HYBRID ADAPTIVE SLIDING MODE CONTROL FOR QUADCOPTER UNMANNED AERIAL VEHICLE

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ABSTRACT

Quadcopter unmanned aerial vehicle (UAV) systems are receiving remarkable attention from researchers due to their numerous applications, particularly at the current time in which the quadcopter unmanned aerial vehicles are playing a significant role in combating the COVID-19 pandemic. The quadcopter is a nonlinear and underactuated system, and such properties require an advanced control technique design to enable the quadcopter to achieve the assigned tasks precisely and successfully. The sliding mode control is among the best robust nonlinear control technique that can be implemented in the quadcopter to perform robust trajectory tracking. However, the drawback of the sliding mode control is the chattering phenomenon. Thus, this research aims to benefit the sliding mode control robust trajectory tracking meanwhile attenuating the unwanted chattering that creates critical problems such as the vibration in the quadcopter UAV mechanical parts and generating heat in the onboard electronic kits. The main objective of this work is to design a hybrid adaptive sliding mode control scheme for quadcopter systems considering the unwanted chattering attenuation induced by unbound parameter uncertainties and unknown disturbances meanwhile provide robust tracking. To implement the proposed control scheme, the dynamic equations of the quadcopter have been formulated and presented into two subsystems, the attitude, and the position dynamics subsystems. The hybrid proposed control scheme is composed of two controllers, an inner control loop and outer control loop. Firstly, the sliding mode controller has been proposed and assigned to act as an inner loop controller, where the improvement covered, the equivalent control, and the switching control terms in the sliding mode control law. The equivalent control term has been estimated and developed based on the Lyapunov approach. Essentially, the switching control term is a multiplication of a switching function and the switching gain. The switching function is approximated by an error function, while the switching gain is calculated based on an improved adaptive formula. Secondly, an interval type-2 fuzzy proportional integral derivative controller has been proposed and assigned to act as an outer loop controller to control the quadcopter position. The performance of the proposed hybrid adaptive sliding mode control scheme has been evaluated and investigated by Matlab/Simulink platform. The simulation results have been obtained in two different scenarios: Firstly, the performance of the proposed hybrid adaptive sliding mode control scheme has been evaluated considering only an ideal case where the parameter uncertainty and external disturbance are ignored. Secondly, the performance of the proposed hybrid adaptive sliding mode control scheme has been investigated in the presence of parameter uncertainty and external disturbance that influence the quadcopter operation. The simulation results have been performed for the quadcopter trajectory tracking in 6-DOFs. The obtained results prove that the proposed hybrid adaptive sliding mode control scheme provided a robust trajectory tracking with integral square error in the attitude and position have been improved by 37%, and 26% respectively, compared to the benchmark adaptive sliding mode control, and significantly attenuating the chattering impact.

