# ROBUST TRACKING CONTROL SYSTEM FOR LONGITUDINAL MANOEUVRE OF LARGE AIRCRAFT

By

NURHANA BINTI MOHMAD ROUYAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Doctor of Philosophy

October 2023

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**DEDICATIONS**

*Arwah abah, mama dan semua..*

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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**Chairman: Prof. Dato' Dr.-Ing. Ir. Renuganth a/l Varatharajoo, PhD**
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A near-stall condition refers to a critical flight situation in which an aircraft is operating at or near its stall velocity or the minimum speed required to maintain lift. During this condition, the aircraft's aerodynamic performance is severely compromised, making precise control essential for the safe and reliable execution of manoeuvres, including terrain avoidance, evasive manoeuvres, and safe landings or climbing. In such a situation, maintaining stability and control becomes paramount to ensure the safety of the aircraft and its occupants. As flight control systems continue to incorporate the latest automation technology, it is essential to assess the effectiveness of these systems in such conditions. However, aircraft models inherit nonlinearity due to near-stall conditions. In addition to addressing the lack of effective control solutions in existing systems, this thesis explores the application of sliding mode control (SMC) to maintaining satisfactory flight performance during manoeuvres that require rapid changes in attitude, altitude, and velocity in the tracking process. A nonlinear aircraft model was developed for this purpose, and the model was transformed into a nonlinear state space to provide an accurate representation of the aircraft dynamics. To verify the model, open-loop analysis was employed based on the trimming and linearisation of the model. Additionally, variants of SMC, including integral SMC (ISMC) and non-singular terminal SMC (NTSMC), were integrated into the aircraft model to evaluate their potential for enhancing flight stability and performance. The model underwent various flight phase scenarios to demonstrate the effectiveness of these control methods in challenging situations. The results were compared with PID and SMC controllers as baselines. The study revealed that the sliding surface variable is critical for determining the stability performance of the aircraft, with the tested controllers outperforming the baselines. Notably, NTSMC exhibited nearly a 60% improvement in response compared to PID. However, achieving simultaneous control for attitudes and velocity has posed challenges, emphasiz-

ing the necessity of a hierarchical control structure.

**Keywords**: Longitudinal manouevre, nonlinear aircraft, robust control, sliding mode control.

**SDG**: GOAL 4: Quality Education.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**SISTEM KAWALAN JEJAK YANG MANTAP KETIKA GERAKAN LONGITUD UNTUK PESAWAT BESAR**

Oleh

**NURHANA BINTI MOHMAD ROUYAN**

**Oktober 2023**

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**Fakulti: Kejuruteraan**

Keadaan menghampiri pegun merujuk kepada keadaan penerbangan yang kritikal sebuah pesawat yang beroperasi menghampiri kelajuan pegun, iaitu kelajuan minimum yang diperlukan untuk mengekalkan daya angkat. Ketika ini, prestasi aerodinamik pesawat terjejas, menjadikan kawalan yang tepat penting untuk pemacuan gerakan yang selamat dan boleh dipercayai, termasuk mengelakkan kawasan berbukit, sewaktu misi mengelak serta ketika pendaratan atau pelepasan. Dalam keadaan sedemikian, mengekalkan kestabilan dan kawalan penting untuk memastikan keselamatan pesawat serta penumpang. Dengan pengintegrasian teknologi automatik dalam sistem kawalan penerbangan yang semakin maju, penilaian keberkesanan sistem semasa gerakan adalah penting. Walau bagaimanapun, pemodelan pesawat mewarisi ketidaksamaan linear disebabkan oleh keadaan menghampiri pegun. Selain itu, kekurangan penyelesaian kawalan yang berkesan dalam sistem-sistem sedia ada menghalang prestasi pesawat yang mantap, terutamanya dalam situasi ini. Tesis ini meneroka aplikasi kawalan mod gelongsor (SMC) yang mantap dalam mengekalkan prestasi penerbangan yang disasarkan semasa pemacuan gerakan yang memerlukan perubahan pantas dalam oreintasi, ketinggian, dan halaju ketika proses penjejakan. Satu model pesawat yang tidak linear telah dibina untuk tujuan ini dan model tersebut diubahsuai menjadi ruang keadaan yang tidak linear untuk mendapatkan representasi dinamik pesawat yang tepat. Analisis gelung-buka dikenakan untuk mengesahkan model berdasarkan pemangkasan dan pelelurusan model. Selain itu, variasi SMC, termasuk SMC integral (ISMC) dan SMC terminal tidak singular (NTSMC), turut dikaji untuk menilai potensi mereka bagi meningkatkan prestasi penerbangan. Model itu dikenakan pelbagai fasa penerbangan untuk membuktikan keberkesanan kaedah kawalan ini dalam situasi yang mencabar. Hasilnya dibandingkan dengan pengawal PID dan SMC sebagai garis panduan. Kajian ini mendapati bahawa pembolehubah permukaan gelongsor adalah penting untuk menentukan prestasi kestabilan pesawat, malah prestasi pengawal melangkaui garis piawaian. Perlu ditekankan bahawa NTSMC menunjukkan peningkatan hampir 60% lebih baik dalam tindak balas berbanding dengan PID. Walaubagaimanapun, kawalan serentak melibatkan orientasi dan kelajuan tidak dapat dicapai dengan baik, menekankan terdapatnya keperluan untuk mempertimbangkan hierarki kawalan.

