HYBRID ACTIVE FORCE CONTROL FOR FIXED BASED ROTORCRAFT

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DEDICATION

This thesis is dedicated to my dear parents for their tireless support since my childhood, who taught me that even the greatest task can be accomplished with step-by-step effort, to my supportive and beloved wife and daughters, who have been my source of encouragement and support throughout my studies, and to everyone who believes in me.

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ABSTRACT

Disturbances are considered major challenges faced in the deployment of rotorcraft unmanned aerial vehicle (UAV) systems. Among different types of rotorcraft systems, the twin-rotor helicopter and quadrotor models are considered the most versatile flying machines nowadays due to their range of applications in the civilian and military sectors. However, these systems are multivariate and highly non-linear, making them difficult to be accurately controlled. Their performance could be further compromised when they are operated in the presence of disturbances or uncertainties. This dissertation presents an innovative hybrid control scheme for rotorcraft systems to improve disturbance rejection capability while maintaining system stability, based on a technique called active force control (AFC) via simulation and experimental works. A detailed dynamic model of each aerial system was derived based on the Euler–Lagrange and Newton-Euler methods, taking into account various assumptions and conditions. As a result of the derived models, a proportional-integral-derivative (PID) controller was designed to achieve the required altitude and attitude motions. Due to the PID's inability to reject applied disturbances, the AFC strategy was incorporated with the designed PID controller, to be known as the PID-AFC scheme. To estimate control parameters automatically, a number of artificial intelligence algorithms were employed in this study, namely the iterative learning algorithm and fuzzy logic. Intelligent rules of these AI algorithms were designed and embedded into the AFC loop, identified as intelligent active force control (IAFC)-based methods. This involved, PID-iterative learning active force control (PID-ILAFC) and PID-fuzzy logic active force control (PID-FLAFC) schemes. To test the performance and robustness of these proposed hybrid control systems, several disturbance models were introduced, namely the sinusoidal wave, pulsating, and Dryden wind gust model disturbances. Integral square error was selected as the index performance to compare between the proposed control schemes. In this study, the effectiveness of the PID-ILAFC strategy in connection with the body jerk performance was investigated in the presence of applied disturbance. In terms of experimental work, hardware-in-the-loop (HIL) experimental tests were conducted for a fixed-base rotorcraft UAV system to investigate how effective are the proposed hybrid PID-ILAFC schemes in disturbance rejection. Simulated results, in time domains, reveal the efficacy of the proposed hybrid IAFC-based control methods in the cancellation of different applied disturbances, while preserving the stability of the rotorcraft system, as compared to the conventional PID controller. In most of the cases, the simulated results show a reduction of more than 55% in settling time. In terms of body jerk performance, it was improved by around 65%, for twin-rotor helicopter system, and by a 45%, for quadrotor system. To achieve the best possible performance, results recommend using the full output signal produced by the AFC strategy according to the sensitivity analysis. The HIL experimental tests results demonstrate that the PID-ILAFC method can improve the disturbance rejection capability when compared to other control systems and show good agreement with the simulated counterpart. However, the selection of the appropriate learning parameters and initial conditions is viewed as a crucial step toward this improved performance.