ABSTRAK

Sistem kenderaan udara tanpa pemandu (UAV) kuadkopter mendapat perhatian yang luar biasa daripada para penyelidik kerana banyak aplikasinya, terutamanya pada masa semasa di mana UAV kuadkopter memainkan peranan penting dalam memerangi pandemik COVID-19. Kuadkopter ialah sistem tak linear dan underactuated, dan sifat sedemikian memerlukan reka bentuk teknik kawalan lanjutan untuk membolehkan kuadkopter mencapai tugas yang diberikan dengan tepat dan berjaya. Kawalan SMC adalah antara teknik kawalan tak linear teguh terbaik yang boleh dilaksanakan pada kuadkopter untuk melakukan pengesanan trajektori yang teguh. Walau bagaimanapun, kelemahan SMC adalah fenomena gelatuk. Oleh itu, penyelidikan ini bertujuan untuk memanfaatkan SMC mengawal penjejakan trajektori teguh sementara itu melemahkan gelatukan yang tidak diingini yang menimbulkan banyak masalah contohnya getaran dalam bahagian mekanikal UAV kuadkopter. Objektif utama kerja ini adalah untuk mereka bentuk skema kawalan SMC suai hibrid untuk sistem kuadkopter memandangkan pengecilan gelatukan yang tidak diingini disebabkan oleh ketidakpastian parameter yang tidak terikat dan gangguan yang tidak diketahui sementara itu menyediakan pengesanan yang mantap. Untuk melaksanakan skim kawalan yang dicadangkan, persamaan dinamik kuadkopter telah dirumus dan dibentangkan kepada dua subsistem, iaitu subsistem dinamik sikap dan kedudukan. Skin kawalan hibrid yang dicadangkan terdiri daripada dua pengawal, gelung kawalan dalam dan gelung kawalan luar. Pertama, pengawal SMC telah dicadangkan dan ditugaskan untuk bertindak sebagai pengawal gelung dalaman, di mana penambahbaikan diliputi, kawalan setara, dan syarat kawalan pensuisan dalam undang-undang kawalan SMC. Istilah kawalan yang setara telah dianggarkan dan dibangunkan berdasarkan pendekatan Lyapunov. Pada asasnya, istilah kawalan pensuisan ialah pendaraban fungsi pensuisan dan keuntungan pensuisan. Fungsi pensuisan dianggarkan oleh fungsi ralat, manakala keuntungan pensuisan dikira berdasarkan formula penyesuaian yang lebih baik. Kedua, pengawal selang T2-FPID telah dicadangkan dan ditugaskan untuk bertindak sebagai pengawal gelung luar untuk mengawal kedudukan kuadkopter. Prestasi skim kawalan SMC suai hibrid yang dicadangkan telah dinilai dan dianalisa oleh platform Matlab/Simulink. Keputusan simulasi telah diperolehi dalam dua senario berbeza: Pertama, prestasi skema kawalan SMC suai hibrid yang dicadangkan telah dinilai hanya dengan mengambil kira kes ideal di mana ketidakpastian parameter dan gangguan luaran diabaikan. Kedua, prestasi skim kawalan SMC suai hibrid yang dicadangkan telah dianalisa dengan kehadiran ketidakpastian parameter dan gangguan luaran yang mempengaruhi operasi kuadkopter. Keputusan simulasi untuk kedua-dua senario ini telah dilakukan berdasarkan penjejakan trajektori kuadkopter dalam 6-DOF. Keputusan yang diperolehi membuktikan bahawa skim kawalan SMC suai hibrid yang dicadangkan menyediakan pengesanan trajektori yang mantap dengan integral ralat kuasa dua dalam sikap dan kedudukan suai telah meningkat masing-masing sebanyak 37%, dan 26%, berbanding penanda aras. SMC suai, dan mengurangkan kesan gelatukan dengan ketara.

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LIST OF ABBREVIATIONS

UAV	-	Unmanned Aerial Vehicle
COG	-	Centre of the Gravity
PID	-	Proportional Integral Derivative
SMC	-	Sliding Mode Control
FBL	-	Feedback Linearization
DOF	-	Degree of Freedom
FPID	-	Fuzzy Proportional Integral Derivative
IT2-FPID	-	Interval Type-2 Fuzzy Proportional Integral Derivative
AIAA	-	American Institute of Aeronautics & Astronautics
DOD	-	US Department of Defence
LQ	-	Linear–Quadratic
COVID-19	-	Coronavirus Disease 2019
DC	-	Direct Current
COG	-	Centre of the Gravity
MIMO	-	Multi-Inputs and Multi-Outputs
FLC	-	Fuzzy Logic Control
efr	-	Error Function
FLS	-	Fuzzy Logic System
ISE	-	Integral Square Error