**Kata Kunci**: Gerakan longitud, kawalan mantap, kawalan mod gelongsor, ketidaksamaan linear pesawat.

**SDG**: MATLAMAT 4: Pendidikan Berkualiti.

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May Allah SWT return all the kindness and blessings for you all.

Sincerely,
.
Hana

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Date: 13 June 2024

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# INTRODUCTION

## 1.1 Background

A mission profile is a thorough plan that defines the many stages of a flight, such as take off, ascent, cruise, descent, and landing. Figure 1.1 illustrates a typical mission profile for a commercial aircraft, beginning with taxiing, followed by take off, climbing to a specified altitude, cruising to the destination, initiating descent and deceleration as it nears the destination, preparing for approach and landing, and finally taxiing to the terminal. This plan is significant as it identifies the specific performance criteria, such as altitude, airspeed, range, fuel consumption, and payload, that the aircraft must maintain during each stage (Filippone, 2012). By defining these criteria, a mission profile guarantees that the aircraft can efficiently fulfill its predetermined mission, whether it involves transporting passengers or cargo, conducting military operations, or executing scientific research. In addition, a meticulously designed mission profile can enhance the aircraft's efficiency and performance, resulting in decreased costs and improved safety measures.

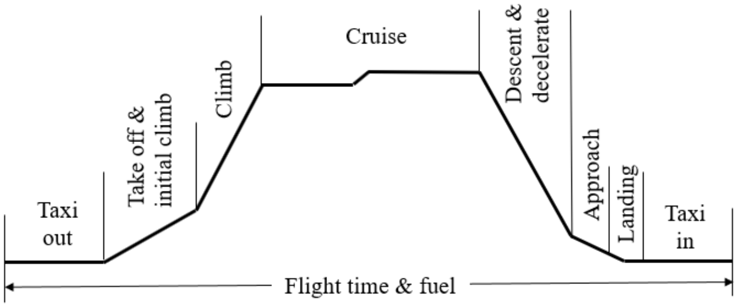


**Figure 1.1: Typical mission profile for a commercial aircraft.** (Source: Yin, 2016)

In a conventional aircraft, the pilot is responsible for operating the aircraft in a safe and efficient manner. This includes the ability to make decisions regarding the aircraft's speed, altitude, heading, and other aspects of flight control. However, as technology continues to advance, system automation is becoming more prevalent in many areas, including flight control systems. Taking account maintaining precise control over the aircraft's path for an extended period of time can be challenging for a human pilot, especially when faced with external factors such as weather conditions or turbulence, but effortless for an AFCS.

Automatic Flight Control Systems (AFCS) provide significant benefits by utilising sophisticated control algorithms to ensure that the aircraft follows a predefined mission with a high level of precision and flight safety. For example in Figure 1.2, the AFCS integrates with the Electronic Flight Instrument System (EFIS), Mode Control Panel (MCP), Air Data Control Unit (ADCU), and Attitude and Heading Reference System (AHRS) to provide comprehensive data inputs and control commands to the Autopilot Control Computer (Jeppu, 2014). It utilises an autopilot system to control and adjust various mechanical, electrical, or hydraulic systems within an aircraft, reducing the need for manual pilot input.

