



MEKELLE INSTITUTE OF TECHNOLOGY UNIVERSITY

**INTEGRAL SLIDING MODE CONTROL OF STEER
BY WIRE SYSTEM**

By

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Approval Page

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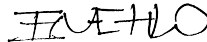


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
Declaration

I hereby declare that the thesis entitled “**Integral Sliding Mode Control of Steer by Wire System**” was prepared by me under the supervision of my advisor. In addition, I declare that any non-original sources used in this work have been properly acknowledged. This thesis work has not been submitted to any other University or Institute for the award of a degree or professional qualification.

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Dedication

Dedicated to

My parents, for their patience and guidance.

Especially to

My dearest mother, for her unending love, appreciation,

And

Her tremendous contribution to my education and success.

Acknowledgment

First, I would like to thank the Almighty God, for blessing me with aptitude, courage and strength to successfully complete my MSc. Thesis work.

I would like to express my deep gratitude and thanks for to my advisor **Dr. Ing. Gebremichael Te-ame (PhD)** with department of Electrical and computer engineering in Adama Science and technology university, Ethiopia), for his irreplaceable guidance and constructive comments.

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Special thanks go to my parents for their unconditional love, support and scarification showered on me throughout my life. The opportunities that they have given me are reasons for my being where I am and what I have accomplished so far.

Abstract

This thesis presents the design and simulation of an Integral Sliding Mode Controller (ISMC) for a Steer-by-Wire (SBW) system, aimed at achieving robust and precise steering control under uncertainties such as parameter variations, external disturbances, and varying road conditions. The proposed system tackles these challenges by integrating a sliding surface with an integral action, enhancing transient performance and disturbance rejection. The dynamic model of the SBW system, including actuator and steering mechanics, is explicitly developed prior to simulating the controller. The ISMC is formulated by designing a nominal control law based on the ideal dynamics of the SBW system, disregarding uncertainties. A switching control action is then incorporated to handle matched uncertainties, ensuring that performance criteria optimized under the nominal model remain unaffected. To further improve the system, a boundary layer is introduced to mitigate chattering, resulting in smooth and efficient control actions. Comparative analysis with Conventional Sliding Mode Control (SMC) demonstrates the ISMC's superior tracking accuracy, robustness, and ability to reject disturbances. MATLAB Simulink simulations confirm the effectiveness of the ISMC under various road conditions, including wet asphalt, snowy, and dry asphalt roads. Additionally, the asymptotic stability of the SBW system is verified using Lyapunov stability theory, ensuring the reliability of the proposed control strategy for modern automotive applications.

The simulation results highlight the effectiveness of the proposed ISMC in maintaining precise and robust steering performance across diverse road conditions. The enhanced tracking accuracy, reduced chattering, and improved disturbance rejection capabilities demonstrate its potential for practical application in modern steer-by-wire systems. This study provides a strong foundation for further research and development, paving the way for advanced control strategies in next-generation automotive steering technologies.

Keywords: Steer-by-Wire, Sliding Mode Control, Integral Sliding Mode Control, Robust Control, Automotive Applications.

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List of Acronyms

ISMC	Integral Sliding Mode Control
SBW	Steer-by-Wire
SMC	Sliding Mode Control
PID	Proportional-Integral-Derivative
LQR	Linear Quadratic Regulator
DOF	Degree of Freedom
RMS	Root Mean Square
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
MATLAB	Matrix Laboratory
HPS	Hydraulic Power-Assisted Steering
ADAS	Advanced Driver-Assistance Systems
EHPS	Electro-Hydraulic Power-Assisted Steering
FTC	Fault-Tolerant Control
EPS	Electric Power-Assisted Steering
ECU	Electronic Control Unit
PMSM	Permanent Magnet Synchronous Motor

List of Nomenclature

J_{sm}	.....	Moment of inertia of the steering motor
B_{sm}	.....	Viscous friction of the steering motor
θ_{sm}	.....	Angular position of the motor shaft
τ_{12}	.....	Torque applied to the motor shaft by the front wheels
u	.....	Torque control input
τ_{dis}	.....	Motor torque pulsation disturbance
τ_{sm6}	.....	6th harmonic torque amplitude
τ_{sm12}	.....	12th harmonic torque amplitude
p	.....	Number of poles in the motor
θ_e	.....	Electrical angle of the rotor
Δ_{ia}	.....	DC current offset in phase aa
Δ_{ib}	.....	DC current offset in phase bb
φ	.....	Constant angular displacement due to current offsets
J_{fw}	.....	3Moment of inertia of the front wheel
B_{fw}	.....	Viscous friction of the front wheel
δ_f	.....	Front wheel steering angle
τ_s	.....	Torque transmitted to the front wheel steering arm
τ_e	.....	Self-aligning moment generated by tire cornering forces
τ_f	.....	Coulomb friction in the motor assembly and steering system
F_s	.....	Coulomb friction constant
$\text{sign}(\delta_f)$	.....	Sign of the derivative of the front wheel steering angle
J_{eq}	.....	Total equivalent inertia of the SBW system
B_{eq}	.....	Total equivalent damping coefficient of the SBW system
J_h	.....	Hand-wheel column moment of inertia
B_h	.....	Viscous friction coefficient of the hand-wheel column
C_h	.....	Stiffness coefficient of the hand-wheel column
θ_h	.....	Angular position of the hand-wheel

τ_r	Feedback torque from the feedback motor
τ_h	Driver input torque
u_0	Nominal feedback controller (NFC)
u_1	Compensator for lumped uncertainty
s	Linear sliding variable
ϵ_θ	Angular tracking error
λ	Positive constant in sliding surface design
V	Lyapunov function
σ	Auxiliary sliding variable
z	Auxiliary variable in sliding mode control

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Appendix A: MATLAB function

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Chapter one

INTRODUCTION

1.1 Background

With the rapid advancement of vehicle control technology, there has been a significant emphasis on the development of innovative systems such as the four-wheel independent steer systems and even in-wheel motor auxiliary automated driving technology. However, as the capabilities of these advanced systems increase, so do the safety and security requirements for vehicles. Among the crucial components that play a vital role in ensuring the safety of vehicles is the steering system[2] .

To meet the increasingly stringent safety standards, it is imperative to expand the vehicle steering range and establish direct communication between the driver and the vehicle. The traditional breakpoint-type mechanical steering system, although widely used, has its limitations. It exhibits limited amplification characteristics, slow response speed, and lacks direct sensory perceptions. Consequently, these drawbacks make it challenging to fulfill the optimization requirements of the overall system. On the other hand, electric power steering systems have shown remarkable potential. They offer excellent flexibility, allowing for easy software upgrades, and present energy-saving advantages[3], [4].

Nevertheless, they do have their shortcomings. One notable drawback of electric power steering systems is the absence of sensory feedback, which can hinder the driver's ability to accurately perceive the conditions and nuances of the road. Additionally, these systems lack security redundancy, which is essential for maintaining a safe and reliable vehicle operation. Addressing these concerns and improving upon the existing steering systems is indispensable in ensuring utmost safety and security while providing enhanced driving experience. Innovation and research in the field of vehicle control technology strive to leverage the benefits offered by electric power steering systems while overcoming their limitations through intelligent solutions [3], [5]. By incorporating sensory feedback mechanisms into electric power steering systems, it is possible to fulfill the driver's need for a direct and intuitive connection with the vehicle, allowing for a heightened sense of control. Furthermore, advancements in safety redundancy measures can be implemented, ensuring the reliability and fault-tolerance of the steering system, even in adverse conditions. The continuous enhancement

of vehicle control technology will undoubtedly pave the way for the development of advanced steering systems that offer a balanced combination of performance, safety, and security. It is through such advancements that future vehicles will be equipped with innovative steering systems that provide optimal control, responsiveness, and reliability, all while meeting the ever-increasing requirements for safety and security [6].

The steer-by-wire system replaces the intermediate steering mechanism with a control unit and multicore wires, realizing communication between the steering actuator and the whole vehicle control system. The system has characteristics of simple mechanization, design flexibility, adjustable auxiliary force, and a disposable derailing system, and it can also provide multiple levels of direct sensory feedback. Thus, it's the development trend of car steering systems in the future. However, these electronic servo control systems are composed of complex computer programs and data communications, and control system errors may lead to system paralysis. If the system fails, the consequences are unimaginable. Research on vehicle steering safe backup systems has important practical significance. The drive-by-wire system should be designed to take into account the driver's potential misuse or system failure, ensuring that it can still maintain the original function in the event of a fault in the control system. The safety control recovery process is achieved through the mechanical connection between the control end and the vehicle mechanical system[7].

The automobile industry is approaching the generation of autonomous vehicles equipped with various driving assist technologies and functions of infotainment systems. The steering system is one of the essential parts of the automobile. Depending on the degree of automation, vehicles are expected to become more complex because each vehicle steering mode requires a different steering system layout. Vehicle steering systems used today can generally be of two basic types: manual and assistance. The assisted systems are designed to help the driver in turns, while a manual system requires a physical connection between the steering wheel and the road wheel. In a steer-by-wire system, there is no mechanical connection between the manual steering and the wheels[8].

The steer-by-wire system has advantages in various respects. However, new challenges have appeared as it is necessary to guarantee the safety of the system. Some fault-tolerant control strategies have been developed for steer-by-wire systems. A fault-tolerant control strategy using the integral sliding mode control in order to guarantee nominal performance in the case

of stuck faults of the motor and sensor faults is presented. Simulations and experimental results show the effectiveness and applicability of the proposed methodology [9].

The advent of steer-by-wire (SBW) systems marks a revolutionary shift in automotive technology, replacing traditional mechanical and hydraulic linkages with fully electronic systems for steering control. SBW technology eliminates the physical connection between the steering wheel and the road wheels, using electronic actuators and sensors to execute and monitor steering commands. This innovation provides enhanced design flexibility, weight reduction, and the potential for improved vehicle performance and safety. However, the reliance on electronic systems introduces vulnerabilities to faults and failures, which could compromise safety and reliability. Consequently, the development of robust fault-tolerant control (FTC) strategies has become a critical focus in the advancement of SBW systems[10].

The significance of SBW systems lies in their ability to support modern vehicle dynamics, such as advanced driver-assistance systems (ADAS), autonomous driving technologies, and customizable driving experiences. By eliminating mechanical linkages, SBW systems enable innovative design opportunities, such as adjustable steering ratios and active vibration damping [6]. Despite these benefits, the inherent complexity of electronic control systems poses challenges in ensuring their reliability and safety. Faults in sensors, actuators, or communication links can lead to catastrophic outcomes, necessitating rigorous fault detection, isolation, and compensation mechanisms.

1.2 Problem Statement

Steer-by-Wire (SBW) systems, which eliminate the traditional mechanical linkage between the steering wheel and the vehicle's wheels, are critical for modern and autonomous vehicles due to their flexibility, weight reduction, and enhanced integration with advanced driver-assistance systems. However, the reliance on electronic components such as sensors, actuators, and controllers makes these systems highly susceptible to faults, including sensor inaccuracies, actuator malfunctions, and communication delays. These faults can significantly compromise the reliability, safety, and performance of SBW systems, posing risks in safety-critical automotive applications. Traditional control strategies often fall short in addressing these challenges comprehensively, particularly under conditions of simultaneous or unexpected faults. There is a pressing need for a robust control approach that ensures system reliability, fault resilience, and optimal performance under such conditions. This research proposes the integration of Integral Sliding Mode Control (ISMC) with fault-tolerant features to address

these challenges, providing a scalable and efficient solution validated through comprehensive simulation.