LIST OF SYMBOLS

x_E	-	x-axis on the Earth-frame
y_E	-	y-axis on the Earth-frame
z_E	-	z-axis on the Earth-frame
x_B	-	x-axis on the Body-frame
y_B	-	The y-axis on the Body-frame
z_B	-	z-axis on the Body-frame
ϕ, θ, ψ	-	The quadcopter Euler angles (roll, pitch, and yaw)
ϕ_d, θ_d, ψ_d		Desired angles
x, y, z	-	The quadcopter position
x_d, y_d, z_d		Desired position
$\boldsymbol{\eta}$	-	Quadcopter position
$\boldsymbol{\eta_1}$	-	Quadcopter linear position
$\boldsymbol{\eta_2}$	-	Quadcopter angular position
$\dot{\boldsymbol{\Gamma}}$	-	The linear velocity of the B-frame with respect to the E-frame
$\boldsymbol{V}$	-	The linear velocity vector in B-frame
$\dot{\boldsymbol{\Theta}}$	-	The angular velocity of the B-frame with respectthe to the E-frame
$\boldsymbol{\omega}$	-	The angular velocity vector in B-frame
$\boldsymbol{e_z}$	-	Unit vector
F_i	-	The thrust
Ω_i	-	The rotor speed
$\boldsymbol{I}$	-	The inertia matrix
$\boldsymbol{G_a}$	-	The gyroscopic
$\boldsymbol{\tau}$	-	The control inputs
$\boldsymbol{J_r}$	-	The rotor inertia
b, C_D, d	-	The drag factor
$\boldsymbol{\xi}$	-	The quadcopter orientation
u_1, u_2, u_3, u_4	-	The quadcopter control inputs
Ω_d	-	The disturbance

$\delta_{\phi}, \delta_{\theta}, \delta_{\psi}, \delta_{z}, \mu_{\phi}, \mu_{\theta}, \mu_{\psi}$	-	Lumped uncertainties and disturbances
$\hat{\delta}_{\phi}, \hat{\delta}_{\theta}, \hat{\delta}_{\psi}, \hat{\delta}_{z}, \zeta_{\phi}, \zeta_{\theta}, \zeta_{\psi}$	-	Estimated lumped uncertainties and disturbances
$\gamma_{\phi}, \gamma_{\theta}, \gamma_{\psi}, \gamma_{z}, \beta_{\phi}, \beta_{\theta}, \beta_{\psi}$	-	Positive constants
$k_{\phi}, k_{\theta}, k_{\psi}, k_{z}, c$	-	Positive constants
N	-	The number of samples
$e(t)$		Trajectory tracking error
μ_{lmf}	-	Lower membership functions
μ_{umf}		Upper membership functions
$s(t)$	-	The sliding surface
n	-	The system order
$V(s)$	-	Lyapunov function
u_{eq}	-	Equivalent control term
u_{c}	-	Switching control term
λ	-	Positive constant
$\tilde{\zeta}_{\phi}, \tilde{\zeta}_{\theta}, \tilde{\zeta}_{\psi}$	-	Errors in estimated uncertainty and disturbance
$\hat{k}$	-	Estimated switching gain
K_P, K_I, K_D	-	PID controller gains
φ, ε	-	Boundary layer thickness
w_i	-	Rule firing strength
N	-	The rules number
$\varphi_{i_{up}}$	-	Switching gain increment rate
$\varphi_{i_{down}}$	-	Switching gain decrement rate
$\alpha_i, \delta_i(t)$	-	Switching gain constant parameters
m	-	Mass
I_x	-	Inertia on x-axis
I_y	-	Inertia on y-axis
I_z	-	Inertia on the z-axis
b	-	Thrust coefficient
J_r	-	Rotor inertia
l	-	The arm length
K_{fax}	-	The aerodynamic coefficient on x
K_{fay}	-	The aerodynamic coefficient on y

K_{faz}		The aerodynamic coefficient on z
K_{fdx}	-	Drag coefficient on x
K_{fdy}	-	Drag coefficient on y
K_{fdz}	-	Drag coefficient on z
K_p	-	Lift force coefficient
C_P, C_d, C_o, C_i, C_e	-	Positive constants FPID controller gains

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

Basically, the UAV is an aircraft operated without a human pilot on board. The UAV is an umbrella that contains three major branches fixed-wing, helicopter, and multirotor as depicted in Figure 1.1 (Kim *et al.*, 2019; Abdelmaksoud *et al.*, 2020). The quadcopter UAV is a most popular family member of the multirotor UAVs shown in Figure 1.2. The advantages and disadvantages of the quadcopter against the fixed wind UAVs and helicopters are summarized and listed in Table 1.1. For instance, the multirotor UAVs have an advantage over the fixed-wing type because of Vertical Take-off and Landing. The disadvantage of the multirotor is energy consumption due to the four motors which restrict the flying time of the UAV. In the past, the UAVs came up with large size which was very expensive. However, the recent technologies in lithium batteries, electronics kits, and mechatronics result in small size and cheap UAVs which can be used for outdoor and indoor applications with high maneuverability as shown in Figure 1.3 and Figure 1.4, respectively.