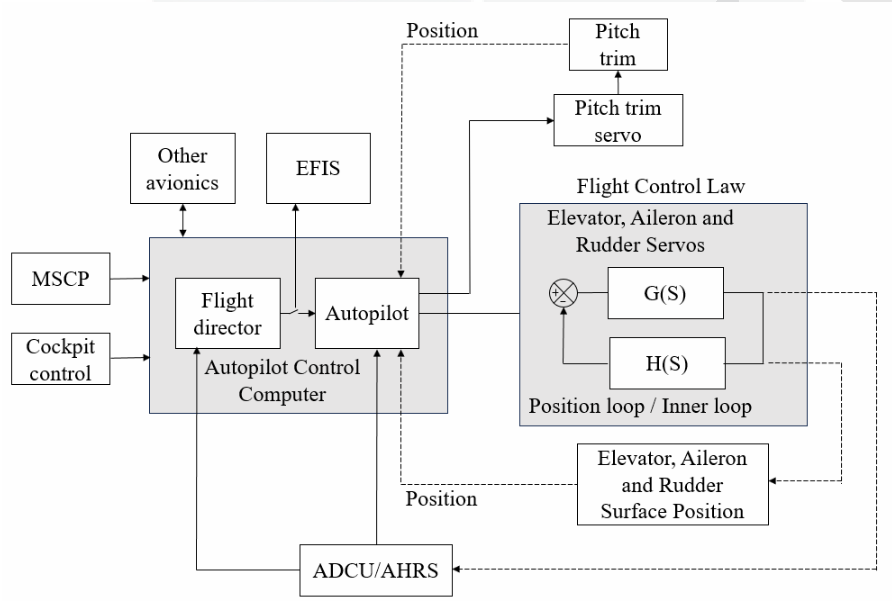


**Figure 1.2: General overview of a Automatic Flight Control System (AFCS).** (Source: Jeppu, 2014)

The advances in control theory and computing technology have been instrumental in facilitating the required improvements in AFCS. This has allowed AFCS to become more sophisticated and capable of performing more complex tasks, such as automated take off and landing, autonomous flight, and collision avoidance, for which it has provided a theoretical foundation for the development of AFCS.

Flight control laws are embedded in AFCS for manipulating control surfaces or desired control signal (refer Figure 1.2). It employs various control solutions or methods to ensure stable aircraft operation such as Proportional-Integral-Derivative (PID), a linear type controller with PID gains which can either be tuned manually with constant gains (Stevens and Lewis, 2003) or by automatic tuning for variable gains (Wahid and Hassan, 2012; Mohammad Salem, 2014; Deepa and Sudha, 2016) to get a better control and enhancement in the performance. Despite its simplicity in many applications, PID control struggled with highly nonlinear systems or those with significant time delays. As an alternative, gain scheduling was adapted (Stilwell, 2001) and has evolved significantly in aircraft autopilot systems since its inception (Saussié et al., 2011; Mendez-Vergara et al., 2014).

In managing such a nonlinear system, various nonlinear control approaches have been introduced for autopilots, including model predictive control (MPC). It utilizes a dynamic model to predict system behavior and adjust control inputs to achieve desired control objectives. But it suffers from drawbacks such as being computationally intensive and requiring accurate modeling (Simon et al., 2014). Another type of nonlinear control in dealing with nonlinearities is nonlinear dynamics inversion (NDI) as reported in (Enns et al., 1994; Ghosh and Tomlin, 2000). Similar to MPC, apart being sensitive to model mismatch, it is said to be not robust due to internal stability of the system (Alam and Celikovsky, 2017; Jia et al., 2018). Therefore, sliding mode control or SMC (Devika and Thomas, 2018), and backstepping (Sartori et al., 2021) were explored to achieve robustness. However, backstepping control methods typically require recursive development for the controller, which can pose challenges for a complex nonlinear system (Tran and González, 2020).