1.3 Objective

1.3.1. General Objectives

The prime objective of this master thesis is to design an Integral Sliding Mode Controller (ISMC) for a Steer-by-Wire (SBW) system to achieve robust and precise steering control under various uncertainties, such as parameter variations, external disturbances, and road condition changes.

1.3.2. Specific Objectives

The study in this thesis will address the following specific objectives:

- To develop the dynamic model of the SBW system
- To design the proposed Integral Sliding Mode Controller.
- To verify the asymptotic stability of the SBW system through Lyapunov stability
- To validate the performance of the proposed system using MATLAB Simulink.

1.4 Significance of Study

To the best of my knowledge, no researcher has attempted to design and simulate an Integral Sliding Mode Controller (ISMC) for a Steer-by-Wire (SBW) system while addressing the combined challenges of parameter variations, external disturbances, and varying road conditions. The proposed ISMC strategy offers inherent advantages, such as superior tracking accuracy, robustness to matched uncertainties, and mitigation of the chattering phenomenon in control inputs. These features are particularly significant in improving system efficiency and ensuring smooth and reliable steering control without imposing excessive torque demands on the steering motor.

The inclusion of a boundary layer in the ISMC effectively reduces chattering, overcoming one of the most significant challenges in adopting conventional sliding mode control strategies for real-world applications. This not only enhances the robustness of the system but also extends the lifespan of steering actuators by minimizing wear, heat generation, and stress in the mechanical components and power circuits.

Additionally, the ISMC ensures that performance requirements optimized based on the nominal SBW model remain unaffected even in the presence of uncertainties, enabling consistent and reliable operation across a wide range of driving conditions. The proposed control strategy is validated under various road conditions, such as wet asphalt, snowy, and dry asphalt roads, demonstrating its effectiveness in maintaining robust steering control and enhancing automotive safety.

In general, this study contributes to the advancement of robust control methodologies for SBW systems, offering a practical and efficient solution for modern automotive applications. The findings and methods presented in this thesis can serve as a foundation for future researchers and students, inspiring further innovation in the development of robust and efficient control systems for automotive and related fields. This work is particularly valuable for underdeveloped nations where precision-designed systems are not widely available, providing an accessible and reliable approach to improving automotive performance and safety.

1.5. Thesis Organization

This thesis is structured as follows:

Chapter 2 presents a comprehensive review of existing control strategies for SBW systems, with a particular focus on Sliding Mode Control (SMC) and its variations. It identifies gaps in the current research and justifies the need for developing an Integral Sliding Mode Controller (ISMC) to enhance steering performance and robustness.

Chapter 3 details the modeling of the SBW system, including the development of dynamic equations for both the actuator and the steering mechanics. It lays the groundwork for controller design by establishing the mathematical representation of the system dynamics.

Chapter 4 outlines the design of the proposed controller. It describes the development of a nominal control law based on the ideal dynamics of the SBW system, as well as the integration of a switching control action to address matched uncertainties. The chapter also discusses the introduction of a boundary layer to mitigate chattering, ensuring smooth and efficient control actions.

Chapter 5 presents the simulation results of the proposed ISMC under various road conditions, including wet asphalt, snowy, and dry asphalt roads. A comparative analysis with Conventional Sliding Mode Control (SMC) is performed to evaluate the performance of the ISMC in terms of tracking accuracy, robustness, and disturbance rejection. The effectiveness and stability of the control strategy are validated through MATLAB Simulink simulations.

This final chapter summarizes the key findings of the thesis, emphasizing the advantages of the proposed ISMC in achieving robust and precise steering control. It also provides recommendations for future work, including suggestions for hardware implementation and further optimization of the control strategy.

Chapter two

Literature Review

This chapter provides an in-depth review of the existing literature to establish a comprehensive understanding of the challenges and advancements in Steer-by-Wire (SBW) systems and their control strategies. The chapter begins with a detailed exploration of SBW systems, including their structure, operational principles, and the technological shift from traditional mechanical steering systems to fully electronic configurations. The advantages of SBW systems, such as enhanced design flexibility, weight reduction, and seamless integration with advanced driver-assistance systems (ADAS) and autonomous driving technologies, are discussed alongside the challenges they face, including reliability concerns, sensitivity to faults, and safety-critical implications.

Following this, the discussion transitions to Sliding Mode Control (SMC), a robust control methodology particularly suited for nonlinear systems like SBW. The fundamental principles of SMC are explained, emphasizing its robustness to disturbances and parameter variations, making it a promising candidate for SBW applications. However, the limitations of SMC, such as the chattering phenomenon, its impact on actuator life, and energy inefficiency, are also examined. Strategies to mitigate these limitations, including advanced chattering reduction techniques and higher-order SMC approaches, are reviewed to highlight their potential in enhancing SBW performance.

The chapter further delves into fault-tolerant control (FTC) strategies, which are crucial for maintaining the reliability and safety of SBW systems in the presence of faults such as sensor errors, actuator malfunctions, and communication delays. The integration of FTC with SMC is explored, focusing on its potential to create a unified framework capable of addressing the unique challenges of SBW systems. Additionally, the role of fault modeling in accurately simulating real-world fault scenarios and its importance in designing effective control strategies is discussed.

Energy efficiency, a growing concern in modern vehicle systems, is also reviewed in the context of SBW systems and SMC-based control approaches. The chapter highlights the need for control strategies that balance robustness with energy optimization, particularly for electric and hybrid vehicles where power efficiency is critical.

Finally, the chapter identifies the existing research gaps, including the limited integration of fault-tolerant features in SMC for SBW systems, the need for advanced and realistic fault models, and the lack of scalable solutions that address simultaneous faults and energy efficiency. These gaps underline the necessity for innovative research to enhance the reliability, robustness, and efficiency of SBW systems, providing the foundation for the proposed study.

2.1. Steering System

Vehicle technology has undergone significant advancements over time, leading to notable improvements in efficiency, safety, and overall performance. Among these advancements, the evolution of steering systems has been particularly transformative, progressing from purely mechanical systems to fully electrical configurations [11], [12]. Initially, mechanical steering systems relied on components like the steering wheel, column, gear, and rack and pinion to transmit driver commands to the tires and ensure they followed the desired path. These systems required considerable physical effort from the driver, as they lacked any form of power assistance [12], [13].

The introduction of **Hydraulic Power-Assisted Steering (HPS)** in 1951 by Chrysler Imperial marked a groundbreaking development in steering technology. By incorporating hydraulic systems, HPS significantly reduced the physical effort required by drivers, provided faster response times, and improved stability and safety. Additionally, the hydraulic mechanism minimized vibrations transmitted to the steering wheel, enhancing the driving experience. However, the high design, assembly, and maintenance costs of HPS led to the development of **Electro-Hydraulic Power-Assisted Steering (EHPS)**. This system replaced the conventional pulley-driven hydraulic pump with an electrically powered pump, which reduced fuel consumption and allowed operation even when the engine was off. EHPS was a significant improvement, with fuel efficiency gains of up to 1% for commercial vehicles during long-haul operations, but it still faced challenges such as limited design flexibility and reliance on hydraulic oil [6].

In 1996, **Electric Power-Assisted Steering (EPS)** was introduced as a commercial alternative that eliminated many of the environmental and acoustic issues associated with hydraulic systems [14]. EPS uses a compact electric motor that operates on a power-on-demand basis, further improving fuel efficiency while offering enhanced steering functions. The motor could be positioned in various locations, such as on the steering column, rack, or pinion, providing flexibility in design. Initially, DC motors were prevalent in EPS systems due to their simplicity,

but advancements in power electronics, control techniques like field-oriented control and direct torque control, and the superior efficiency of permanent magnet synchronous motors (PMSM) led to a shift toward PMSM-driven systems. EPS gained widespread adoption in passenger vehicles because of its lower weight, compact design, reduced complexity, and minimal maintenance costs. Despite these advantages, EPS still faced limitations due to the continued reliance on a steering column, which restricted certain design possibilities[15] [16].

The latest evolution in steering systems is **Steer-by-Wire (SBW)**, which removes the mechanical connection between the steering wheel and the tires. SBW relies entirely on electronic components, replacing the traditional steering column with an electrical connection. This system offers several advantages, such as reducing the transmission of road vibrations to the steering wheel, thereby improving driver comfort [14]. SBW operates through two independent control loops: one manages the steering wheel, while the other controls the road wheels. The road wheel motor drive ensures accurate transmission of driver commands to the tires, while the steering wheel motor drive provides feedback to the driver, simulating the feel of road surfaces. These advancements make SBW systems highly promising for improving vehicle control, safety, and comfort, and they represent the forefront of modern steering technology[6], [17], [18], [19], [20].

2.2. Steer-by-Wire (SBW) Systems

Steer-by-Wire (SBW) technology replaces the mechanical connection between the steering wheel and the vehicle wheels with electronic control, enhancing design flexibility and enabling advanced driver-assistance systems (ADAS) and autonomous driving. This system eliminates components like the steering column and hydraulic fluids, reducing vehicle weight and energy consumption [18].

With advancements in the automotive industry, autonomous vehicles and self-driving systems have garnered significant attention in recent years. Their development serves various purposes, such as improving ride comfort, optimizing fuel efficiency, reducing pollution, and, most importantly, enhancing safety [21]. Autonomous vehicles operate independently, responding to their environment without requiring human intervention by perceiving and adapting to external conditions.

Industrial adoption of Steer-by-Wire (SBW) systems faces several significant challenges [17]. One major issue is their susceptibility to road disturbances, sensor noise, and unpredictable mechanical friction during operation, which complicates achieving precise tracking control. Furthermore, the removal of traditional mechanical components reduces system reliability, as it relies entirely on electronic subsystems. Additionally, SBW systems incorporate more electrical components compared to mechanical steering systems, which substantially increases the likelihood of system failures. As a result, steering angle tracking and the development of fault-tolerant control strategies have become critical areas of focus in SBW system research [22][17] [6] [17], [23].

2.3. SBW System Introduction

The next generation of steering systems in the auto manufacturing industry would be steer-by-wire (SBW) in which the mechanical connection between vehicle steering wheel and tires is removed [6]. Steer-by-Wire technology removes traditional steering columns, utilizes a steering motor to generate steering torques and a feedback motor to provide feedback torques for drivers [24]. Compared with the conventional steering systems in road vehicles, the SBW systems aim at providing a better overall steering performance, reducing the energy consumption, and further improving the passengers' safety and comfort [24]

The SBW system consists of two main subsystems, hand wheel subsystem and front wheel subsystem. The main duty of steering hand wheel subsystem is to receive the driver commands and to convert the demanded angle to an electronic signal using appropriate sensors located on steering hand wheel motor shaft. The electronic signal is transmitted via connection wires to electronic control unit (ECU) to determine a relevant command for the vehicle wheels motor drive. The ECU also receives other information from sensors on the front wheel subsystem to determine corresponding commands to be sent to the handwheel feedback motor[6], [25]. The electric motor in the steered front wheel subsystem receives commands from the ECU and attempts to change the front wheel angle accordingly.

The central issue on the performance of SBW systems is the steering robustness against parameter variations, external disturbances, and road condition changes [26]. Recently, several researchers have applied various methods to control the SBW system with the aim of achieving good steering performance. In [24], [27], [28], [29], [30]the conventional proportional-derivative (PD) was used with the aim of achieving good tracking performance. In [30], [31] a state feedback controller using the linear quadratic control technique was proposed to drive the

SBW motorcycle to track the reference steering signal. However, the disadvantage of the conventional feedback control is that the closed-loop system can be stabilized near the equilibrium, and the closed-loop performance may not be guaranteed as the road conditions have large uncertainties [26].