In recent years, especially the quadcopter UAV is getting remarkable interest and focus from researchers, and it has been involved in numerous applications in both military and civil sectors (Shakhatreh *et al.*, 2019). Although in the past the quadcopter was mainly used for military purposes, however over time it gradually involved in civilian applications such as traffic surveillance, photography, delivery, rescue, etc. From a structural point of view, the quadcopter UAV is a mechatronic system with a simple structure and consists of the main body include power source and control hardware along with four brushless dc motor which is fixed in a cross configuration as shown in Figure 1.2.

The quadcopter is an underactuated system with high nonlinear dynamics. Consequently, advanced and robust control techniques have been used in the literature, such as sliding mode, backstepping, and adaptive control, etc. to ensure smooth and robust trajectory taking navigation.

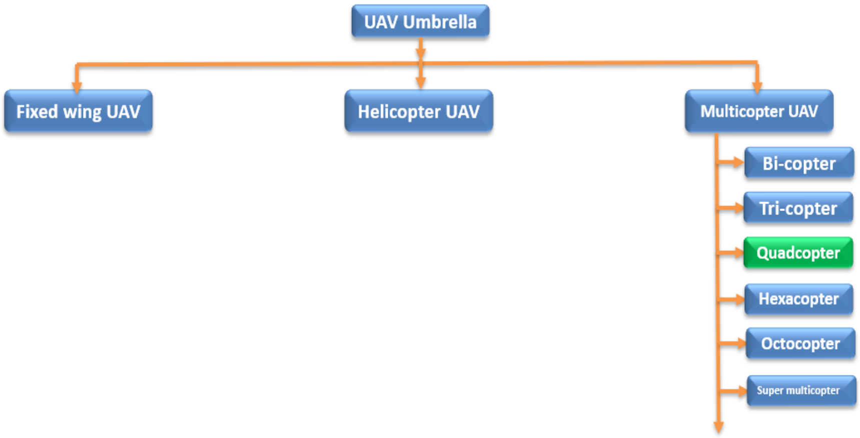

Figure 1.1 Unmanned Aerial Vehicles (UAVs) Hierarchical.

Table 1.1 summarizes the advantages and disadvantages of the quadcopter UAV compared to other UAV families such as helicopter and fixed-wing UAVs.

Table 1.1 The advantages and disadvantages of the UAVs.

Summary comparison			
Maneuverability	☑		
Take-off/ landing	☑		☑
Payload capacity	☑		☑
Power consumption		☑	☑
Price	☑		☑
Portability/size	☑		☑
Safety		☑	
Remote control distance		☑	
Stability			
Complex engine parts	☑	☑	

Figure 1.2 The quadcopter UAV system.

1.1.1 Indoor Quadcopter Applications

Indoor quadcopters (mini and Nano quadcopters) as depicted in Figure 1.3 can move in a limited area only such as closed houses or offices, and they have concise control distances determined by the manufacturer. The advantage of the indoor quadcopter is the absence of wind-gust disturbance compared to the outdoor space. There are numerous applications of indoor quadcopters, such as military applications, inspections, and photography.

Figure 1.3 Small size of quadcopter UAV.

1.1.2 Outdoor Quadcopter Applications

The outdoor quadcopter is manufactured in a strong physical shape to overcome the harshness of the outdoor environment as depicted in Figure 1.4. The outdoor quadcopters have long remote-control distances and can fly longer compared to the indoor quadcopters. The disadvantage of the outdoor area is the wind-gust disturbance. The outdoor quadcopters are involved in many applications such as military applications and most civilian applications, for instance, lifting a payload, outdoor inspections, and agriculture care.