In some occasions,an autopilot disengagement can occur for several reasons, including manual override, system malfunctions, upset flight conditions, or at the command of the pilot (Schroeder, 2016). An upset happens when an aircraft enters a flight regime beyond its normal operating parameters, characterized by highly dynamic conditions involving rapid changes in attitude, altitude, and airspeed. This situation can lead to stall or loss of control (LOC) if not promptly addressed. Considering this, it is essential to design autopilot systems capable of managing such challenging flight conditions to ensure the safety and stability of the aircraft throughout all phases of flight and to mitigate the risk of human error.

Similarly, as an aircraft reaches a large angle of attack, i.e., nearing the stall angle, it demonstrates unpredictable behaviour that may compromising the safety and performance of the aircraft (Wang and Shi, 2010). Capturing these nonlinearities into a model poses a significant challenge as there are uncertainties in its aerodynamic properties and not straightforward (Tol et al., 2016). As a result, control laws based on linearised models become inadequate. An alternative strategy is to employ nonlinear design techniques, particularly in this critical flight conditions where the nonlinearities of the aircraft become pronounced. In parallel to the development of AFCS, there is growing interest in equipping AFCS to have the capability to perform beyond this regime, which can be advantageous in situations where a human pilot may not have the capacity to respond quickly or where precise control is critical (Bailey, 2021).

## 1.2 Problem Statement

An aircraft mission such as a climbing manoeuvre can be complex due to the dynamic and nonlinear nature of the flight conditions. The aircraft experiences changes in altitude, airspeed, and angle of attack during the climb, leading to significant variations in its dynamic responses. As a result, accurately following a predefined trajectory and maintaining stability and control during the climb have garnered significant attention (Buelta et al., 2022). The subsequent paragraphs will elaborate more factors on challenges in maintaining flight at such conditions.

While linear models can be used to approximate nonlinear systems, they are limited in their ability to accurately capture the behaviour of the system, especially under nonlinear conditions (Abdulhamitbilal, 2014; Tol et al., 2016). Thus, nonlinear aircraft models are needed for precise aircraft behaviour predictions to effectively design a control system. However, due to limited access to the complete aerodynamics model, modeling inaccuracies are expected due to the aerodynamic uncertainties. It should be taken into account as it confers the desired performance over the entire operating range.

Concurrently, invertibility of the input-output dynamics in a system is crucial for ensuring precise trajectory tracking. However, the aircraft system is categorized as a nonminimum phase system, indicating the presence of unstable zero dynamics that cannot be precisely canceled (Alam and Celikovsky, 2017). Failure to carefully address this non-minimum phase condition may lead to instability in the internal dynamics of the system.

Thus, nonlinear control is necessary to address these issues. However, NDI methods alone seem to encounter challenges in effectively handling the inherent nonlinearities, while backstepping tends to aggravate the complexity of the problem. The lack of effective control solutions in existing systems significantly hinders a robust aircraft performance, especially during near stall conditions.

On the other hand, the implementation of sliding mode control (SMC) on a nonlinear aircraft model has promised robustness due to its insensitivity to modelling inaccuracies, nonlinearities and reduction in the complexity of feedback design (Shtessel et al., 2013). The sliding surface may be chosen from the state variables according to the control objective and the desired performance specifications. However, tracking the climb profile of an aircraft can be daunting due to the multiple sliding variable options, such as the angle of attack and the pitch angle, that can affect the tracking performance (Salahudden et al., 2021). Therefore, a question on how the selection of a sliding variable impacts the control objective is an important consideration.

The effectiveness of SMC as a nonlinear control approach has been widely acknowledged, outperforming traditional linear control methods in various scenarios. As such, there is considerable interest in exploring whether SMC can be utilized to achieve high climb rates or steep attitude angles, even in the face of challenging nonlinear conditions typically encountered during manoeuvres in challenging conditions. This potential application of SMC is particularly intriguing given its proven advantages, such as reducing landing distances as demonstrated in previous studies (Ramamurthi et al., 2016). Thus, there is optimism that SMC could offer significant benefits in improving the aircraft performance in demanding flight conditions.