The utilization of sliding mode control technique is widely recognized in both linear and nonlinear systems for achieving tracking control and stabilization, especially when dealing with bounded uncertainty information. Sliding mode control technique was utilized in SBW systems in references [25], [26], [32] leading to good steering performance in the face of uncertainties in parameters and variations in road conditions. In reference [9] an SBW system was represented by a nominal model and an unknown portion. Then a nominal feedback controller was used to stabilize the nominal model, and a sliding mode compensator (SMC) was designed to remove the effects of both the unknown system dynamics and uncertain road conditions on the steering performance [26].

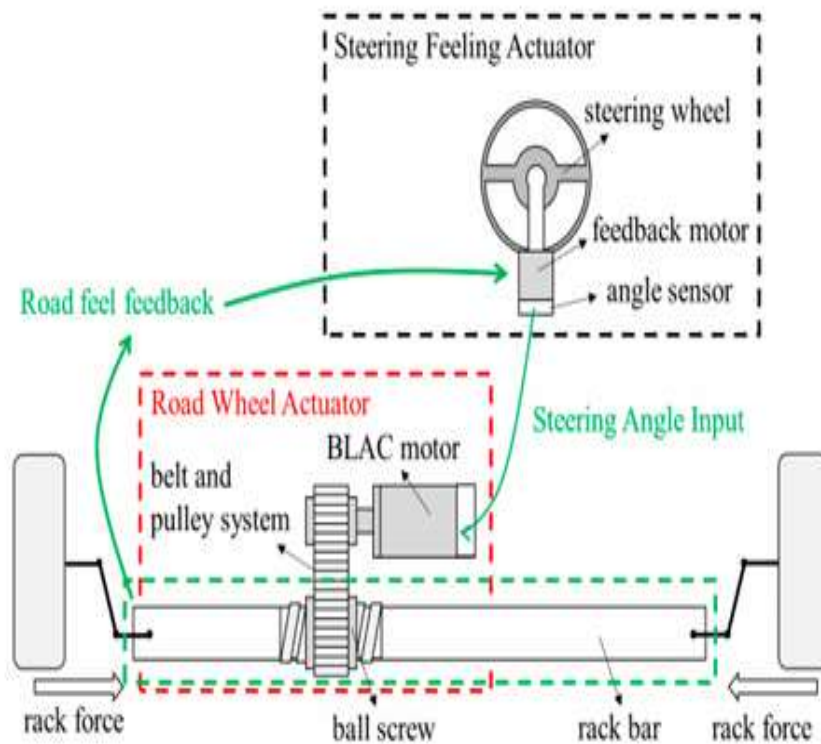


Figure 2. 1: Fundamental components of steer-by-wire system [33].

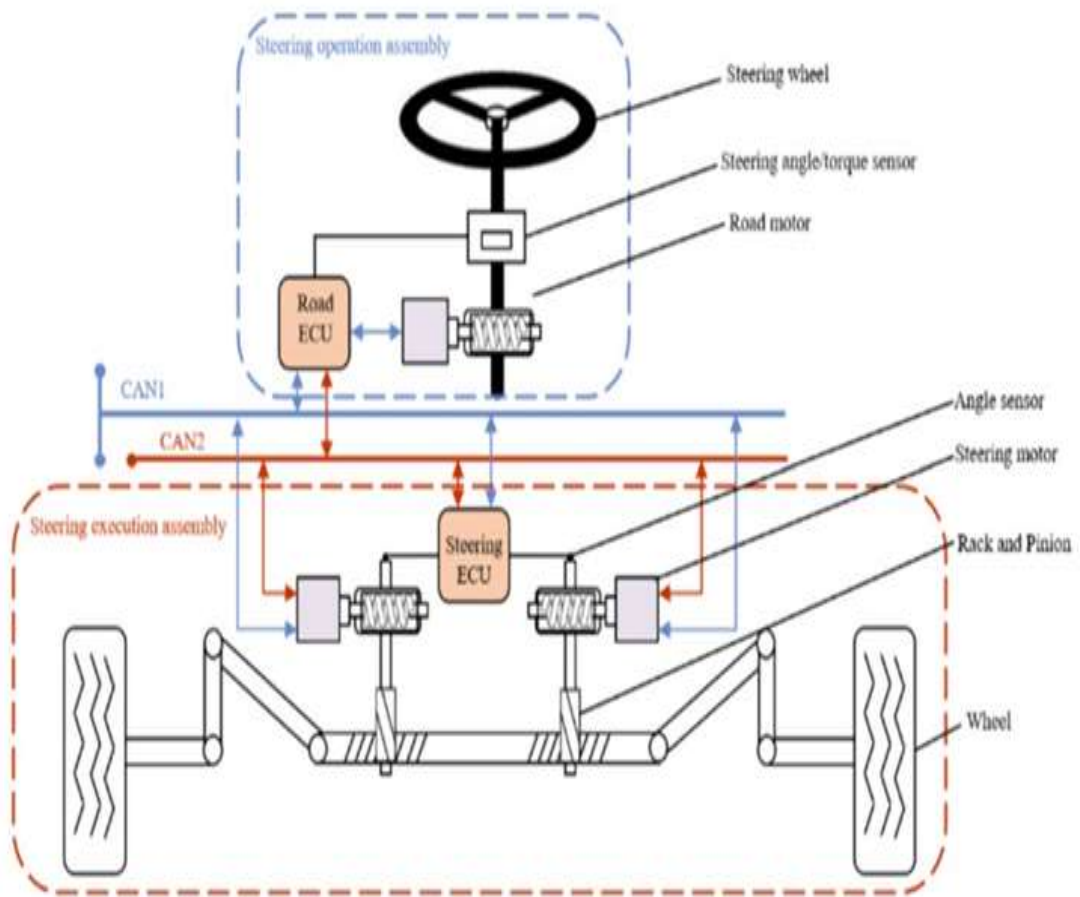


Figure 2. 2: Structure of dual-motor SBW system [34]

2.4. Fault-Tolerant Control (FTC) in Automotive Systems

In compliance with the ASIL-D standard, all components within a steering system, including sensors, communication links, power electronic converters, actuators, and microcontrollers, are required to exhibit fault-tolerance for at least one failure [35]. One widely adopted approach to achieve fault tolerance is duplication, which can be implemented through replication, redundancy, or diversity [36], [37]. Replication involves operating multiple identical units in parallel, while redundancy introduces additional similar units that are activated in the event of a critical failure. Diversity, on the other hand, entails using multiple dissimilar units with comparable functional specifications in parallel, ensuring operational integrity [37], [38]. To support these methods, fault detection and isolation mechanisms are crucial for identifying faulty units.

These mechanisms can be implemented using either signal-based or model-based. Although redundancy effectively reduces system failure rates, it also increases costs, weight, and volume, which can be undesirable for certain applications. Analytical redundancy offers a more efficient alternative, enhancing system reliability without adding physical components. This method relies on dynamic mathematical models, estimation techniques, or state observers to monitor system behavior and detect faults [35] [39]. For instance, Zheng utilized a dual motor and microcontroller architecture to enable fault tolerance against single-point failures and allow system self-reconfiguration [9]. Another approach, triple modular redundancy with a voting system, has been applied to steer-by-wire (SBW) microcontrollers to improve fault tolerance. Analytical redundancy, as proposed by Anwar, provides predictive fault-tolerant control for SBW systems. By leveraging dynamic modelling, an adaptive observer can estimate the road wheel angle based on motor currents, effectively replacing one of the redundant sensors with an analytical reading [40]. This model-based approach facilitates real-time fault diagnosis and system reconfiguration with minimal false alarms or missed detections, even in the presence of noise or model uncertainties [41].

The use of robust observers has also been investigated for handling faults such as power switch open-circuit failures and current sensor malfunctions in permanent magnet synchronous motor (PMSM) drives [42]. Fault-tolerant control strategies, like those proposed by Ito and Hayakawa, focus on reducing sensor redundancy while maintaining system safety through separate controllers [10]. Additionally, sensor less control techniques for motor drives have emerged as a promising solution to enhance reliability against position and speed sensor faults, further improving the resilience of SBW systems [8], [43]. These advancements underscore the

potential of analytical and model-based methods in overcoming the challenges of fault tolerance in modern steering technologies

Fault-Tolerant Control (FTC) is vital for safety-critical systems like SBW, ensuring continued functionality despite faults in sensors, actuators, or communication. FTC is categorized into passive and active strategies. Passive FTC designs the system to handle predefined faults without reconfiguration, while active FTC detects, isolates, and compensates for faults in real time. The integration of FTC in SBW systems is particularly challenging due to the high complexity of fault scenarios, such as simultaneous sensor and actuator failures. Developing an effective FTC strategy that leverages SMC's robustness can significantly enhance the reliability and safety of SBW systems.

2.5 Integral Sliding Mode Control

Sliding Mode Control (SMC) is a variable structure control approach that employs a switching control law to modify the plant dynamics, enabling the system states to follow a specific trajectory known as the sliding surface. This technique has found extensive applications in industrial informatics, as illustrated in [44], [45], [46], [47], [48]. The SMC process consists of two main phases: the reaching phase and the sliding phase [49]. During the reaching phase, the system states are directed to converge to a predefined sliding surface within a finite time. Once on the sliding surface, the closed-loop system transitions to a sliding mode, guiding the system states towards the origin along the sliding surface in what is termed the sliding phase. In this phase, the system's behavior becomes robust against both parametric and nonparametric uncertainties [49]. However, during the reaching phase, this robustness is not assured, and the system response may be susceptible to disturbances [50].

To address these limitations, Integral Sliding Mode Control (ISMC) eliminates the reaching phase by enforcing the sliding mode throughout the entire system response, ensuring invariance from the initial time instant [47]. Despite its advantages, the high frequency switching inherent in SMC can lead to chattering in control responses [51]. To mitigate this, ISMC employs a low-pass filter based on the equivalent control method, alongside modifications to the integral sliding variable to facilitate stability analysis, as demonstrated in [52]. This method has been successfully applied to joint position control in robotic manipulators and load pressure control in die cushion cylinder drives, as seen in [4]

A more widely adopted strategy to minimize chattering in ISMC involves integrating high-order SMC [3], [50], [53]. In high-order ISMC, the switching element is shifted to a time derivative of the sliding variable, thereby smoothing the control law through an integral [54].

Recent advancements in control strategies for Steer-by-Wire (SBW) systems have focused on enhancing robustness and performance under various uncertainties.. Notable studies include:

Abbas et al. introduced an AISMC designed to manage parameter variations in Vehicle Steer-by-Wire (VSBW) systems. This controller combines integral sliding mode control with adaptive mechanisms to address uncertainties without prior knowledge of perturbation bounds. The AISMC effectively handles system parameter uncertainties and eliminates the reaching phase in trajectory solutions, enhancing robustness and performance. The study primarily relies on simulations for validation. Experimental implementation is necessary to confirm real-world applicability.

Wang et al. developed an SMC scheme for SBW systems equipped with AC motors, modeling the system as a second-order equivalent and designing the controller to manage uncertain dynamics. The controller offers strong robustness against significant nonlinear system uncertainties, ensuring the front-wheel steering angle aligns asymptotically with the handwheel reference angle. The research is based on theoretical modeling and simulations. Practical implementation and testing are required to assess performance under real driving conditions.

Ye and Wang proposed a RAITSMC approach for SBW systems, incorporating an extreme learning machine to adaptively estimate and compensate for system uncertainties. This method enhances the system's ability to handle nonlinearities and external disturbances, improving overall stability and performance. The approach's complexity may increase computational demands, potentially affecting real-time implementation feasibility.