Figure 1.4 Example of the quadcopter UAV application.

1.2 Quadcopter Setup

The quadcopter has four fixed-pitch propellers in a cross configuration (Idrissi *et al.*, 2022; Gupte *et al.*, 2012), the two pairs (1,3) and (2,4) of propellers turn in opposite directions to remove the need for a tail rotor as shown in Figure 1.5.

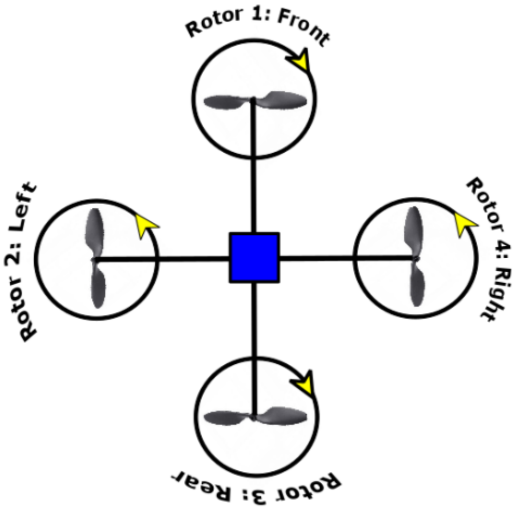

Figure 1.5 The quadcopter Setup.

1.3 Motivation

Recently, the quadcopter UAV is earning more focus from researchers, engineers, and hobby, due to the wide range of applications in which the quadcopter is involved, including military and civilian applications. The rapid progress in lithium batteries and electronics kits technologies reflected in the quadcopter UAV design and manufacturing with different small sizes such as mini and nano quadcopter UAV, as a result, the quadcopter UAV becomes highly demanded commercially. The quadcopter UAV is classified as a complex system in terms of nonlinearity, coupled dynamics, unmodeled dynamics, and under-actuated system, all these challenges make the quadcopter is one of the best choices for the researcher and engineers to design and develop robust control algorithms. Furthermore, the harsh environment surrounds the quadcopter during the operation, such as the system parameters uncertainties, and the wind guest disturbances are another challenge and must be considered in the control design stage. The design of an autonomous flight control system for small-scale quadcopter UAVs in the presence of uncertainty and wind guest disturbances is a challenging task due to its high nonlinearity in the dynamical model, underactuated property, and external wind gest disturbances (S Islam *et al.*, 2015). Therefore, this work is motivated by the control problem design for the quadcopter UAV in the presence of parameter uncertainties, unmodeled dynamics, and external wind gest disturbances.

Numerous research studies have investigated the quadcopter UAV control design, and the attempts are reported as follows. Firstly, linear control designs for the quadcopter; in this approach, the quadcopter UAV nonlinear dynamics equations are linearized with some assumptions around the equilibrium points and conditions, then the proposed linear control algorithm can be applied (Mokhtari *et al.*, 2006; Grau *et al.*, 2018; Bouaiss *et al.*, 2020; Wu and Liu, 2018). The main drawback of this approach is that the designed control system will become unstable when the quadcopter model deviates from these selected equilibrium points which may be accrued due to either parameter uncertainty or external disturbances. While the other approach is to design the proposed control algorithm for the quadcopter UAV model in the form of the nonlinear dynamic equations (Walid *et al.*, 2018; Idrissi and Annaz, 2020), concerning parameter uncertainty and the external disturbances (Mofid and Mobayen, 2018a; Xu *et al.*, 2017; Liao *et al.*, 2018). Furthermore, the nonlinear dynamic equations of the quadcopter contain DC motors dynamics, aerodynamics, gyro, and unmodeled dynamics (Patel *et al.*, 2017; Zuo, 2013; Ryll *et al.*, 2015; Bo *et al.*, 2016). In addition to the model parameters uncertainty and external wind-gust disturbances (Fernández *et al.*, 2017; Huang *et al.*, 2019). All these challenges must be taken into consideration in the control design stage, and the performance and robustness of the proposed control strategy are evaluated and verified against these prior mentioned challenges.