Nevertheless, the application of high gain SMC has been observed to detrimentally affect aircraft performance due to the chattering effect (Devika and Thomas, 2018; Raza et al., 2022). Therefore, it is imperative to explore variations of SMC to mitigate this effect while enhancing aircraft performance. However, the integrator approach, as implemented by Mukherjee et al. (2016), is susceptible to integrator windup prompting a need for improvements in the SMC approach. For these reasons, it is essential to develop a nonlinear aircraft model to address the aforementioned issues. Having a comprehensive nonlinear simulation model provides a valuable opportunity to validate and test SMC design methodology, ensuring its applicability across all flight conditions.

## 1.3 Research Objectives

The aim of this thesis is to employ a robust control in maintaining satisfactory flight performance of an aircraft during challenging manoeuvres that requires rapid changing in attitude, altitude and velocity in the tracking process. The controller should be able to provide robust performance and stability margins while maintaining the desired performance parameters and the necessary safety criteria despite the nonlinearities in the model. Stated below are the objectives that have been highlighted:

a) To develop a mathematical model of nonlinear aircraft flight dynamics, comprising equations of motion and relevant flight parameters, and incorporating the effects of saturation and rate limiting from the aircraft actuator model.
b) To design and implement a sliding mode control or SMC, integral sliding mode control or ISMC and non-singular terminal sliding mode control or NTSMC for the developed aircraft model, encompassing the SISO and MIMO model for affine model.
c) To investigate optimal flight control performance by designing manoeuvre scenarios affecting angle of attack, pitch angle, and thrust, while assessing the final values for all the state variables.

## 1.4 Research Overview

The overall research flow is illustrated as in Figure 1.3. It commences with a thorough exploration on the background, clarifying the motivation for the study within its broader context. This involves a detailed review of existing literature to understand the current knowledge, theories, and methods relevant to the research topic. The objectives were established in guiding the focus and scope of the research. These objectives serve as a roadmap, to outline specific goals related to aircraft modeling and robust control design.

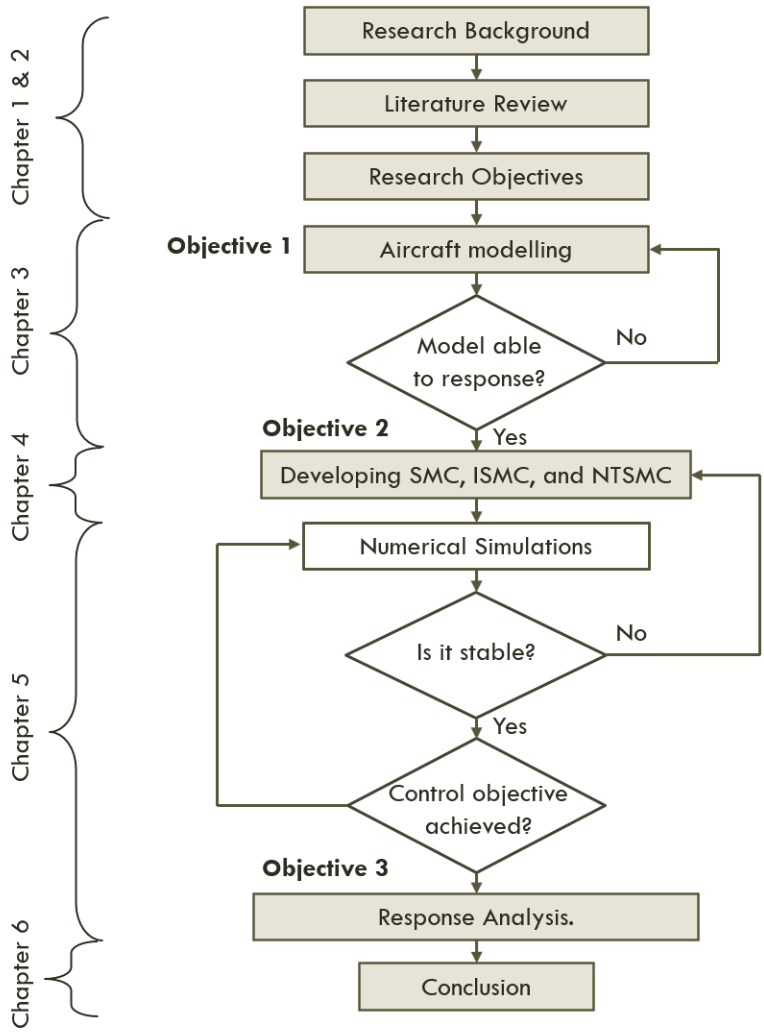


**Figure 1.3: Research overview.**

The first objective focuses on aircraft modeling, involving the development and verification of a mathematical model to represent the dynamics of the aircraft. This process entails building a model based on theoretical principles and collected aerodynamic data, followed by rigorous testing and verification to ensure its reliability. If errors are identified for example, the run simulation failed during verification, the model is revised and updated accordingly before proceeding with the next step.