ABSTRAK

Gangguan dianggap sebagai cabaran utama yang dihadapi dalam penggunaan sistem pesawat pemutar tanpa pemandu (UAV). Antara pelbagai jenis sistem pesawat pemutar, model helikopter pemutar berkembar dan empat-pemutar dianggap sebagai pesawat terbang paling serba boleh kerana kepelbagaian aplikasinya dalam sektor awam dan ketenteraan. Walau bagaimanapun, sistem ini adalah bersifat pelbagai-varian dan tak-lelurus serta sukar untuk dikawal dengan tepat. Kehadiran gangguan dan ketidakpastian boleh menjejaskan prestasi kendaliannya. Disertasi ini membentangkan skim kawalan hibrid inovatif untuk sistem pesawat pemutar bagi meningkatkan keupayaan menghindar gangguan di samping mengekalkan kestabilan sistem menggunakan teknik kawalan daya aktif (AFC) melalui simulasi dan eksperimen. Model dinamik terperinci bagi setiap sistem diperolehi melalui kaedah Euler-Lagrange dan Newton-Euler. Pengawal berkadar-kamiran-terbitan (PID) telah direkabentuk untuk mencapai dan mengawal pergerakan pada ketinggian yang diperlukan. Disebabkan oleh ketidakupayaan PID untuk menghindar gangguan, strategi AFC telah digabungkan dengan pengawal PID, yang dikenali sebagai PID-AFC. Untuk menganggar parameter secara automatik, beberapa algoritma kecerdasan buatan (AI) telah digunakan, iaitu algoritma pembelajaran berulang (IL) dan logik kabur (FL). Peraturan pintar algoritma AI ini telah direka bentuk dan dibenamkan ke dalam gelung AFC, yang dikenali sebagai kaedah kawalan daya aktif pintar (IAFC). Ini melibatkan kawalan daya aktif pembelajaran PID-ulangan (PID-ILAFC) dan kawalan daya aktif logik kabur PID (PID-FLAFC). Untuk menguji prestasi dan keteguhan sistem kawalan hibrid, model gangguan gelombang sinusoidal, berdenyut, dan tiupan angin Dryden telah dipilih. Ralat kamiran kuasa dua telah dipilih sebagai prestasi indeks untuk membandingkan di antara skim kawalan yang dicadangkan. Dalam kajian ini, keberkesanan strategi PID-ILAFC ke atas prestasi sentakan badan dengan kehadiran gangguan telah disiasat. Dari segi kajian ekperimen ujian perkakasan dalam gelung (HIL) telah dijalankan untuk sistem UAV pesawat pemutar asas bagi menyiasat keberkesanan skim PID-ILAFC hibrid. Simulasi domain masa mendapati kaedah kawalan IAFC hibrid sangat berkesan dalam membatalkan kesan pelbagai gangguan di samping berupaya mengekalkan kestabilan sistem pesawat pemutar, berbanding dengan pengawal PID konvensional. Hasil simulasi menunjukkan pengurangan lebih daripada 55% dalam masa penyelesaian. Prestasi sentakan badan meningkat sekitar 65%, bagi sistem helikopter pemutar berkembar, dan 45% untuk sistem empat-pemutar. Berdasarkan analisis sensitiviti, bagi memperolehi prestasi terbaik, hasil kajian mengesyorkan penggunaan isyarat keluaran penuh yang dihasilkan oleh strategi AFC. Keputusan ujian HIL menunjukkan kaedah PID-ILAFC boleh meningkatkan keupayaan penolakan gangguan berbanding sistem kawalan lain dan ia selari dengan keputusan simulasi. Walau bagaimanapun, pemilihan parameter pembelajaran yang sesuai dan keadaan awal dilihat sebagai langkah penting ke arah prestasi yang lebih baik ini.

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LIST OF ABBREVIATIONS

UAV	-	Unmanned Aerial Vehicle
VTOL	-	Vertical Take-Off and Landing
AFC	-	Active Force Control
IAFC	-	Intelligent Active Force Control
DOF	-	Degree Of Freedom
HIL	-	Hardware-In-The-Loop
PID	-	Proportional-Integral-Derivative
AI	-	Artificial Intelligence
IL	-	Iterative Learning
FL	-	Fuzzy Logic
PID-ILAFC	-	PID-Iterative Learning Active Force Control
PID-FLAFC	-	PID-Fuzzy Logic Active Force Control
MTOW	-	Maximum Take-Off Weight
CW	-	Clockwise
CCW	-	Counter-Clockwise
TEM	-	Trial-And-Error Method
BFO	-	Bacterial Foraging Optimization
FOPID	-	Fractional-Order Proportional-Integral-Derivative
SQP	-	Sequential Quadratic Programming
SMDO	-	Stochastic Multi-Parameters Divergence Optimization
LQR	-	Linear Quadratic Regulator
FSF	-	Full State Feedback
BC	-	Backstepping Control
SMC	-	Sliding Mode Control
MFBS	-	Model-Free Backstepping
DBCIBC	-	Dual Boundary Conditional Integral BC
GPI	-	Generalized Proportional Integral
MIMO	-	Multiple-Input Multiple-Output
TRMS	-	Twin-Rotor MIMO System
SMDO-SMC	-	Sliding Mode Disturbances Observer-Sliding Mode Control

ANG-CNF	-	Adaptive Non-Linear Gain-Based Composite Non-Linear Feedback
RMSE	-	Root Mean Square Error
FOAR-MRAC	-	Fractional-Order Adjustment Rule-Based Model Reference Adaptive Control
FBL	-	Feedback Linearization
MPC	-	Model Predictive Control
ILC	-	Iterative Learning Control
FLC	-	Fuzzy Logic Control
ANN	-	Artificial Neural Network
TSF	-	Takagi-Sugeno Fuzzy
MFC	-	Model-Free Control
MFC-TSF	-	Model Free Control-Takagi Sugeno Fuzzy
GA	-	Genetic Algorithm
RBF	-	Radial Basis Function
IDC	-	Inverse Dynamic Control
ZN	-	Ziegler-Nichols
PSO	-	Particle Swarm Optimization
ES	-	Evolution Strategies
DE	-	Differential Evolutionary
CS	-	Cuckoo Search
ST	-	Self-Tuning
LQG	-	Linear Quadratic Gaussian
LESO	-	Linear Extended State Observer
FT-SMO	-	Finite-Time Sliding Mode Observer
FOSMC	-	Fractional-Order Sliding Mode Control
ESO	-	Extended State Observer
ADRC	-	Active Disturbance Rejection Control
ASMC	-	Adaptive Sliding Mode Control
MOHEPSO	-	Multi-Objective High Exploration Particle Swarm Optimization
EKF-FTIC	-	Extended Kalman Filter-Based Fuzzy Tracking Incremental Control