The SMC control technique can be classified as one of the nonlinear control strategies that has deserved much focus from the researchers. The attractive advantage of selecting the SMC-based control design method compares to the other control techniques lies in its ability to overcome the system parameter uncertainty, external disturbance, and simplicity in the design and implementation. However, the main drawback of the SMC control is the chattering phenomena that occur due to the unknown or unmodeled system dynamic and the external disturbances. Since the mathematical dynamics model does not represent the exact physical system as in reality. Therefore, the presence of unmodeled dynamics exists; as a result, the chattering is occurring depends on the obtained mathematical dynamic model and how it is accurate and close to the physical system. Therefore, the motivation of this work is to enhance the performance of the SMC control algorithm in terms of chattering reduction and robust trajectory tracking considering the presence of parameter uncertainties and wind-gust external disturbance.

As per the reported works in the literature [17], where the adaptive SMC has been developed to control the quadcopter attitude and altitude in which the switching gain is constant and selected manually to overcome the changes in the parameters uncertainties, and external disturbance influences. Thus, a robust trajectory tracking may achieve; but the designed adaptive SMC does not consider the chattering attenuation, especially when the parameters uncertainties rabidly change. An adaptive SMC control algorithm is designed in such way to combine adaptive law with the SMC term to handle the parametric uncertainties associated with, mass, inertia, and aerodynamic force (Shafiqul Islam *et al.*, 2015). However, the proposed work did not study and investigate the impact of the unwanted chattering. While work reported in (Cibiraj and Varatharajan, 2017) is proposed based on adaptive neural gain scheduling SMC control to handle the unwanted chattering problem, nonetheless the designed adaptive switching gain is kept with limitation that governed by the selected membership function and rule which may handle the paramedic uncertainties and external disturbances within the restricted bounds.

An adaptive control law has been proposed in (Baek *et al.*, 2016) whereas a fast adaptation in the switching gain has been achieved and chattering attenuation have been attained. The adaptive SMC control law used an adaptive formula to calculate the switching gain adaptively against the changes in the parameter uncertainties to keep robust trajectory tracking meanwhile attenuating the unwanted chattering. However, the behaviour of the generated adaptive switching gain can be furtherly enhanced to better performance.

Therefore, motivated by the feasibility of applying adaptive SMC-based control to the quadcopter nonlinear system to achieve robust trajectory tracking and handling the unwanted chattering, a hybrid adaptive SMC control scheme has been proposed in this study.

1.4 Problem Statement

As well known, the uncertainties occur in the quadcopter UAV dynamics. Furthermore, the quadcopter UAV is very susceptible to external disturbances. Therefore, all these influences may result in a critical deviation of the predefined quadcopter UAV trajectory tracking. The system uncertainties generated by the parameter variations and the external disturbances are commonly unknown. Therefore, a high robust control design is required for quadcopter UAV to overcome these challenges, the parameters uncertainties, and external disturbances.

The conventional SMC control is not recommended to be implemented in some applications due to the chattering phenomenon, which may lead to serious problems, for instance, a vibration in the quadcopter UAV mechanical parts and heating in electronics kits which results in fast battery consumption. The chattering phenomena associated with SMC is remaining as an open problem in the field of SMC, and many research concepts can be implemented.

1.5 Research Gap

Based on the literature concerned with the adaptive SMC-based control design approaches for the nonlinear quadcopter UAV systems, the research gap can be summarized as follows:

- Essentially, the SMC control law consists of two terms, the equivalent control, and the switching control terms, and the switching control is a multiplication of the switching gain and the switching function. To the best of the author’s knowledge, several simulation-based works related to the adaptive SMC-based design for the attitude of the quadcopter system are reported in the literature in which the adaptive design approach performed to develop the equivalent control term and/or the switching gain. However, for better performance for achieving the robust trajectory tracking and attenuating the unwanted chattering, simultaneously, against the parameter uncertainties and wind-gust disturbance, further improvement on the adaptive SMC-based control design can be accomplished to enhance the development of the adaptation switching gain and approximating the switching function by hyperbolic tangent function which significantly contribute on the chattering attenuation.