Once a mathematical model is set up, various analyses can be performed, including numerical trim analysis depending on the flight conditions and control input setting of the model while taking into account aircraft parameter changes. The dynamics of the system can be learned from the eigenvalue structure from the open-loop analysis, thus allowing the control and stability of the aircraft to be further designed. With the information provided, the operating envelope of the aircraft can also be defined. Then the cross-coupling effect in the longitudinal and lateral-directional directions can be investigated through the numerical simulation.

Based on the information from the eigenvalue analysis, the research progresses to the second objective, which involves the design and implementation of robust control strategies. This includes developing various control techniques such as Sliding Mode Control (SMC), Integral Sliding Mode Control (ISMC), and Nonlinear Time-Scale Modeling (NTSM) as well as the PID controller as the benchmark controller. These control strategies are then integrated into the nonlinear aircraft model and subjected to numerical simulation to evaluate their effectiveness in stabilizing the aircraft and achieving desired performance objectives.

The response analysis involves running simulations to assess the stability and performance of the control designs under various operating conditions. If instability is observed, the control parameters are adjusted iteratively until satisfactory results are achieved. Once the control objectives are met, the research proceeds to analyze the system's response to the designed control inputs, evaluating its dynamic behavior and performance characteristics. The results are compared between each controller that has been developed by assessing their performances.

Lastly, the research was concluded based on the findings. Additionally, the limitations of the study are acknowledged, providing opportunities for further refinement and expansion of the research in subsequent studies.

## 1.5 Scope

Previous applications of SMC to aircraft tracking controls have been limited to linearised aircraft models and often do not consider the dynamics of the actuators. This thesis aims to address these limitations by considering both factors and developing a control strategy that includes multi-input multi-output (MIMO) control allocation to supply control more efficiently to the system at a near stall condition. The aim is to have a universal controller suitable for all flight conditions, spanning from take off to landing. By considering the full nonlinear dynamics of the aircraft and the actuator dynamics, the proposed control approach is expected to enhance the tracking performance and robustness of the system.

The focus of this thesis is a numerical study investigating the application of robust flight control techniques for a rigid wing aircraft. Specifically, the research examines the design and implementation of SMC, on the longitudinal aircraft model to ensure that the aircraft trajectory converges to predefined reference trajectories or desired states and remains within specified performance bounds, despite the nonlinearities inherent in the aircraft model. This encompasses the ability to adeptly adapt to varying conditions like airspeed, altitude, and manoeuvres while ensuring safety and desired performance. However, it is important to note that the nonlinear longitudinal model considered in this study is subjected to limitations, particularly with respect to the inputs from thrust and horizontal stabilator deflection only. Major works in the thesis are regarding take off and climbing scenarios where no significant contribution in lateral-directional mode as presented (Mukherjee et al., 2016). In contrast, this could not be enough in the case of an actuator failure that may causes the coupling between the longitudinal and the lateral-directional dynamics.

The chosen model aircraft for this study is based on the F/A-18, a large fighter aircraft with maximum take off weight (MTOW) about 30000 kg. It is recognized for its roles in supporting the research and enhancing pilot proficiency that was manufactured by Boeing (Dinius, 2009). The F/A-18 presents distinctive challenges due to its dynamic response, complex aerodynamic characteristics, and wide range of flight conditions. The stability and control properties of an aircraft have a substantial impact on its dynamic behavior, the origins of which can be traced back to the aerodynamics of the aircraft. For the purpose of building the model of the aircraft, the aerodynamic data was collected from the sources available in open literature. However, this data was subjected to the change of angle of attack, horizontal stabilator deflection, aileron deflection, rudder deflection, roll rate, pitch rate, and yaw rate for a 6-degree-of-freedom (DoF) model.

