model scaled helicopter can reach pitch and roll rates up to 200 deg/s with stabilizer bar, yaw rates up to 1000 deg/s and produces thrust as high as two or three times the vehicle weight (Mettler *et al.,* 2002a). The helicopter dynamics are inherently unstable and require velocity feedback as well as attitude feedback to stabilize and control. Velocity feedback needs the accurate velocity estimates, which can be obtained by the use of an inertial navigation system. The inertial navigation system in turn requires external aids so that the velocity and position estimates do not diverge with the uncompensated bias and drift of the inertial instruments, i.e., accelerometers and rate gyroscopes. Another irony is that, even though UAVs are typically smaller than the full-size manned vehicles, they usually require more accurate sensors because the demanded sensor accuracy is higher when the vehicle is smaller.

An autopilot system is a mechanical, electrical, or hydraulic system used to guide a vehicle without assistance from a human being. In the early days of transport aircraft, aircraft required the continuous attention of a pilot in order to fly in a safe manner and results to a very high fatigue. The autopilot is designed to perform some of the tasks of the pilot. The first successful aircraft autopilot was developed by Sperry brothers in 1914 where the autopilot developed was capable of maintaining pitch, roll and heading angles. Lawrence Sperry has demonstrated the effectiveness of the design by flying his aircraft with his hands up (Nelson, 1998). Modern autopilots use computer software to control the aircraft. The software reads the aircraft's current position and controls a flight control system to guide the aircraft.

As an unmanned vehicle, issues such as remote sensing, terrain and obstacle recognition, radio link and data acquisition must be solved for absolute reliability. The design must be proven to work given the constraints of the environment especially due to lack of immediate and flexible human intervention available on board. An autonomous control mechanism should be able to accommodate and manage all of the issues mentioned above in real-time. It also must be able to plan its flight and mission goals without continuous human guidance. As general remarks, the autonomous helicopter is built basically by putting together state-of-the-art navigation sensors and high performance onboard computer system with real-time software control on commercially available remote-control helicopter model (Shim, 2000). The autonomous unmanned helicopter system design problem alone encompasses many challenging research topics such as system identification, control system architecture and design, navigation sensor design and implementation, hybrid systems, signal processing, real-time control software design, and component-level mechanical-electronic integration. The vehicle communicates with other agents and the ground posts through the broadband wireless communication device, which will be capable of dynamic network internet protocol (IP) forwarding. The vehicle will be truly autonomous when it is capable of self-start and automatic recovery with a single click of a button on the screen of the vehicle-monitoring computer.

1.2 Research Problem Description

Among many issues that must be addressed in the important area of autonomous helicopter, this thesis will cover three important issues only, i.e. the helicopter mathematical modeling and identification, hardware, software and system integration and control system design. To begin with, in order to determine the most effective control strategy that governs the overall architecture of a model scaled helicopter, a detailed knowledge of the structure and functions of the helicopter in the form of a mathematical model is necessary. Secondly, the analytical mathematical model must then be provided with physical parameters accurately representing a real helicopter model. This analytical mathematical model of helicopter is important for the design of an autopilot system that provides artificial stability to improve flying qualities of helicopter model. Lastly, a good waypoint navigation planning method that fundamentally guides an on-board computer control mechanism must be devised.

1.3 Research Objective

The objective of this research study is to develop an autopilot system that could enable the helicopter model to perform autonomous hover maneuver using only on-board intelligence and computing power.

1.4 Research Scope

The scopes set forth for the research work as follows:

i. Establishing scaled helicopter model dynamic characteristics for the control system design of autopilot system
ii. Developing an electronic control system that enables the helicopter model to perform its mission goal.
iii. Fabricating and testing the electronic control system (autopilot) performance on helicopter model in autonomous hovering.