AFFTTC	-	Active Fuzzy Fault-Tolerant Tracking Control
IBVS	-	Image-Based Visual Servo
MLP	-	Minimal Learning Parameter
BCTTC	-	Backpropagating Constraints-Based Trajectory Tracking Control
DIC-ANN	-	Direct Inverse Control-Artificial Neural Network
NARMA	-	Non-Linear Auto-Regressive Moving Average
FTR	-	Fourier Transform Regression
NDI	-	Non-Linear Dynamic Inversion
RRT	-	Rapidly Exploring Random Tree
DMPs	-	Dynamic Movement Primitives
PAC	-	Parsimonious Controller
PALM	-	Parsimonious Learning Machine
BI-FWMAV	-	Bio-Inspired Flapping-Wing Micro Aerial Vehicle
G-Controller	-	Generic Controller
GENEFIS	-	Generic Evolving Neuro-Fuzzy Inference System
CFD	-	Computational Fluid Dynamic
PSD	-	Power Spectral Density
MSL	-	Mean Sea Level
ITD	-	Improved Tracking Differentiator
NLPID	-	Non-Linear Proportional-Integral-Derivative Controller
rpm	-	Revolutions Per Minute
KE	-	Total Kinetic Energy
PE	-	Total Potential Energy
DC	-	Direct Current
Sm, Md, and Lg	-	Small, Medium, And Large Of The Linguistic Variables Of The Fuzzy Logic
CTF	-	Closed-Loop Transfer Function
FFT	-	Fast Fourier Transform
TP	-	Peak Time
TS	-	Settling Time
SSE	-	Steady-State Error
rad	-	Radian

RMS	-	Root Mean Square
SNR	-	Signal-To-Noise Ratio
PC	-	Personal Computer
I/O	-	Input/Output
SPI	-	Serial Peripheral Interface
DAQ	-	Data Acquisition
PWM	-	Pulse-Width Modulation
ADC	-	Analog-Digital Converter
QUARC	-	*Quanser* Real-Time Control Software
VAC	-	Volts Alternative Current
IMU	-	Inertial Measurement Unit
CPR	-	Cycles Per Revolution

LIST OF SYMBOLS

$S_{a-wind}(f)$, $S_{c-wind}(f)$, and $S_{v-wind}(f)$	-	Power spectral densities of wind gusts for the along-wind, cross wind, and vertical wind directions, respectively
L_{a-wind}, L_{c-wind}, and L_{v-wind}	-	Scale lengths of wind gusts for the along-wind, cross wind, and vertical wind directions, respectively
σ_{a-wind}, σ_{c-wind}, and σ_{v-wind}	-	Turbulence intensities in the along-wind, cross wind, and vertical wind directions, respectively
f	-	Spatial frequency
$d_i(t)$	-	A time-dependent description of the wind disturbance in a given time t
n	-	The number of sinusoidal sinusoids
$d_{i,0}$	-	The static wind disturbance
$a_{i,K}$, $\varpi_{i,k}$, and $q_{i,k}$	-	The amplitude, frequency, and phase shift of the corresponding sinusoid, respectively
h	-	The altitude from sea level (ft)
$u_{wind-20}$	-	The wind speed at 20 ft above ground level
T_C	-	A transformation of the coordinates based on the pitch and yaw rotation matrices
c	-	Cosine function
s	-	Sine function
l_{cm}	-	Distance of the centre of mass and intersection of the pitch and yaw axes
J_θ	-	Total moment of inertia about the pitch axis
J_ψ	-	Total moment of inertia about the yaw axis
m_{h}	-	Total mass of the twin-rotor helicopter
g	-	Gravitational acceleration

$\tau_{\theta}(t)$	-	Torque acting on the pitch axis
$\tau_{\psi}(t)$	-	Torque acting on the yaw axis
$u_{\theta}(t)$	-	Control action applied as motor voltage to the pitch rotor of the twin-rotor helicopter
$u_{\psi}(t)$	-	Control action applied as motor voltage to the yaw rotor of the twin-rotor helicopter
$K_{\theta\theta}$	-	Torque thrust gain from the pitch rotor
$K_{\theta\psi}$	-	Cross-torque thrust gain acting on the pitch from the yaw rotor
$K_{\psi\theta}$	-	Cross-torque thrust gain acting on the yaw from the pitch rotor
$K_{\psi\psi}$	-	Torque thrust gain from the yaw rotor
D_{θ}	-	Damping about the pitch axis
D_{ψ}	-	Damping about the yaw axis
q_{g}	-	Generalized coordinates where $q_{g} = [q_1\ q_2\ q_3\ q_4]$
Lg	-	Lagrange variable, which corresponds to the difference between the kinetic and potential energy of the system
Q_{g}	-	Generalized forces vector where $Q_{g} = [Q_1, Q_2]$
Fr_{E}	-	Earth (inertial) fixed frame
Fr_{B}	-	Body fixed frame
θ_d and ψ_d	-	Desired pitch and yaw angles
x_d, y_d, and z_d	-	Desired forward, sideward, and upward motions of the quadrotor
ϕ , θ & ψ	-	Angles of roll, pitch, and yaw that determine the rotation of the body frame with respect to the earth frame (*Euler* angles)
x_E-y_E-z_E	-	Earth (inertial) fixed frame axes
x_B-y_B-z_B	-	Body fixed frame axes
ξ	-	Absolute distance between the centre of gravity of the quadrotor and the earth fixed frame
$R_{E}^{f_1}$	-	Rotation from the earth fixed frame to the first intermediate frame