- Furthermore, the design of the outer loop controller to control the position of the quadcopter is significant where the outer loop controller supplies the inner loop controller with the generated desired attitude. Therefore, an interval type-2 fuzzy PID controller can be designed as an outer loop controller, which is adaptively tuned to adapt to the variations in the parameter uncertainties, wind-gust disturbance, and arbitrary desired position as well, meanwhile generating an accurate desired attitude to be supplied to the inner loop improved adaptive SMC controller for an arbitrary desired attitude. Consequently, the overall proposed control scheme is a combination of an improved adaptive SMC control to control the attitude and an interval type-2 fuzzy PID control to control the position which is called hybrid adaptive SMC control for the quadcopter UAV.

1.6 Research Objectives

The objectives of the research are:

i. To design a hybrid adaptive SMC control scheme for the quadcopter system considering the parameter uncertainties and wind-gust disturbance.
ii. To improve the performance of the developed hybrid adaptive SMC control scheme for providing robust trajectory tracking and attenuate the unwanted chattering influences.
iii. To implement the developed proposed hybrid adaptive SMC control scheme to the quadcopter model by simulation using MATLAB/SIMULINK platform and investigate the performance of the proposed control scheme considering

different operating scenarios with or without parameter uncertainty and wind-gust disturbance.

1.7 Research Scope and Limitations

The scopes of work limitations for this research are outlined as follows:

i. The work will cover the motion of the nonlinear quadcopter systems with the coupled dynamics in 6-DOFs.

ii. The model of the quadcopter will be built and presented in Matlab/Simulink platform.

iii. The proposed controller will be developed based on the adaptive sliding mode control technique.

iv. The performance of the proposed control scheme will be tested and verified by the simulation.

v. The performance of the proposed control scheme will be evaluated considering three different flying tests in two different scenarios for each: the nominal and uncertain parameters.

vi. The wind-gust disturbance model is considered to be based on Dryden Wind-Gust model (Wang, 2009), and has been assumed to act on x, y, and z directions to represent the effects of the outdoor environment.

vii. The physical parameters of the quadcopter system are taken from (Koesdwiady, 2013).

viii. The quadcopter structure is a rigid body (Grau *et al.*, 2018).

ix. The quadcopter frame is symmetric.

x. The center of mass of the quadcopter and B-frame origin are identical.

xi. The lift and the drag forces are proportional to the square of the rotor speed.

1.8 Thesis Organization

The thesis consists of six chapters which are organized into the following pattern.

CHAPTER 1 is dedicated to the introduction and presents the problem background of the quadcopter system, the quadcopter setup, motivation, problem statement, research objectives, the scope of work, and thesis organization.

CHAPTER 2 reports some of the literature review on the quadcopter system modeling and recent control techniques implemented to quadcopter systems and identifying the research gap.

CHAPTER 3 is mainly devoted for the research methodology and quadcopter modeling where the Newton-Euler method has been used to extract the quadcopter dynamic equations.

CHAPTER 4 is dedicated for the proposed control scheme development of the quadcopter system. Where the improved adaptive SMC has been developed to control the quadcopter attitude, and the interval type-2 FPID has been developed to control the quadcopter position. Therefore, the overall developed controller called hybrid adaptive SMC control system.

CHAPTER 5 shows various simulation flying tests of the proposed control scheme implemented to the quadcopter system. Including several simulation scenarios, with and without parameter uncertainty and wind-gust disturbance.

CHAPTER 6 presents the conclusion of the research work. In addition to some possible recommendations for future works.

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Appendix C

LIST OF PUBLICATIONS

Indexed Journal with Impact Factors

1. **A. Eltayeb**, M. F. Rahmat, M. A. M. Basri, M. A. M. Eltoum and S. El-Ferik, (2020). An Improved Design of an Adaptive Sliding Mode Controller for Chattering Attenuation and Trajectory Tracking of the Quadcopter UAV. *IEEE Access*, vol. 8, pp. 205968-205979. (**Q1, IF: 3.745**).