It is important to note that the work only involves the conceptual design of the controller, and practical implementation and validation are beyond the scope of this study. The following software tools are intended to be used during the research:

- MATLAB - a technical computer programming language and software platform developed by The MathWorks. It is widely used for numerical computing, data analysis, visualization, and simulation in various disciplines such as engineering, science, and mathematics.
- Simulink - a software tool developed by The MathWorks that works in tandem with MATLAB for simulation and model-based design. It is suitable for simulating nonlinear dynamic systems and designing novel control strategies.

Simulink comes equipped with a library of pre-installed blocks that can be used to represent models, and it can also be combined with user-defined MATLAB files to create custom functions.

## 1.6 Thesis Organisation

The thesis is composed of six chapters that document the various stages of the research conducted to achieve the predetermined objectives using methodological approaches. A brief summary of the contents of the thesis is given as follows:

Chapter 1 serves as an introduction to the thesis topic, setting out the aims and objectives of the research project. The chapter provides an overview of the research problem and its significance and outlines the scope of the thesis. It establishes the foundation for subsequent chapters.

In Chapter 2, a literature survey is conducted on previous studies related to the development of aircraft simulation models and aircraft control. The chapter provides a detailed overview of the existing literature in the field and highlights the key findings and contributions of each study.

Chapter 3 details the development of a mathematical aircraft model. It describes the kinematic and dynamic model for a fixed-wing aircraft and the collected aerodynamics data used for the model from the public domain. Additionally, modal analyses were conducted to study the aircraft's longitudinal and lateral-directional behavior.

Chapter 4 begins with a review of the mathematical preliminaries of sliding mode control (SMC). The chapter also presents the design of a flight control system based on SMC and its variants, such as integral sliding mode control (ISMC) and nonlinear terminal sliding mode control (NTSMC), for both single-input single-output (SISO) and multiple-input multiple-output (MIMO) aircraft models. The design methodology is thoroughly elaborated to provide a comprehensive understanding of the effectiveness of the proposed control approach.

In Chapter 5, the control design from Chapter 4 is applied to the aircraft model presented in Chapter 3. The chapter describes the numerical simulations that were conducted to evaluate the control system's performance, and the results of the simulations are thoroughly discussed.

Finally, Chapter 6 highlighted the research's main findings and consequences and discussed its shortcomings and limits. Additionally, recommendations for future research directions were provided.

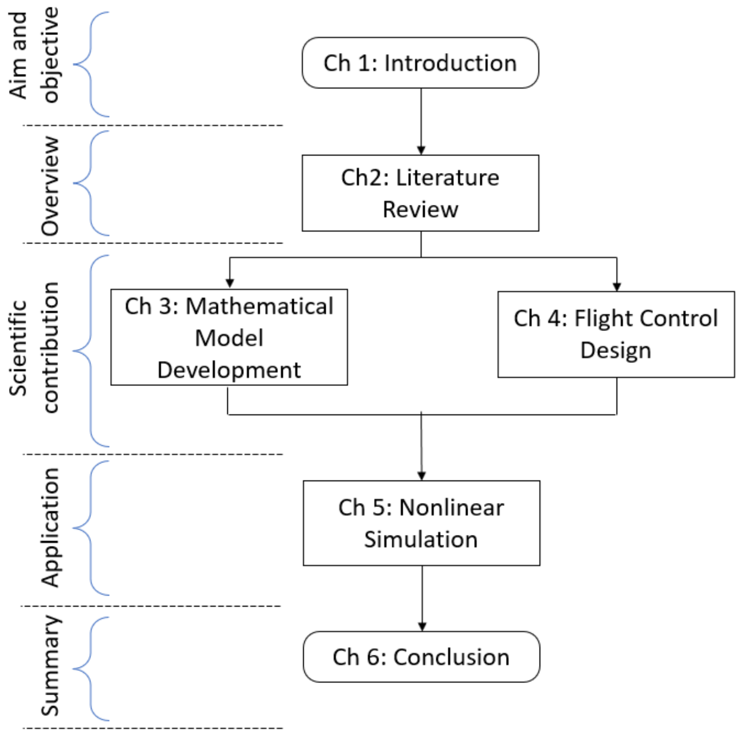


**Figure 1.4: Organisation of the thesis.**

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