1.5 Research Design and Implementation

In order to design an autopilot system for scaled model helicopter, a performance and stability analysis will be conducted using several physical measurements, experimental testing and similarity analysis. The helicopter model is derived from a general full-sized helicopter with the augmentation of servo rotor dynamics. The nonlinear model derived from general full-sized helicopter model will be simplified through linearization in order to obtain a linear model controller design. The helicopter platform was then integrated with navigation sensors and onboard flight computer. Linearized control theory will be applied for helicopter stabilization using the model obtained. After the design of low-level vehicle stabilization controller, vehicle guidance logic will be developed. The vehicle guidance logic can be used as a user interface part on the ground station and sequencer on the UAV side. The complete autopilot system integration with the helicopter had been done after all the electronics were built and installed considering several factors such as power requirement, mounting, electromagnetic and radio interference. The implementation of the project research is shown in Figure 1.1

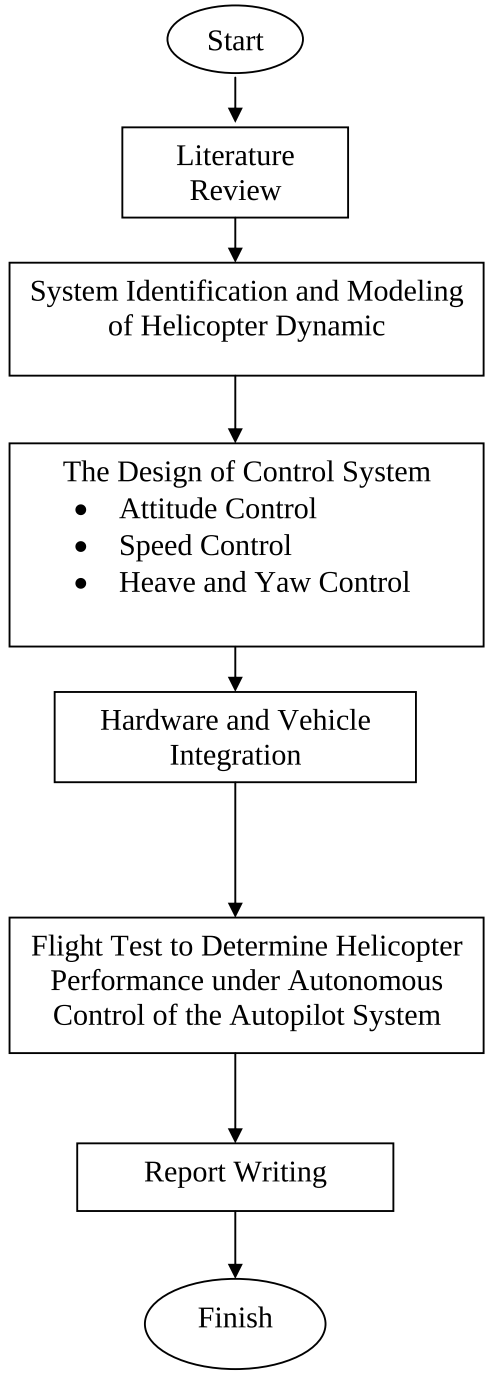

Figure 1.1 The research project implementation flow chart

1.6 Project Contribution

The project contributions are as follows:

i. Simulation models for controller design, stability and performance analysis of a UAV helicopter model had been developed.

ii. The low level stabilization controller had been designed based on the control theory developed from the simulation model.

iii. The prototype of autopilot system integration with the helicopter was developed taking into consideration the power requirement, mounting, electromagnetic and radio interference.

iv. A prototype of UAV helicopter capable of hovering autonomously had been developed. This is the major break through in the effort of developing a completely autonomous UAV helicopter.

1.7 Thesis Organization

This thesis is organized into seven chapters. The first chapter introduced the motivation, research objective, scopes of work and contribution of this project.

Chapter 2 reviews the UAV development history, principle of rotary wing aircraft, helicopter dynamic modeling, control and autonomous system design are also explained in this chapter.

Chapter 3 presents the helicopter dynamic modeling procedures and simulation results while Chapter 4, Hardware, Software and Vehicle Integration, described the hardware and software development of the system and system integration into the helicopter model.

Chapter 5 presents the control design methodology and result for each controller for the autopilot system.

Chapter 6 presents the flight test conducted in order to test the functionality of the autopilot system. The preliminary tests were also conducted to ensure that the system developed works properly.

In the final chapter, Chapter 7, the research work is summarized and the potential future works are outlined.