2. **A. Eltayeb**, M. F. Rahmat, M. A. M. Eltoum, M. A. M. Basri (2020). Robust adaptive sliding mode control design for quadrotor unmanned aerial vehicle trajectory tracking. *Int. J. Comput. Digit. Syst*., vol. 9, no. 2, pp. 249-257. (**Indexed by SCOPUS**).

3. **A. Eltayeb,** M. F. Rahmat, M. A. M. Basri (2020). Sliding mode control design for the attitude and altitude of the quadrotor UAV. *Int. J. SMART Sens. Intell. Syst***.,** vol. 13, no. 1, pp. 1–13. (**Q4, IF(JCI): 0.25**).

4. **A. Eltayeb**, M. F. Rahmat, and M. A. M. Basri (2020). Adaptive feedback linearization controller for stabilization of Quadrotor UAV. *Int. J. Integr. Eng.*, vol. 12, no. 4, pp. 1–17. (**Q3, IF(JCI): 0.21**).

5. **A. Eltayeb**, M. F. Rahmat, M. A. M. Basri, and M. S. Mahmoud (2020). An Improved Design of Integral Sliding Mode Controller for Chattering Attenuation and Trajectory Tracking of the Quadrotor UAV. *Arab. J. Sci. Eng.* (**Q2, IF: 2.807**).

6. **A. Eltayeb**, M. F. ad Rahmat, M. A. M. Basri, and A. M. Mohammed Mansour (2020). Adaptive Sliding Mode Control Design for the Attitude of the Quadrotor Unmanned Aerial Vehicle (UAV). *IOP Conference Series: Materials Science and Engineering*, vol. 884, no. 1. (**Indexed by SCOPUS**).

7. **A. Eltayeb**, M. F. Rahmat, M. A. M. Basri, M. A. M. Eltoum and M. S. Mahmoud (2022). Integral Adaptive Sliding Mode Control for Quadcopter UAV Under Variable Payload and Disturbance. *IEEE Access*. (**Q2, IF: 3.476**).

Indexed Conference Proceedings

1. **A. Eltayeb**, M. F. ad Rahmat, M. A. M. Basri, and A. M. Mohammed Mansour (2020). Adaptive Sliding Mode Control Design for the Attitude of the Quadrotor Unmanned Aerial Vehicle (UAV). *IOP Conference Series: Materials Science and Engineering*, vol. 884, no. 1. (**Indexed by SCOPUS**).

2. **A. Eltayeb**, M. F. Rahmat, M. A. Mohammed Eltoum, I. M. H. Sanhoury, and M. A. M. Basri (2019). Adaptive sliding mode control design for the 2-DOF robot arm manipulators. *International Conference on Computer, Control, Electrical, and Electronics Engineering, ICCCEEE* 2019. (**Indexed by SCOPUS**).

3. **A. Eltayeb**, M. F. Rahmat, M. A. Mohammed Eltoum, and M. A. Mohd Basri (2019). Adaptive fuzzy gain scheduling sliding mode control for quadrotor UAV systems. *8th Int. Conf. Model. Simul. Appl. Optim. ICMSAO 2019*, pp. 1–5, 2019**. (Indexed by SCOPUS).**

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5. **A. Eltayeb**, M. F. Rahmat, M. A. Mohammed Eltoum, I. M. H. Sanhoury, and M. A. M. Basri (2020). Trajectory Tracking for the Quadcopter UAV utlizing Fuzzy PID Control Approach. *International Conference on Computer, Control, Electrical, and Electronics Engineering, ICCCEEE 2020*. (**Indexed by SCOPUS**).

Book Chapter

1. **Eltayeb**, M. F. Rahmat, and M. A. M. Basri (2021). Quadcopter UAV Dynamic Modeling and PID Trajectory Tracking Control Design. *Sensor & Instrumentation System 24.*