$R_{f_1}^{f_2}$	-	Rotation from the first intermediate frame to the second intermediate frame
$R_{f_2}^{B}$	-	Rotation from the second intermediate frame to the body fixed frame
R_E^B	-	Rotation matrix from the earth fixed frame to the body fixed frame
$R = R_B^E$	-	Rotation matrix from the body fixed frame to the earth fixed frame
B	-	Quadrotor body
r_i	-	Rotor number, where i is from 1 to 4
O_E	-	Centre of gravity of the earth fixed frame
O_B	-	Centre of gravity of the body fixed frame
O_{r_i}	-	Centre of gravity of rotor frame, where i is from 1 to 4
x, y, z	-	The position of the quadrotor defined in the earth fixed frame
$p, q, \& r$	-	Angular rates defined in the body fixed frame
F^E	-	Applied force described in the earth frame
m	-	Mass of the quadrotor
V^E	-	Linear velocity vector described in the earth frame
F^B	-	Applied force described in the body frame
ω^B	-	Angular velocity vector described in the body frame
v^B	-	Linear velocity vector described in the body frame
J	-	Inertia matrix, $[I_{xx}\ I_{yy}\ I_{zz}]$
I_{xx}, I_{yy}, and I_{zz}	-	Moments of inertia about the principal axes
M^E	-	Torque vector described in the earth frame
ω^E	-	Angular velocity vector described in the earth frame
M^B	-	Torque vector described in the body frame
F_{ng}	-	Non-gravitational forces acting on the quadrotor
F_d	-	Drag force due to air resistance
F_i	-	Thrust force of rotor i, where i is from 1 to 4
K_F	-	Aerodynamic force coefficient
ω_i	-	Rotational speed of rotor i, where i is from 1 to 4

u_1	-	Control input for the total thrust force generated by the four rotors
$k_1, k_2, \& k_3$	-	Aerodynamic translational coefficients
M	-	Moments acting on the quadrotor in the body frame
M_{G}	-	Gyroscopic moments due to rotors' inertia
J_r	-	Rotor inertia
ω_r	-	Rotor relative speed
M_{Ar}	-	Air friction moment
K_M	-	Aerodynamic moment coefficient
$k_4, k_5, \& k_6$	-	Aerodynamic friction coefficients
M_{i}	-	Moment of rotor i, where i is from 1 to 4
l	-	Distance between the centre of the rotor and the centre of gravity of the body frame
u_2	-	Control input for the thrust difference between the left rotor and the right rotor
u_3	-	Control input for the thrust difference between the back rotor and the front rotor
u_4	-	Control input for the torque difference between clockwise rotating rotors and the counter-clockwise rotating rotors
x	-	State vector of the Twin-rotor helicopter
p_{A}	-	Effect of the additive perturbation on the twin-rotor helicopter system
u	-	Control input vector of the twin-rotor helicopter
X	-	State vector of the quadrotor
U	-	Control input vector of the quadrotor
P_{A}	-	Effect of the additive perturbation on the quadrotor system
K_{P}	-	Proportional gain of the PID controller
K_{I}	-	Integral gain of the PID controller
K_{D}	-	Derivative gain of the PID controller
$G(s)$	-	The transfer function of the PID controller
$m(s)$	-	The output of the PID controller