G.Shie et al. introduced a control strategy based on a terminal sliding mode rack force observer to enhance the steering feel authenticity in SBW systems. The strategy aims to improve driver experience by providing a more realistic steering feel, crucial for vehicle handling and safety. The implementation complexity and potential computational load of the terminal sliding mode observer may pose challenges for real-time applications.

Recent advancements in control strategies for Steer-by-Wire (SBW) systems have introduced various Sliding Mode Control (SMC) methodologies to enhance system performance and robustness. Notable studies include:

Researchers developed an ESO-FOSMC strategy to address uncertainties and external disturbances in vehicle SBW systems. The extended state observer estimates system uncertainties, while the fractional order sliding mode controller enhances robustness and control precision (Li et al., 2023).

This approach effectively compensates for system uncertainties and disturbances, improving steering performance and stability. The complexity of implementing fractional-order controllers and observers may increase computational demands, potentially affecting real-time application feasibility.

A study introduced an FTARSM control scheme for SBW automated guided vehicles to enhance robustness against uncertainties and improve steering performance. The controller adapts to system parameter variations within a fixed time, ensuring consistent performance (Chen et al., 2023). The FTARSM controller provides robust steering control, maintaining vehicle stability and maneuverability under varying operational conditions.

The fixed-time convergence and adaptive mechanisms may introduce complexity in tuning controller parameters, requiring careful calibration for optimal performance.

An article proposed a control strategy based on a terminal sliding mode rack force observer to enhance the authenticity of steering feel in SBW systems. This method aims to replicate the tactile feedback of traditional steering systems, improving driver experience (Zhang et al., 2024).

The strategy enhances driver perception by providing realistic steering feedback, crucial for vehicle handling and safety. Implementing terminal sliding mode observers may increase system complexity and computational load, posing challenges for real-time applications.

Researchers applied a sliding mode control algorithm to the angle tracking problem in SBW systems, utilizing a Proportional-Integral (PI) observer to estimate unmeasurable states and improve control accuracy (Wang et al., 2023).

The SMC algorithm effectively handles the nonlinear dynamics of SBW systems, providing precise angle tracking and improved system responsiveness. The reliance on state estimation may introduce errors, and the PI observer's performance is sensitive to parameter tuning, necessitating careful design considerations.

Chapter Three

Methodology

3.1. Introduction

This chapter outlines the methodology used for developing and validating Integral Sliding Mode strategies for steer-by-wire (SBW) systems. The approach is structured to address key challenges such as system stability, reliability, and fault tolerance through mathematical modelling, control design, and simulation validation. The foundation of this research lies in accurately modelling the SBW system's dynamics and faults while designing robust control strategies to ensure effective fault management.

The first step involves mathematical modelling, where state-space representations are developed to capture the dynamics of the SBW system. These models incorporate potential faults, such as sensor malfunctions and actuator failures, as well as external disturbances that might impact system performance. The models provide a comprehensive framework for analyzing the system's behavior under various operating conditions and fault scenarios.

Building on this foundation, controller design employs an integral sliding mode control strategy. This robust approach is chosen for its capability to handle uncertainties and disturbances, ensuring system stability even in the presence of faults. The design includes defining a sliding surface that guides the system states toward desired trajectories while mitigating the effects of faults and disturbances. Stability analysis, grounded in Lyapunov theory, is conducted to confirm the reliability of the control strategy under varying conditions.

To evaluate the effectiveness of the proposed strategy, a simulation framework is implemented using MATLAB/Simulink. The simulation tests the SBW system's performance across scenarios such as fault-free operation and fault-injected conditions. Metrics like tracking accuracy, stability, and fault recovery are analyzed to validate the robustness of the control design. This structured methodology ensures that the SBW system remains reliable and fault-tolerant, meeting the stringent demands of modern automotive applications.

In summary, this chapter provides a cohesive methodology for advancing Integral Sliding Mode in SBW systems. The combination of mathematical modelling, robust control design,

and simulation validation lays the groundwork for enhancing the safety and performance of these systems, focusing solely on simulation-based validation for comprehensive analysis.

3.2. Mathematical Modelling

The basic principle of an SBW system in road vehicles is shown in Fig. 1 [32]. It is seen that the SBW system can be divided into two parts: The upper part includes the handwheel, the handwheel angle sensor, and the feedback motor, respectively, and the lower part is composed of the steering motor, the pinion angle sensor, the rack and pinion gearbox, and the steered front wheels [8]. In this paper, for simplicity, the vehicle is represented by its bicycle model [8]. We then consider the modeling of the steering system from the steering motor to the two front wheels via the rack and pinion gearbox [26], [32].

The dynamic equation of the steering motor is given by [26], [32], [55].

$$J_{sm}\ddot{\theta}_{sm} + B_{sm}\dot{\theta}_{sm} + \tau_{12} = u + \tau_{dis} \quad (3.1)$$

where J_{sm} is the moment of inertia, B_{sm} is the viscous friction, θ_{sm} is the angular position of the motor shaft, τ_{12} represents the torque applied to the shaft of the steering motor by the front wheels via the rack and pinion gearbox, and u is the torque control input. And τ_{dis} represents the motor torque pulsation disturbance and is given by [32]: In this study, the front-wheel motor is a permanent magnet synchronous motor (PMSM). Flux harmonics and dc current offsets are the two main sources of τ_{dis} [25], [55], [56], [57], [58]

The expression of τ_{dis} is given by [25], [31], [54] [55], [56], [57].

$$\tau_{dis} = \tau_{sm6} \cos(6\theta_e) + \tau_{sm12} \cos(12\theta_e) + \frac{3p}{2} \psi_{d0} \frac{2}{\sqrt{3}} \sin(\theta_e + \varphi) \times \sqrt{(\Delta i_a^2) + \Delta i_a \Delta i_b + (\Delta i_b^2)} \quad (3.2)$$

Where τ_{sm6} and τ_{sm12} are the 6th and 12th harmonic torque amplitudes, respectively. And p is the number of poles (even number). And where θ_e is the electrical angle of the rotor that is related to the rotor mechanical angle as $\theta_e = \frac{p}{2} \theta_{sm}$, Δi_a and Δi_b are the dc current offsets in the measured currents of phases a and b, respectively, φ is a constant angular displacement depending on Δi_a and Δi_b [25], [31].

The rotation of the steered central front wheel can be expressed as [25]:

$$J_{fw}\ddot{\delta}_f + B_{fw}\dot{\delta}_f + \tau_f + \tau_e = \tau_s \quad (3.3)$$

where J_{fw} , and B_{fw} are the moment of inertia and the viscous friction of the front wheel, respectively, δ_f is the front wheel steering angle, τ_s represents the torque transmitted to the steering arm of the front wheel by the coupled front-wheel motor via the rack and pinion gearbox, τ_e is the self-aligning moment generated by the tyre cornering forces during turning, and τ_f is the coulomb friction in the motor assembly and the steering system, which is defined as motor assembly and the steering system, which is defined as:

$$\tau_f = F_s \text{sign}(\dot{\delta}_f) \quad (3.4)$$

with F_s the Coulomb friction constant and $\text{sign}(\dot{\delta}_f)$ the sign function expressed as:

$$\text{sign}(\dot{\delta}_f) = \begin{cases} 1, & \text{for } \dot{\delta}_f > 0 \\ 0, & \text{for } \dot{\delta}_f = 0 \\ -1, & \text{for } \dot{\delta}_f < 0 \end{cases} \quad (3.5)$$

Under the assumption that the tire slip angle is small, a hyperbolic tangent signal can be used to pattern the self-alignment torque exerted on front wheels, where its expression is [25], [57]:

$$\tau_e = \alpha \tanh(\delta_f) \quad (3.6)$$

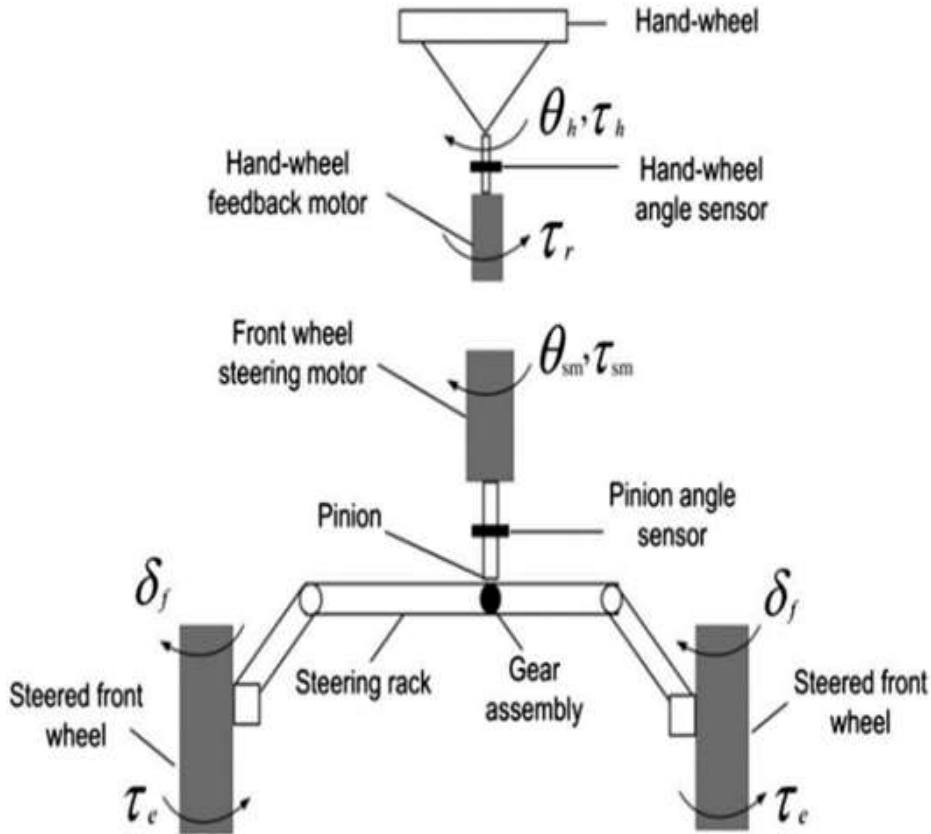


Figure 3. 1: SBW system model [9]

where α is a time-varying coefficient with respect to road conditions, and $\tanh(\cdot)$ represents the hyperbolic tangent function.

Assuming that no backlash exists between the rack and pinion gear teeth, we obtain the following relationships about δ_f , θ_{sm} , and their derivatives [25], [31]

$$\frac{\delta_f}{\theta_{sm}} = \frac{\dot{\delta}_f}{\dot{\theta}_{sm}} = \frac{\ddot{\delta}_f}{\ddot{\theta}_{sm}} = \frac{1}{K_r} = \frac{\tau_{12}}{\tau_s} \quad (3.7)$$

where K_r is the steering ratio.

Then, using (5) in (2) and eliminating θ_{sm} , we have [9]

$$J_{eq}\ddot{\delta}_f + B_{eq}\dot{\delta}_f - K_r\tau_{dis} + \tau_f + \tau_e = K_r u \quad (3.8)$$

where J_{eq} and B_{eq} are the total inertia and damping coefficient of the SBW system model, respectively, which are defined as [25].

$$J_{eq} = J_{fw} + (K_r)^2 J_{sm} \quad (3.9)$$

$$B_{eq} = B_{fw} + (K_r)^2 B_{sm} \quad (3.10)$$

Multiplying both sides by $1/K_r$, Equation (5) can also be rewritten as [25], [31]

$$\frac{J_{eq}}{K_r} \ddot{\delta}_f + \frac{B_{eq}}{K_r} \dot{\delta}_f - \tau_{dis} + \frac{\tau_f}{K_r} + \frac{\tau_e}{K_r} = u \quad (3.11)$$

$$a = \frac{J_{eq}}{K_r} \quad (3.12)$$

$$b = \frac{B_{eq}}{K_r} \quad (3.13)$$

$$\tau_{fa} = \frac{F_s \text{sign} \dot{\delta}_f}{K_r} \quad (3.14)$$

$$\tau_{ea} = \frac{\tau_e}{K_r} \quad (3.15)$$

Then, we have [9]

$$a \ddot{\delta}_f + b \dot{\delta}_f - \tau_{dis} + \tau_{fa} + \tau_{ea} = u \quad (3.16)$$

Considering the uncertainties, we express (3.10) - (3.13) as [9]

$$a = a_0 + \Delta a \quad (3.17)$$

$$b = b_0 + \Delta b \quad (3.18)$$

$$\tau_{fa} = \tau_{fa0} + \Delta \tau_{fa} \quad (3.19)$$

$$\tau_{ea} = \tau_{ea0} + \Delta \tau_{ea} \quad (3.20)$$

And

$$\tau_{dis} = \tau_{dis0} + \Delta \tau_{dis} \quad (3.21)$$

where $a_0 = \frac{J_{eq0}}{K_{r0}}$, $b_0 = \frac{B_{eq0}}{K_{r0}}$, J_{eq0} , B_{eq0} , and K_{r0} are the nominal values of the system parameters, $\tau_{fa0} = \frac{F_{s0} \text{sign} \dot{\delta}_f}{K_{r0}}$, F_{s0} , τ_{dis0} , and $\tau_{ea0} = \frac{\tau_{e0}}{K_{r0}}$ are the nominal values of the system disturbances that can be identified by the preliminary experiments, Δa , Δb , $\Delta \tau_{fa} = \Delta F_s \text{sign} \dot{\delta}_f$, ΔF_s , $\Delta \tau_{dis}$, and $\Delta \tau_{ea}$ denote the unknown bounded uncertainties. In particular, τ_{ea0} is defined as the known external tire self-aligning torque on the wet asphalt road. Thus, $\Delta \tau_{ea}$ is the difference between the actual tire self-aligning torque and the predetermined self-aligning torque for the wet asphalt road [25].

And τ_{dis0} is defined as [25], [31]

$$\tau_{dis0} = \tau_{sm6,nom} \cos(6\theta_e) + \tau_{sm12,nom} \cos(12\theta_e) + \frac{3}{2} \frac{p}{2} \psi_{d0} \frac{2}{\sqrt{3}} \sin(\theta_e + \varphi) \times \sqrt{(\Delta i_{a0}^2) + \Delta i_{a0} \Delta i_{b0} + (\Delta i_{b0}^2)} \quad (3.22)$$

where $\tau_{sm6,nom}$ and $\tau_{sm12,nom}$ are the nominal values of τ_{sm6} and τ_{sm12} , Δi_{a0} and Δi_{b0} are the nominal values of Δi_a and Δi_b , respectively.

In addition, the uncertainty in the torque pulsation disturbances $\Delta\tau_{dis}$ in (3.18) can be described as follows [25]:

$$\Delta\tau_{dis} = \Delta\tau_{sm6} \cos(6\theta_e) + \Delta\tau_{sm12} \cos(12\theta_e) + \Delta i \frac{3}{2} \frac{p}{2} \psi_{d0} \frac{2}{\sqrt{3}} \sin(\theta_e + \varphi) \quad (3.23)$$

where $\Delta\tau_{sm6}$ and $\Delta\tau_{sm12}$ represent the uncertainties in the 6th and 12th harmonic torque amplitudes, respectively, and Δi denotes the uncertainties in the dc current offsets.

Now, (3.16) can be written as [25], [31]

$$a_0 \ddot{\delta}_f + b_0 \dot{\delta}_f - \tau_{dis0} + \tau_{fa0} + \tau_{ea0} = u + \rho \quad (3.24)$$

Where ρ represents the lumped uncertainty as follow [9]:

$$\rho = -\Delta a \ddot{\delta}_f - \Delta b \dot{\delta}_f + \Delta\tau_{dis} - \Delta\tau_{fa} - \Delta\tau_{ea} \quad (3.25)$$

The lumped uncertainty consists of the parameter uncertainties in the front-wheel motor, rack and pinion gearbox and the front wheel, and the estimation errors of the Coulomb friction, tire self-aligning torque, and motor torque pulsations.

The following system with no uncertainty is defined as the nominal system [25]

$$a_0 \ddot{\delta}_f + b_0 \dot{\delta}_f - \tau_{dis0} + \tau_{fa0} + \tau_{ea0} = u_0 \quad (3.26)$$

where u_0 is the nominal control signal.

We assume the following bounded property in the parameter uncertainties:

$$|\Delta a| < \beta_0 \quad (3.27)$$

$$|\Delta b| < \beta_1 \quad (3.28)$$

$$|\Delta\tau_{fa}| < \beta_2 + \beta_3 |\dot{\delta}_f| \quad (3.29)$$

$$|\Delta\tau_{ea}| < \beta_4 + \beta_5 |\delta_f| \quad (3.30)$$

$$|\Delta\tau_{dis}| < \beta_6 + \beta_7 |\delta_f| \quad (3.31)$$

where β_i ($i = 0, \dots, 7$) are positive constants.

Furthermore, the closed-loop control signal is chosen to be upper bounded by the following polynomial function:

$$|u| < \lambda_0 + \lambda_1|\delta f| + \lambda_2|\dot{\delta}_f| \quad (3.32)$$

Now, using the expressions in (3.27) - (3.32), we can be shown that the lumped uncertainty in (3.25) is upper bounded [9];

$$|\rho| < \bar{\rho} \quad (3.33)$$

With

$$\bar{\rho} = c_0 + c_1|\delta_f| + c_2|\dot{\delta}_f| \quad (3.34)$$

where c_0 , c_1 and c_2 are designed positive constants.

The hand-wheel dynamics can be expressed as [8]

$$J_h\ddot{\theta}_h + B_h\dot{\theta}_h + C_h\theta_h + \tau_r = \tau_h \quad (3.35)$$

where J_h is the hand-wheel column moment of inertia, B_h is the column viscous friction coefficient, C_h is the stiffness coefficient, θ_h is the angular position, τ_r represents the feedback torque from the feedback motor, and τ_h is the driver input torque.

Thus, the desired reference steering signal of the SBW system is given by:

$$\theta_{hr} = \frac{1}{N_\theta} \theta_h \quad (3.36)$$

where N_θ denotes the scale factor between the actual handwheel angle θ_h and the front wheel steering angle δ_f .

We can rearrange (3.35) with the help of (3.36) as follows:

$$\ddot{\theta}_{hr} = -\frac{C_h}{J_h}\theta_{hr} - \frac{B_h}{J_h}\dot{\theta}_{hr} + \frac{\tau_h - \tau_r}{J_h} \quad (3.37)$$

The structural constraint of the closed-loop control signal $u(t)$ in (32) indicates that no angular acceleration signal of the front wheel is used in practice. This is because the measured acceleration signal is often disturbed by noises and the control performance will be degraded if inaccurate measurements of the acceleration signal are involved [9].

Thus, $\ddot{\theta}_{hr}$ in (37) is upper bounded as follows:

$$|\ddot{\theta}_{hr}| \leq \bar{\ddot{\theta}}_{hr} \quad (3.38)$$

with

$$\bar{\ddot{\theta}}_{hr} = \gamma_0 + \gamma_1|\theta_{hr}| + \gamma_2|\dot{\theta}_{hr}| \quad (3.39)$$

where γ_0 , γ_1 and γ_2 are positive constants.

It is noted that the parameters γ_1 and γ_2 in (3.39) are related to the hand-wheel model parameters J_h , B_h , and C_h . In addition, the parameter γ_0 depends on the maximum steering torque τ_h that can be found in the studies of steering effort for a typical automobile in emergency maneuvers [9].

After the preceding discussions regarding the modeling of SBW systems and the constrained characteristics of both the system lumped uncertainty and the hand-wheel angular acceleration, we are now prepared to explore the design of controllers. This includes the nominal feedback controller, Conventional Sliding Mode Control (CSMC), and the proposed Integral Sliding Mode Control (ISMC) for the closed-loop SBW systems.

The objective of the control is to ensure that the steered front wheels can asymptotically follow the hand-wheel reference angle despite uncertainties and disturbances, as elaborated in the subsequent section.

3.3. Controller Design

First, the tracking error between the front wheel steering angle δ_f and the hand-wheel reference angle θ_{hr} is defined as:

$$\varepsilon_\theta = \delta_f - \theta_{hr} \quad (3.40)$$

And the first and second derivatives of the tracking error can be expressed as:

$$\dot{\varepsilon}_\theta = \dot{\delta}_f - \dot{\theta}_{hr} \quad (3.41)$$

$$\ddot{\varepsilon}_\theta = \ddot{\delta}_f - \ddot{\theta}_{hr} \quad (3.42)$$

Given the system model in (3.24), we obtain the error dynamics of the closed-loop SBW system as follows [9]:

$$\ddot{\varepsilon}_\theta = -\frac{b_0}{a_0}\dot{\varepsilon}_\theta + \frac{u - \tau_{fa0} - \tau_{ea0} + \tau_{dis0}}{a_0} + \rho' - \frac{b_0}{a_0}\dot{\theta}_{hr} \quad (3.43)$$

where ρ' is the new bounded lumped uncertainty of the closed-loop error dynamics and defined as:

$$\rho' = \frac{\rho}{a_0} - \ddot{\theta}_{hr} \quad (3.44)$$

3.3.1. NFC Design of Nominal System

Without considering the uncertainties, (43) can be simplified into the error dynamics of the nominal system in (3.26) as [9]:

$$\ddot{\varepsilon}_\theta = -\frac{b_0}{a_0}\dot{\varepsilon}_\theta + \frac{u_1 - \tau_{fa0} - \tau_{ea0} + \tau_{dis0}}{a_0} - \frac{b_0}{a_0}\dot{\theta}_{hr} \quad (3.45)$$

To stabilize the error dynamics in (3.45), the nominal control signal u_0 is chosen as [9]:

$$u_0 = \tau_{fa0} + \tau_{ea0} - \tau_{dis0} + a_0(k_1\varepsilon_\theta + k_2\dot{\varepsilon}_\theta) + b_0\dot{\theta}_{hr} \quad (3.46)$$

where k_1 and k_2 are the feedback gains [9].

Then using (3.46) in (3.45), we obtain

$$\ddot{\varepsilon}_\theta + \left(\frac{b_0}{a_0} - k_2\right)\dot{\varepsilon}_\theta - k_1\varepsilon_\theta = 0 \quad (3.47)$$

The control gains, k_1 and k_2 , must be chosen to ensure that the characteristics of (3.47) are strictly Hurwitz, indicating that the polynomial roots reside in the open left-half of the complex plane. This condition guarantees the exponential convergence of the tracking error ε_θ to zero.

The nominal system model is constructed using the recognized nominal system parameters and the dynamics of the components. When system parameter uncertainties are minimal, and road conditions closely resemble the nominal state, the NFC effectively stabilizes the closed-loop SBW system. Nevertheless, in situations where road conditions significantly deviate from the nominal state, robust compensation becomes necessary, as elaborated in the subsequent section.