$e(s)$	-	The error of the closed loop system
u_{ff}	-	The non-linear feed-forward term for the pitch angle of the twin-rotor helicopter
k_{ff}	-	Feed-forward control gain of the twin-rotor helicopter
Q'	-	Estimated/Measured disturbance on a system
T'	-	Measured torque of a system
I'	-	Estimated mass moment of inertia of a system
α'	-	Measured angular acceleration of a system
I_{m}	-	Motor current
K_{t}	-	Motor torque constant
$u_{\mathrm{k+1}}(t)$	-	Next value of the output of the iterative learning algorithm
$u_{\mathrm{k}}(t)$	-	Current output value of the iterative learning algorithm
$e_{\mathrm{k}}(t)$	-	Current error value of the iterative learning algorithm
λ	-	Designed parameter of the iterative learning algorithm
γ, β, and ε	-	learning parameters of the iterative learning algorithm
$IM_{\mathrm{k+1}}$	-	Next value of the estimated inertia matrix
IM_{k}	-	Current value of the estimated inertia matrix
K	-	Actuator gain of the system
PL	-	Rotorcraft model/process
ω_{h_i}	-	Hover angular speed of rotor i, where i is from 1 to 4
N_s	-	The sample size of the root mean square error formula
$\mathcal{H}$	-	The output signal of the root mean square error formula
M_{b}	-	Mass of body of the *Quanser AERO*
D_{m}	-	Centre of mass of the *Quanser AERO*
J_{P}	-	Pitch inertia of the *Quanser AERO*
J_{y}	-	Yaw inertia of the *Quanser AERO*
D_{t}	-	Thrust displacement of the *Quanser AERO*
k_{d}	-	Drag/Air resistance coefficient
J_{h}	-	Propeller hub inertia of the *Quanser AERO*
J_{pr}	-	Propeller inertia of the *Quanser AERO*
J_{eq}	-	Equivalent moment of inertia

τ_{m}	-	Motor torque
L_{m}	-	Motor inductance
V_{m}	-	Motor input voltage
K_{EM}	-	Motor back-electromotive force constant
ω_{m}	-	Motor speed
R_{m}	-	Motor resistance
V_{nom}	-	Nominal input voltage of the motor
τ_{nom}	-	Nominal torque of the motor
ω_{nom}	-	Nominal speed of the motor
I_{nom}	-	Nominal current of the motor

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CHAPTER 1

INTRODUCTION

1.1 Research Background and Motivation

There is no doubt that the field of unmanned aerial vehicle (UAV) systems is one of the main areas of research attracting researchers, industrialists, and hobbyists from various disciplines. Not surprisingly, more attention was given to UAVs due to their versatile uses in numerous applications such as surveillance, aerial photography and video, mapping and traffic monitoring, search and rescue, and meteorological reconnaissance. They are also used in risky missions with a high degree of mission success and safety compared to manned vehicles. For instance, measuring hazardous gases (Bashi et al., 2018), monitoring real-time forest fire (Berie & Burud, 2018), and searching for survivors in dangerous situations, leading to the continuous expansion of the UAVs industry for civilian and military sectors. Undoubtedly, this widespread in the UAVs is due to the rapidly-growing global technological prosperity in advanced materials, electronics, microcontrollers, sensors, 3D printers, etc., and their many desirable features such as light-weight, high manoeuvrability, and low cost which leads to better efficacy exceeding the human capabilities. All these factors have led to a high concentration in the UAVs industry.

UAV systems are usually classified into three categories; fixed-wing, rotary-wing (rotorcraft), and flapping-wing aircraft (Ghazbi et al., 2016). The rotorcraft or so-called vertical take-off and landing (VTOL) systems are heavier-than-air aircraft that use lift generated by rotors. They form a large and significant category of the UAVs, because they are characterized, among other sorts, by their ability to take off and land vertically, hover in one spot or limited zone, perform quick manoeuvring, and fly in a backward or sideways direction. They can be used in a variety of applications for instance mapping and surveying, inspection, payload transportation, modern agriculture and crop spraying, etc. Rotorcraft systems can be classified as twin-rotor helicopters, quadrotors, hexacopters, octocopters, etc (Ferdaus et al., 2018).

Among the different types of rotorcraft UAVs, helicopter and quadrotor systems are considered the most versatile flying machines nowadays. They are distinguished by their small size and weight, ease to control, high manoeuvrability, and ability to hover, which results in their use in a wide range of applications such as surveillance, emergency medical assistance, search and rescue, and aerial inspection.

On the other hands, there are several obstacles and challenges in these aerial systems, such as the handling disturbances and uncertainties. This is dealt with by applying different control methods. The need for stable, safe, and efficient flight operations is encountered by these control techniques. Besides, the ability to reject different forms of known and unknown perturbations, i.e., robustness against various disturbances and uncertainties in normal or complex environments is also vital. This represents one of the current bottlenecks in UAV development, and is considered to be a major and basic requirement in flight industries (Lungu, 2020).

Accordingly, this study will mainly concentrate on proposing an intelligent hybrid control technique for the twin-rotor helicopter and quadrotor systems to improve disturbance rejection capability and enhance systems performance.

1.2 Problem Statement

Although twin-rotor helicopter and quadrotor models are widespread in use in several applications, they are multivariate, highly non-linear, and strongly coupled systems that make them difficult to control (Noordin et al., 2021; Xin et al., 2019). They are also sensitive to disturbances and uncertainties during operation, which may degrade the flight performance and stability and this may cause failures in their motors, actuators, and sensors leading to unsafe flight and crashes (Abichandani et al., 2020; Khalili & Rezaei, 2016). Approach that tackles these challenges remains open and requires dedicated research to propose a sound control strategy to effectively reject the disturbances and uncertainties, i.e., robust against disturbances and uncertainties.