3.3.2. Control Design Under Uncertainty

Addressing the uncertainties present in the SBW system outlined in equation (3.24), the closed-loop control input u is comprised of two distinct components:

$$u = u_0 + u_1 \quad (3.48)$$

By substituting (3.48) and (3.46) into (3.43), the closed-loop error dynamics can be written as:

$$\ddot{\varepsilon}_\theta = -\frac{b_0}{a_0}\dot{\varepsilon}_\theta + k_1\varepsilon_\theta + k_2\dot{\varepsilon}_\theta + \frac{u_1}{a_0} + \rho' \quad (3.49)$$

the upper bound of ρ' is estimated as follows:

$$\rho' \leq \bar{\rho}' \quad (3.50)$$

Where

$$\bar{\rho}' = \frac{\bar{\rho}}{a_0} + \bar{\theta}_{hr} \quad (3.51)$$

$\bar{\rho}$ and $\bar{\theta}_{hr}$ are given in (3.34) and (3.39), respectively.

u_0 represents the nominal feedback controller (NFC) as defined in equation (3.46), while u_1 acts as a compensator specifically designed to handle the lumped uncertainty.

In this section, our approach begins with the application of Conventional Sliding Mode Control (CSMC) from reference [9]—chosen for its strategic design in addressing the challenges associated with the uncertainties. CSMC is employed both as a reference point for comparative analysis and as a benchmark.

Furthermore, Integral Sliding Mode Control (ISMC) is introduced to address the unique challenges posed by lumped uncertainty. While CSMC serves as a baseline for comparison, the objective of Integral Sliding Mode Control (ISMC) introduced is to ensure the asymptotic convergence of the tracking error in the closed-loop SBW system towards zero.

A. Conventional Sliding Mode Controller (CSMC)

To apply the conventional sliding mode approach in formulating the compensator, one can establish a linear sliding variable in the following manner:

$$s = \dot{\varepsilon}_\theta + \lambda \varepsilon_\theta \quad (3.52)$$

Where λ is a positive number.

Considering the closed-loop SBW system in (3.24) with the error dynamics in (3.49), the tracking error ε_θ will asymptotically converge to zero if the control law is designed such that:

$$u = u_0 + u_1 \quad (3.53)$$

where u_0 is the NFC given by expression (3.46) and u_1 is the CSMC designed as follows [9]:

$$u_1 = -a_0 \text{sign}(s) \left(\bar{\rho}' + |k_1| |\varepsilon_\theta| + \left| \lambda - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| \right) - q_1 s - q_2 \text{sign}(s) \quad (3.54)$$

Where $\bar{\rho}'$ is the upper bound of ρ' given in (3.51), k_1 and k_2 are two designed parameters as in (47). And q_1 and q_2 are designed for controlling the convergence of the sliding variable [25], [31].

Considering a Lyapunov function $V = \frac{1}{2} s^2$ and taking the time derivative of V , we obtain:

$$\begin{aligned} \dot{V} &= s \dot{s} \\ &= s(\ddot{\varepsilon}_\theta + \lambda \dot{\varepsilon}_\theta) \\ &= s \left(-\frac{b_0}{a_0} \dot{\varepsilon}_\theta + k_1 \varepsilon_\theta + k_2 \dot{\varepsilon}_\theta + \frac{u_1}{a_0} + \rho' + \lambda \dot{\varepsilon}_\theta \right) \end{aligned}$$

$$\begin{aligned}
&= s \left(-\frac{b_0}{a_0} \dot{\varepsilon}_\theta + k_1 \varepsilon_\theta + k_2 \dot{\varepsilon}_\theta \right) + s \frac{u_1}{a_0} + s \rho' + s \lambda \dot{\varepsilon}_\theta \\
&= s \left(\lambda - \frac{b_0}{a_0} + k_2 \right) \dot{\varepsilon}_\theta + s k_1 \varepsilon_\theta + s \frac{u_1}{a_0} + s \rho' \\
&= s \left(\lambda - \frac{b_0}{a_0} + k_2 \right) \dot{\varepsilon}_\theta + s k_1 \varepsilon_\theta + s \rho' \\
&\quad - \left(\frac{s}{a_0} \right) a_0 \text{sign}(s) \left(\bar{\rho}' + |k_1| |\varepsilon_\theta| + \left| \lambda - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| \right) \\
&\quad + \left(\frac{s}{a_0} \right) [-q_1 s - q_2 \text{sign}(s)] \\
&= s \left(\lambda - \frac{b_0}{a_0} + k_2 \right) \dot{\varepsilon}_\theta - |s| \left| \lambda - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| + s k_1 \varepsilon_\theta - |s| |k_1| |\varepsilon_\theta| + s \rho' - |s| \bar{\rho}' - \frac{q_1 s^2}{a_0} \\
&\quad - \frac{q_2 |s|}{a_0} \\
&< |s| \left| \lambda - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| - |s| \left| \lambda - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| + |s| |k_1| |\varepsilon_\theta| - |s| |k_1| |\varepsilon_\theta| + |s| |\rho'| \\
&\quad - |s| \bar{\rho}' - \frac{q_1 s^2}{a_0} - \frac{q_2 |s|}{a_0} \\
&= -|s| \bar{\rho}' + |s| |\rho'| - \frac{q_1 s^2}{a_0} - \frac{q_2 |s|}{a_0} \\
&= -|s| (\bar{\rho}' - |\rho'|) - \frac{q_1 s^2}{a_0} - \frac{q_2 |s|}{a_0} \\
&\leq -\frac{q_2}{a_0} |s| < 0, \quad \text{for } |s| \neq 0 \tag{3.55}
\end{aligned}$$

Inequality (3.55) ensures that the sliding variable s reaches the sliding mode surface $s = 0$ in a finite time [25], [31]. Thus, the error dynamics of the closed-loop SBW system exponentially converges to zero on the sliding mode surface.

The parameters q_1 and q_2 are chosen in the sense that 1) the sliding variable should be driven to the sliding mode surface in a finite time, and 2) the control amplitude should not reach the saturation level [25], [31].

B. Integral Sliding Mode Controller (ISMC)

The main objective of an integral sliding mode controller is to ensure robustness from the initial point in the state-space by eliminating the influences of bounded matched uncertainties [1].

Given the error dynamics outlined in equation (49), within a fundamental ISMC algorithm, the control input u_1 is divided into two components:

$$u_1 = u_x + u_y \quad (3.56)$$

Where u_x serves as the auxiliary sliding mode control input intended to compensate for the lumped uncertainty in (49) right from the start. It ensures that the corresponding auxiliary sliding variable is set to zero from the initial point itself. However, the effect of uncertainty is not present from the beginning. So, u_y is the control input is designed to drive the main sliding variable to zero.

The main sliding variable is given as follows:

$$s = \dot{\varepsilon}_\theta + \lambda_2 \varepsilon_\theta \quad (3.57)$$

Where λ_2 is a positive number. And the first derivative of s can be expressed as:

$$\dot{s} = \ddot{\varepsilon}_\theta + \lambda_2 \dot{\varepsilon}_\theta \quad (3.58)$$

And substituting (3.49) in (3.58), we obtain:

$$\dot{s} = -\frac{b_0}{a_0} \dot{\varepsilon}_\theta + k_1 \varepsilon_\theta + k_2 \dot{\varepsilon}_\theta + \frac{u_1}{a_0} + \rho' + \lambda_2 \dot{\varepsilon}_\theta \quad (3.59)$$

$$\dot{s} = -\frac{b_0}{a_0} \dot{\varepsilon}_\theta + k_1 \varepsilon_\theta + k_2 \dot{\varepsilon}_\theta + \frac{u_x}{a_0} + \frac{u_y}{a_0} + \rho' + \lambda_2 \dot{\varepsilon}_\theta \quad (3.60)$$

And the auxiliary sliding variable is defined as:

$$\sigma = s - z; z(0) = s(0) \quad (3.61)$$

Here, $z(0)$ is set equal to $s(0)$ to ensure $\sigma = 0$ from the initial point.

Let the integral part derivative be defined as:

$$\dot{z} = -\frac{b_0}{a_0} \dot{\varepsilon}_\theta + k_1 \varepsilon_\theta + k_2 \dot{\varepsilon}_\theta + \frac{u_y}{a_0} + \lambda_2 \dot{\varepsilon}_\theta \quad (3.62)$$

And the derivative of the auxiliary sliding variable, σ can be expressed as:

$$\dot{\sigma} = \dot{s} - \dot{z} \quad (3.63)$$

$$\begin{aligned} \dot{\sigma} = & \left(-\frac{b_0}{a_0} \dot{\varepsilon}_\theta + k_1 \varepsilon_\theta + k_2 \dot{\varepsilon}_\theta + \frac{u_x}{a_0} + \frac{u_y}{a_0} + \rho' + \lambda_2 \dot{\varepsilon}_\theta \right) \\ & - \left(-\frac{b_0}{a_0} \dot{\varepsilon}_\theta + k_1 \varepsilon_\theta + k_2 \dot{\varepsilon}_\theta + \frac{u_y}{a_0} + \lambda_2 \dot{\varepsilon}_\theta \right) \end{aligned} \quad (3.64)$$

$$\dot{\sigma} = \frac{u_x}{a_0} + \rho' \quad (3.65)$$

Now, we choose u_x as:

$$u_x = -a_0(\bar{\rho}' \text{sign}(\sigma) + q_3 \sigma) \quad (3.66)$$

Where $\bar{\rho}'$ is the upper bound of ρ' given in (3.51), and q_3 is a constant ensuring faster converging rate of σ . Substituting (3.66) into (3.65), and considering a Lyapunov function $V = \frac{1}{2}\sigma^2$ one obtains:

$$\dot{V} = \sigma \dot{\sigma} \quad (3.67)$$

$$\dot{V} = \sigma(-\bar{\rho}' \text{sign}(\sigma) - q_3\sigma + \rho') \quad (3.68)$$

$$\dot{V} = (\rho' - \bar{\rho}') |s| - q_3\sigma^2 \quad (3.69)$$

$$\dot{V} \leq (|\rho'| - \bar{\rho}') |s| - q_3\sigma^2 \quad (3.70)$$

$$\dot{V} \leq -q_3\sigma^2 < 0, \text{ for } |\sigma| \neq 0 \quad (3.71)$$

Inequality (3.67) ensures that choosing q_3 a positive number, the auxiliary sliding variable σ reaches zero in a finite time.