While preserving the stability of the flight system with responsive convergence with respect to time (Hua et al., 2019; Dorf & Bishop, 2017; Navabi & Mirzaei, 2017).

Some control strategies used for rejecting disturbances and uncertainties are either complex, require a large number of control parameters to be tuned, are difficult to use in experimental work, must be adjusted in offline mode, or are not well suited for operations with large time delays (Ha & Park, 2020; Ma et al., 2016; Yang et al., 2016). Thus, the need for an efficient and easy-to-implement controller, online and automatic tuning of control parameters, and efficacious performance in rejecting disturbances and uncertainties is a major matter in simulation and experimental works that need to be tackled (Wang et al., 2019).

Among different control techniques, the active force control (AFC) strategy represents one of the robust controllers that is easy to be implemented in practice (Sabzehmeidani et al., 2021; Ali & Mailah, 2019; Tahmasebi et al., 2017). Estimated inertia/mass value is the only control parameter that needs to be determined or fine-tuned (Tahmasebi et al., 2017). AFC is efficient in rejecting various forms of external or internal disturbances and uncertainties, and it could be readily integrated with most of the classical, modern, and intelligent control systems for various operating and loading conditions, making it the appropriate strategy to overcome robustness issues.

1.3 Research Objectives

The main objectives of this research are:

(a) To design and to model hybrid PID-IAFC controller schemes for stability control and improvement of robustness of rotorcraft.

(b) To benchmark the performance of the IAFC-based control scheme against the conventional PID controller through simulation and experiment testing.

(c) To evaluate and to compare the performance and robustness of the PID-ILAFC and PID-FLAFC in improving disturbance rejection capability.

1.4 Research Scope

The scope of work for this research is outlined as follows:

(a) Non-linear models of twin-rotor helicopter and quadrotor systems are adopted in this study to investigate the effectiveness of PID-IAFC schemes in disturbance rejection.

(b) Proposed intelligent hybrid AFC controllers are developed based on the combination of PID controller and IAFC schemes, involving PID-iterative learning AFC (PID-ILAFC) and PID-fuzzy logic AFC (PID-FLAFC).

(c) Simulation work is performed on both twin-rotor helicopter and quadrotor systems through the computation platform provided by MATLAB/Simulink©.

(d) Robustness is assessed by exposing both aerial Simulink models to different disturbances, like sinusoidal, pulsating, and *Dryden* wind gust models. These input disturbances are assumed to be added before the plant dynamics to simulate the exposure of aerial systems to wind gust disturbances.

(e) Fixed-base rotorcraft UAV system by *Quanser AERO* apparatus, with one DOF, was chosen to be HIL experimentally tested owing to its simplicity to verify the effectiveness of intelligent hybrid AFC controller in suppressing the applied disturbances. Only PID-ILAFC was benchmarked because it is easy to be implemented, effective, and its control parameters could be automatically fine-tuned online.

1.5 Research Significance and Contributions

The main research contributions of the research study are listed as follows:

(a) The PID controller has been integrated with the IAFC technique to design hybrid control schemes to improve the robustness in the presence of uncertainties or disturbances for twin-rotor helicopter and quadrotor systems. The proposed hybrid control schemes feature ease of design, simplicity of implementation in practice, and estimated inertia/mass value is the only control parameter that needs to be determined or fine-tuned.

(b) So far, PID-IAFC based controller has never been developed and studied for the improvement of twin-rotor helicopter and quadrotor systems robustness. From most of the works of literature found, they never use the practical IAFC-based control approach for rotorcraft models. The hybrid PID-ILAFC controller enhances the disturbance rejection capability of a fixed-base rotorcraft model, the *Quanser AERO* apparatus, via the HIL experiments.

(c) The establishment of an optimization method for fine-tuning the nominal control parameters. Conventionally, control parameters of the AFC are often selected using the trial and error method (TEM) (Omar et al., 2017). Here, the IL algorithm and fuzzy rules are employed as key ideas to determine the optimal value of the AFC parameter.

(d) Based on most of the works of literature found, various control techniques have never studied their effectiveness in relation to body jerk performance. The proposed hybrid PID-ILAFC controller is efficient in relation to body jerk performance and third-order dynamics in the rotorcraft systems in the presence of applied disturbances.