Once $\sigma = 0$ is reached in finite time due to u_x , $\dot{\sigma} = 0$. This implies from (3.65):

$$u_x = -a_0(\rho') \quad (3.72)$$

And substituting (65) into (59), we obtain:

$$\dot{s} = -\frac{b_0}{a_0} \dot{\varepsilon}_\theta + k_1 \varepsilon_\theta + k_2 \dot{\varepsilon}_\theta + \frac{u_y}{a_0} + \lambda_2 \dot{\varepsilon}_\theta \quad (3.73)$$

Now, u_y can be selected as:

$$u_y = -a_0 \text{sign}(s) \left(|k_1| |\varepsilon_\theta| + \left| \lambda_2 - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| \right) - q_4 s \quad (3.74)$$

Where k_1 and k_2 are two designed parameters as in (47). And c_2 is designed for controlling the convergence of the sliding variable [31]. And considering a Lyapunov function $V = \frac{1}{2}s^2$ we obtain:

$$\dot{V} = s \dot{s} \quad (3.75)$$

$$= s \left(-\frac{b_0}{a_0} \dot{\varepsilon}_\theta + k_1 \varepsilon_\theta + k_2 \dot{\varepsilon}_\theta + \frac{u_y}{a_0} + \lambda_2 \dot{\varepsilon}_\theta \right) \quad (3.76)$$

$$= s \left(-\frac{b_0}{a_0} \dot{\varepsilon}_\theta + k_1 \varepsilon_\theta + k_2 \dot{\varepsilon}_\theta \right) + s \frac{u_y}{a_0} + s \lambda_2 \dot{\varepsilon}_\theta \quad (3.77)$$

$$= s \left(\lambda_2 - \frac{b_0}{a_0} + k_2 \right) \dot{\varepsilon}_\theta + s k_1 \varepsilon_\theta + s \frac{u_y}{a_0} \quad (3.78)$$

$$= s \left(\lambda_2 - \frac{b_0}{a_0} + k_2 \right) \dot{\varepsilon}_\theta + s k_1 \varepsilon_\theta - \left(\frac{s}{a_0} \right) a_0 \text{sign}(s) \left(|k_1| |\varepsilon_\theta| + \left| \lambda_2 - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| \right) + \left(\frac{s}{a_0} \right) [-q_4 s] \quad (3.79)$$

$$\dot{V} = s \left(\lambda_2 - \frac{b_0}{a_0} + k_2 \right) \dot{\varepsilon}_\theta - |s| \left| \lambda_2 - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| + s k_1 \varepsilon_\theta - |s| |k_1| |\varepsilon_\theta| - \frac{q_4 s^2}{a_0}$$

$$\begin{aligned}\dot{V} &< |s| \left| \lambda_2 - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| - |s| \left| \lambda_2 - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| + |s| |k_1| |\varepsilon_\theta| - |s| |k_1| |\varepsilon_\theta| - \frac{q_4 s^2}{a_0} \\ \dot{V} &\leq -\frac{q_4 s^2}{a_0} < 0, \quad \text{for } |s| \neq 0\end{aligned}\quad (3.80)$$

Inequality (68) ensures that, choosing q_4 a positive number, the main sliding variable s reaches the surface $s = 0$ in a finite time. Thus, the error dynamics of the closed-loop SBW system converges exponentially to zero once on the main sliding surface.

Now from (56), the Integral Sliding Mode Control input u_1 can be written as:

$$u_1 = -a_0 \left(\bar{\rho}' \text{sign}(\sigma) + q_4 \sigma + \text{sign}(s) \left(\bar{\rho}' + |k_1| |\varepsilon_\theta| + \left| \lambda_2 - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| \right) \right) - q_4 s$$

Whereas the total control input, u is given by:

$$u = u_0 + u_1 \quad (3.81)$$

where u_0 is the NFC given by expression (3.46).

Due to the signum function included in the CSMC, and ISMC, there exists chattering in the control signal. This chattering issue can be tackled by using the boundary layer technique.

The control inputs with boundary layer compensator are given below:

CSMC:

$$u_1 = -a_0 \text{sat}(s) \left(\bar{\rho}' + |k_1| |\varepsilon_\theta| + \left| \lambda_2 - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| \right) - q_1 s - q_2 \text{sat}(s) \quad (3.82)$$

ISMC:

$$u_1 = -a_0 \left(\text{sat}(\sigma) + q_3 \sigma + \text{sat}(s) \left(\bar{\rho}' + |k_1| |\varepsilon_\theta| + \left| \lambda_2 - \frac{b_0}{a_0} + k_2 \right| |\dot{\varepsilon}_\theta| \right) \right) - q_4 s \quad (3.83)$$

where $\text{sat}(s)$ is the saturation function defined as:

$$\text{sat}(s) = \begin{cases} \frac{s}{\delta}, & \text{for } |s| < \delta \\ \text{sign}(s), & \text{for } |s| \geq \delta \end{cases} \quad (3.84)$$

And $\text{sat}(\sigma)$ is defined as:

$$\text{sat}(\sigma) = \begin{cases} \frac{\sigma}{\delta}, & \text{for } |\sigma| < \delta \\ \text{sign}(\sigma), & \text{for } |\sigma| \geq \delta \end{cases} \quad (3.85)$$

3.4. Matlab/Simulink Implementation

In this section, the detailed design procedure of the proposed system is presented. First, the overall schematic diagram of the proposed system is depicted, providing a high-level overview of the various components and their interactions. This diagram outlines the key elements of the system, such as the steering mechanism, actuator dynamics, and the control algorithm, which works in conjunction to achieve precise steering control in the Steer-by-Wire (SBW) system. Following the overall schematic, a detailed description of each component is provided. This includes the modeling of the SBW system's dynamics, the design of the Integral Sliding Mode Controller (ISMC), and the incorporation of additional features such as the boundary layer for mitigating chattering.

In this section, the detailed design procedure of the proposed system is presented. As shown below, the overall schematic diagram of the proposed system is first illustrated, followed by a detailed description of the individual components and their functions within the system.

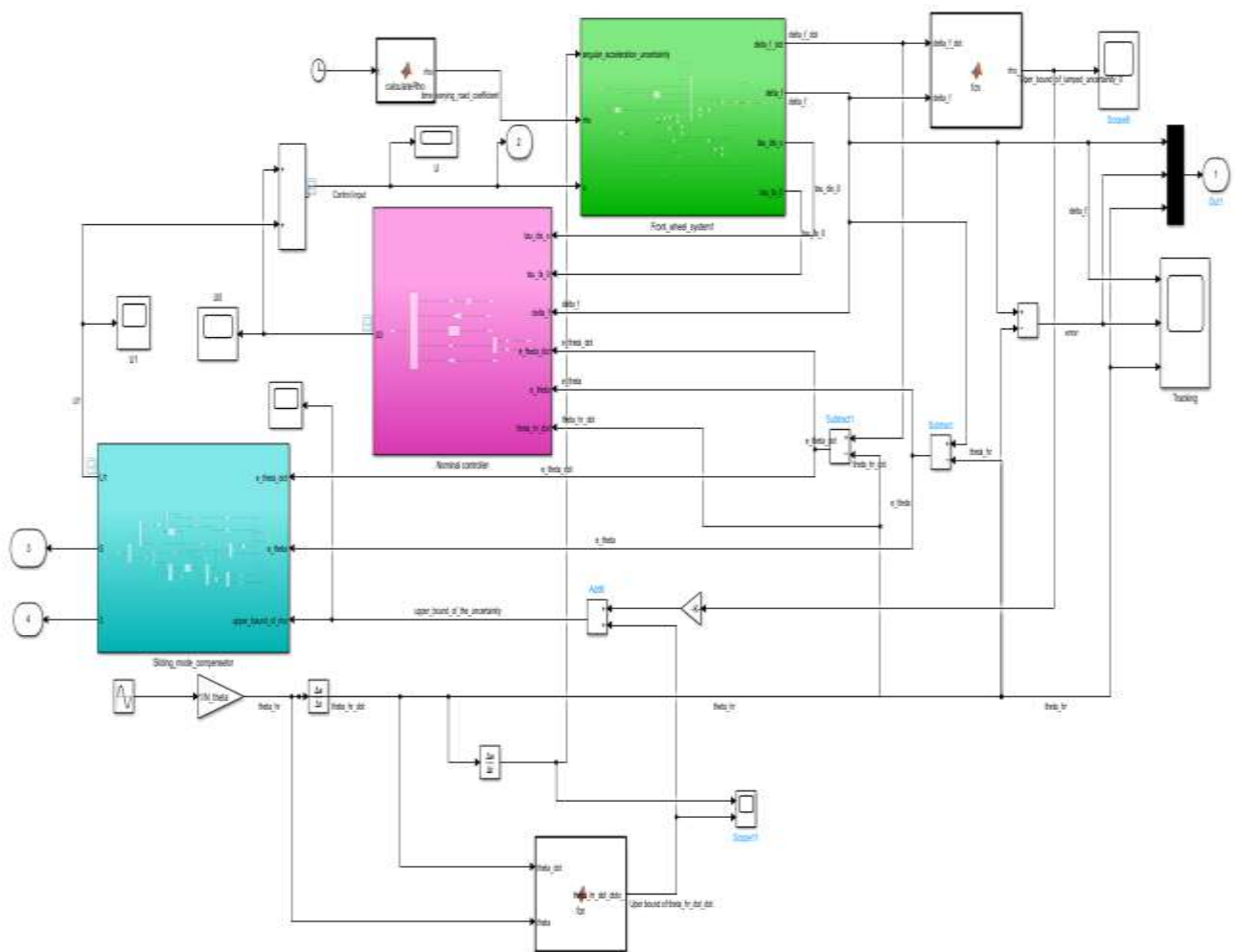


Figure 3. 2: The overall proposed schematic diagram

Figure 3.2 illustrates the overall proposed Simulink model for the integral sliding mode controller applied to a steer-by-wire system. The diagram begins with the driver's steering command input, which serves as the desired reference signal. External disturbances (bounded matched uncertainties) are incorporated to simulate real-world operating conditions. The system integrates the dynamic model of the steer-by-wire mechanism, including actuator dynamics and nonlinearities, to emulate actual system behavior. The error between the desired and actual steering response is processed through the integral sliding mode controller, which ensures robust tracking and disturbance rejection. Finally, the controlled output is fed back into the system for closed-loop operation, ensuring precise and stable steering performance.

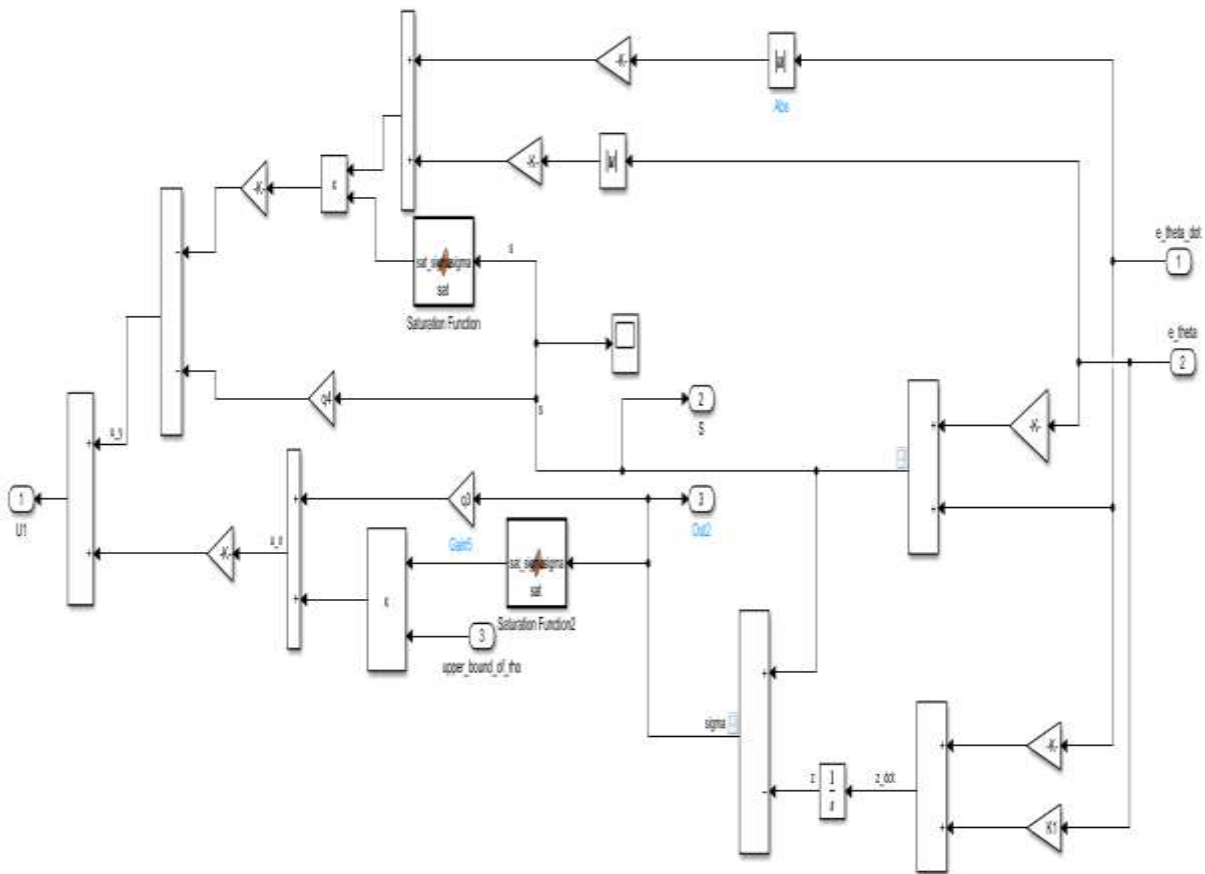


Figure 3. 3:Simulink diagram of Switching Control input

Figure 3.3 depicts the Simulink diagram of the switching control input used in the integral sliding mode controller. In this diagram, a boundary layer implemented using a saturation block is integrated into the switching control law to mitigate chattering effects typically associated with sliding mode control.