1.6 Research Methodology

This research begins with a thorough review of various control strategies of rotorcraft UAVs in general, and the twin-rotor helicopter and quadrotor systems in particular, to gain in-depth knowledge about that topic and determine which research gaps remain and need to be tackled. A detailed nonlinear detailed mathematical model is initially derived for each rotorcraft system, i.e., the twin-rotor helicopter and quadrotor, based on the *Euler-Lagrange* and *Newton-Euler* formulations, considering certain assumptions and conditions. To attain the required behaviour, a PID controller is designed as its gains are tuned heuristically. Due to the unsuccessful compensation of the PID controller for applied disturbances and uncertainties, it was proposed to be merged with an innovative control method known as the AFC technique to create a hybrid control scheme. Meanwhile, AI-based methods are introduced employing IL and FL methods and embedding them into the AFC loop to automatically tune (self-tuning) the proposed AFC strategy to be later identified as IAFC-based hybrid controllers including PID-iterative learning active force control (PID-ILAFC) and PID-fuzzy logic active force control (PID-FLAFC) schemes. The effectiveness of the PID-ILAFC in fending off various disturbances is examined. These disturbances took the form of sinusoidal wave, pulsating, or *Dryden* wind gust model. To analyse the performance, the PID-ILAFC strategy is compared to the PID-FLAFC scheme. As a means of improving the body jerk performance of the rotorcraft system, the proposed hybrid PID-ILAFC system is investigated for its effectiveness. To obtain the best possible performance of the proposed AFC-based control strategy, a sensitivity analysis is also conducted based on three different cases, namely, the variation in the estimated inertia value, in the payload mass (parameter variation), and in the AFC output signal percentage.

Regarding the experimental work, only PID-ILAFC method was chosen because it is easy to be implemented, effective, and its control parameters could be automatically fine-tuned online. The proposed hybrid PID-ILAFC strategy is designed and embedded into a laboratory module system of a fixed-base rotorcraft UAV system, the *Quanser AERO* apparatus, to evaluate its effectiveness, through HIL experimental tests. The system's ability to improve the disturbance rejection capability in the presence of two types of disturbances, in the form of impulsive force and payload mass, is investigated. It is noteworthy that the link between the twin-rotor helicopter and quadrotor models lies in that they all express different types of rotorcraft UAV systems but with different DOF, and also through the same proposed hybrid control system designed and implemented into them, the hybrid PID-ILAFC strategy, which expresses the IAFC-based control hybrid schemes, and its ability to enhance performance and disturbance rejection capability, as shown in the flowchart of this research **in Figure 1.1**.

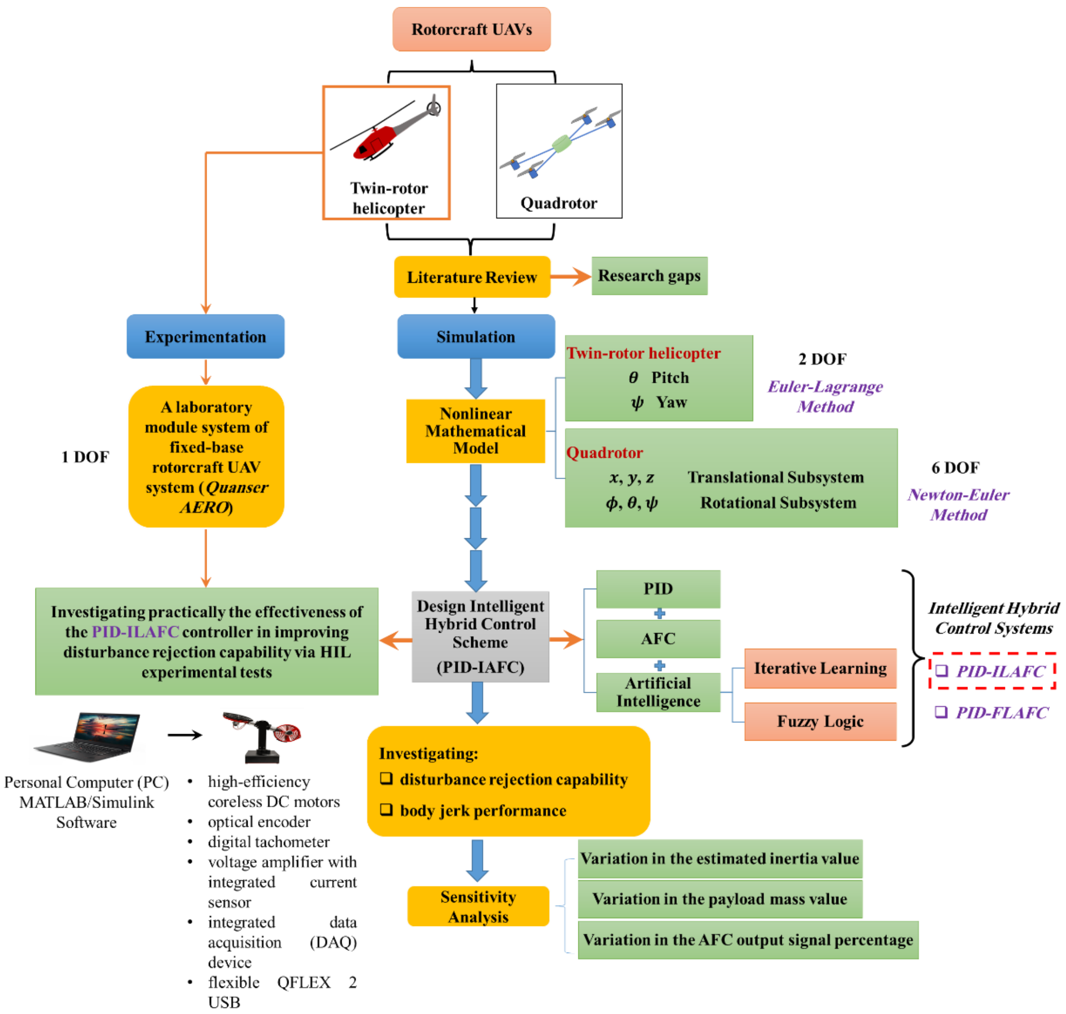

Figure 1.1 A flowchart of the research methodology.

1.7 Thesis Outline

This thesis is arranged into seven chapters, as follows:

Chapter 1 presents a brief background on the unmanned aircraft, the statement of the problem, objectives of the research, scope of the work, and the contribution of the study.

Chapter 2 provides a review of the literature and previous work on topics related to this thesis. In this chapter, the definitions, configurations, components, advantages, disadvantages, and applications of the UAVs, in general, and of rotorcraft systems, in particular, are demonstrated. After that, a comprehensive investigation of various control strategies for rotorcraft UAVs is also presented, to provide solutions to the different possible difficulties.

Chapter 3 exhibits the mathematical modelling for both rotorcraft systems. The twin-rotor helicopter model is derived based on the *Euler-Lagrange* formulation. Simultaneously, the quadrotor system is developed based on the *Newton-Euler* method, both of which take into account various forms of disturbances and certain considerations. Subsequently, a representation of both systems into the state space is also presented.

Chapter 4 discusses the proposed controller design based on the derived models. An innovative hybrid control strategy called the intelligent active force control-based control strategy is proposed to improve disturbance rejection capability.

Chapter 5 presents the findings of the system behaviours. Simulated results are shown based on several tests, including certain assumptions and considerations. After that, a detailed discussion depends on a comparative analysis is carried out to assess the model performance based on the proposed control strategies.

Chapter 6 details how to evaluate model performance via HIL experiments. A laboratory module system of fixed-base rotorcraft UAV that employs a mechatronic approach is used to verify the effectiveness of the proposed hybrid control strategy that is embedded into the system to improve disturbance rejection capability. Experimental results are shown based on several tests.

Chapter 7 presents the conclusion, negative, and positive aspects of the research. This chapter also deals with recommendations for possible future directions.

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LIST OF PUBLICATIONS

Journal papers

1. Sherif I. Abdelmaksoud, Musa Mailah, Ayman M. Abdallah, "Robust Intelligent Self-Tuning Active Force Control of a Quadrotor With Improved Body Jerk Performance", *IEEE Access*, vol. 8, pp. 150037 - 150050, 2020. **(ISI Impact Factor: 3.745 - Q1)**

2. Sherif I. Abdelmaksoud, Musa Mailah, Ayman M. Abdallah, "Control Strategies and Novel Techniques for Autonomous Rotorcraft Unmanned Aerial Vehicles: A Review", *IEEE Access*, vol. 8, pp. 195142 - 195169, 2020. **(ISI Impact Factor: 3.745 - Q1)**

3. Sherif I. Abdelmaksoud, Musa Mailah, Ayman M. Abdallah, "Disturbance Rejection for a Quadrotor Using Robust Active Force Control with Genetic Algorithm", International Journal of Modelling, Identification and Control, vol. 36, pp. 200-210, 2020. **(Scopus Impact Factor: 2.9- Q3)**.

4. Sherif I. Abdelmaksoud, Musa Mailah, Ayman M. Abdallah, "Practical Real-time Implementation of a Disturbance Rejection Control Scheme for a Twin-rotor Helicopter System Using Intelligent Active Force Control", IEEE Access, vol. 9, pp. 4886 - 4901, 2020. **(ISI Impact Factor: 3.745 - Q1)**.

5. Sherif I. Abdelmaksoud, Musa Mailah, Ayman M. Abdallah, "Enhancing Disturbance Rejection Capability and Body Jerk Performance of a Twin-rotor Helicopter Model Using Intelligent Active Force Control ", Jurnal Mekanikal, vol. 44, pp. 1 - 20, 2020.

Conference papers

1. Sherif I. Abdelmaksoud, Musa Mailah, Ayman M. Abdallah, "Improving Disturbance Rejection Capability for a Quadcopter UAV System Using Self-Regulating Fuzzy PID Controller," *Proceedings of 2020 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE)*, pp. 1- 6, 2021. **(Scopus).**

2. Sherif I. Abdelmaksoud, Musa Mailah, Ayman M. Abdallah, " Sensitivity Analysis of Intelligent Active Force Control Applied to a Quadrotor System", Proceedings of *International Conference on Emerging Technologies and Intelligent Systems (ICETIS 2021*), vol 322, PP 153-164. **(Scopus).**