The diagram highlights the generation of the sliding surface, computation of the control input, and application of the saturation function to smooth the discontinuous control action. This ensures robustness against disturbances and uncertainties while maintaining improved system performance and stability, particularly in practical implementations.

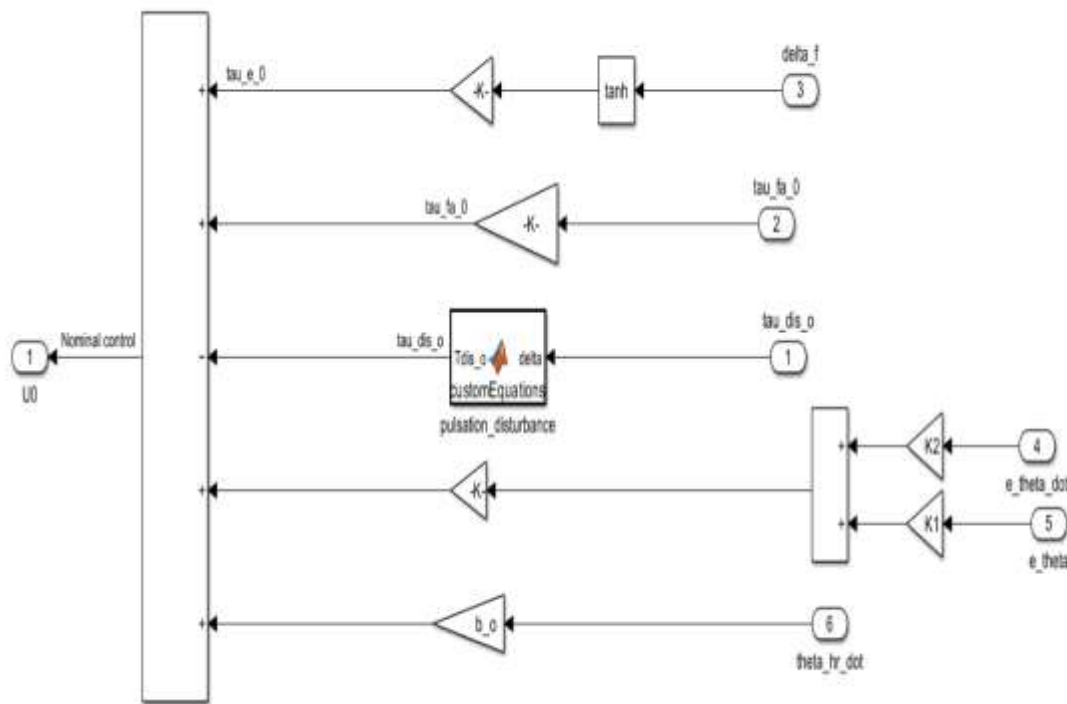


Figure 3. 4: The Simulink diagram of nominal control input

Figure 3.4 presents the Simulink diagram of the nominal control input in the integral sliding mode controller. This subsystem generates the smooth control signal required to drive the steer-by-wire system toward the desired trajectory under ideal conditions, without accounting for disturbances or uncertainties. The nominal control input is calculated based on the linearized model of the system dynamics and utilizes the state feedback to ensure stability and accurate tracking of the reference input. This component forms the baseline control strategy, which is augmented by the switching control to handle model uncertainties and external disturbances.

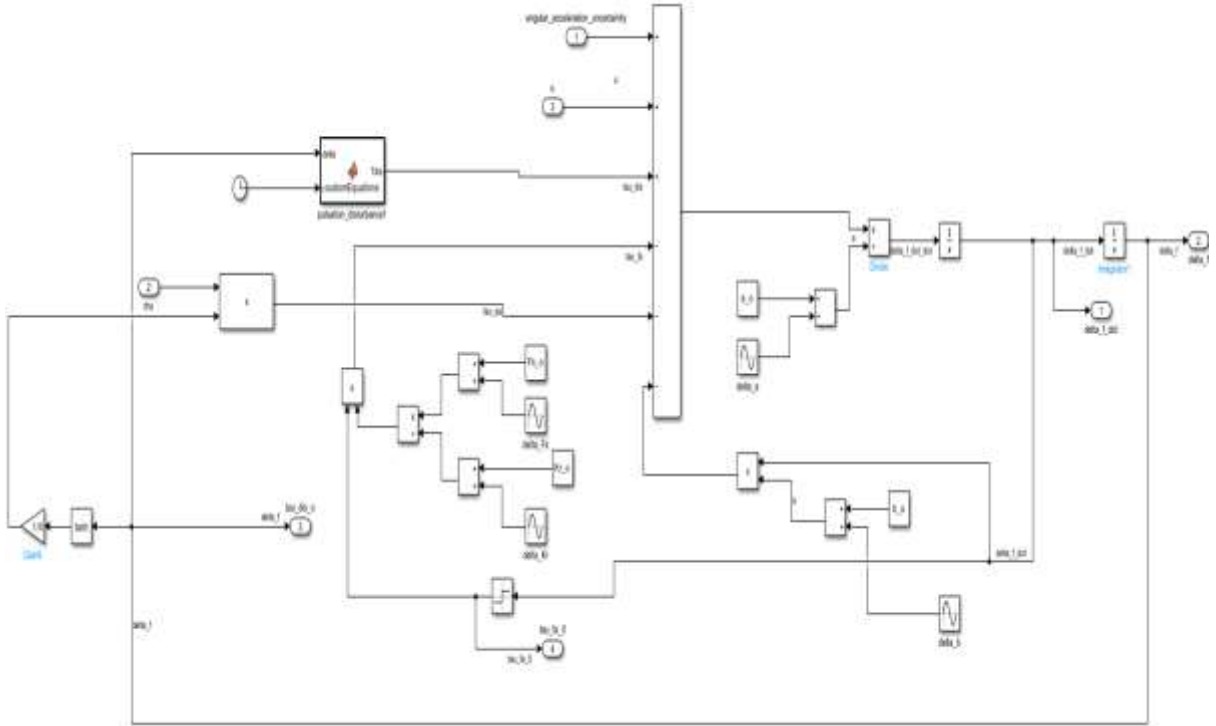


Figure 3. 5: Dynamic model of the system

The following hyperbolic tangent signal is used to represent the self-aligning torque, τ_e [9].

$$\tau_e = \begin{cases} \frac{\rho_1}{\chi} \tanh(\delta_f), & \text{for } 0 < t < 15 \text{ sec (Wet Asphalt)} \\ \frac{\rho_2}{\chi} \tanh(\delta_f), & \text{for } 15 < t < 25 \text{ sec (Snowy road)} \\ \frac{\rho_3}{\chi} \tanh(\delta_f), & \text{for } 25 < t < 35 \text{ sec (Dry Asphalt)} \end{cases} \quad (3.86)$$

The self-aligning torque in (3.86) describes three different road conditions, i.e., wet asphalt, snowy, and dry asphalt roads, respectively [8], [9], [26]. ρ_1, ρ_2, ρ_3 represent the tire-dependent parameters under three different road conditions and are chosen as $\rho_1 = 520$, $\rho_2 = 150$, and $\rho_3 = 950$, respectively. $\chi = 273.5$ is the ratio between the actual self-aligning torque and the input voltage of the servo driver [9]. Considering that, in the nominal SBW model, the wet asphalt road condition is assumed, the predetermined nominal tire-dependent parameter is chosen as $\rho_0 = 300$.

Table 3.1 and Table 3.2 show the nominal parameters of the SBW system and parameters of the implemented controllers.

Table 3. 1: Nominal Parameters of the SBW System

Parameter	Value
a_0	0.064
b_0	0.16
k_{r0}	18
$F_{s0}(\text{Nm})$	3.04
$\tau_{sm6,nom}(\text{Nm})$	0.03
$\tau_{sm12,nom}(\text{Nm})$	0.005
$\Delta i_{a0}(\text{A})$	0.1
$\Delta i_{b0}(\text{A})$	-0.06
$J_h (\text{Kg} \cdot \text{m}^2)$	0.0791
$B_h (\text{Nms/rad})$	0.15
$C_h (\text{Nm/rad})$	0.2
N_θ	12
Rated speed (rpm)	2000
Rated torque (Nm)	4.77
Rated power (KW)	1.0
Rated voltage (V)	200
Rated current (A)	5.3
Peak instantaneous Torque (Nm)	14.3
Number of Poles	6
Constant Magnetic flux (Wb)	0.2

Table 3. 2: Parameters of Implemented Controllers

Parameter	Value
k_1	-80
k_2	-15.5
$\lambda, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6$	12
δ	0.4
c_0	1.0
c_1	0.3
c_2	0.1
γ_0	6
γ_1	2.8
γ_2	2.2
q_2	0.01
$q_1, q_3, q_4, q_5, q_6, q_7$	0.5
p	3
q	5

In this simulation, a sinusoidal signal with amplitude 3.6 and frequency 1 rad per second is used. And a steering ratio 1/12 is used. And we assume that the upper bounds of parameter uncertainties are 10% of the nominal values, as follows:

$$\overline{\Delta a} = 0.1a_0 \quad (3.87)$$

$$\overline{\Delta b} = 0.1b_0 \quad (3.88)$$

$$\overline{\Delta k_r} = 0.1k_{r0} \quad (3.89)$$

$$\overline{\Delta F_s} = 0.1F_{s0} \quad (3.90)$$

$$\overline{\Delta \tau_{sm6}} = 0.1\tau_{sm6,nom} \quad (3.91)$$

$$\overline{\Delta \tau_{sm12}} = 0.1\tau_{sm12,nom} \quad (3.92)$$

Chapter Five

Results and Discussion

This section presents the results of the proposed Integral Sliding Mode Controller (ISMC) applied to the Steer-by-Wire (SBW) system and provides a detailed analysis of its performance. The findings are derived from simulations conducted using MATLAB Simulink, considering various road conditions, including wet asphalt, snowy, and dry asphalt roads. The discussion focuses on evaluating the system's tracking performance, robustness, and disturbance rejection capabilities.

The effectiveness of the proposed ISMC is compared with the Conventional Sliding Mode Control (SMC) to highlight its advantages in handling model uncertainties, external disturbances, and varying road surfaces. Key performance metrics, such as tracking accuracy, control effort, chattering reduction, and robustness under different scenarios, are analyzed to validate the superiority of the ISMC.

The results are further examined in terms of their practical implications for modern automotive applications, emphasizing the controller's potential to enhance safety, reliability, and efficiency in SBW systems. This chapter also includes a comprehensive discussion on the limitations of the current study and the opportunities for further research and improvement.

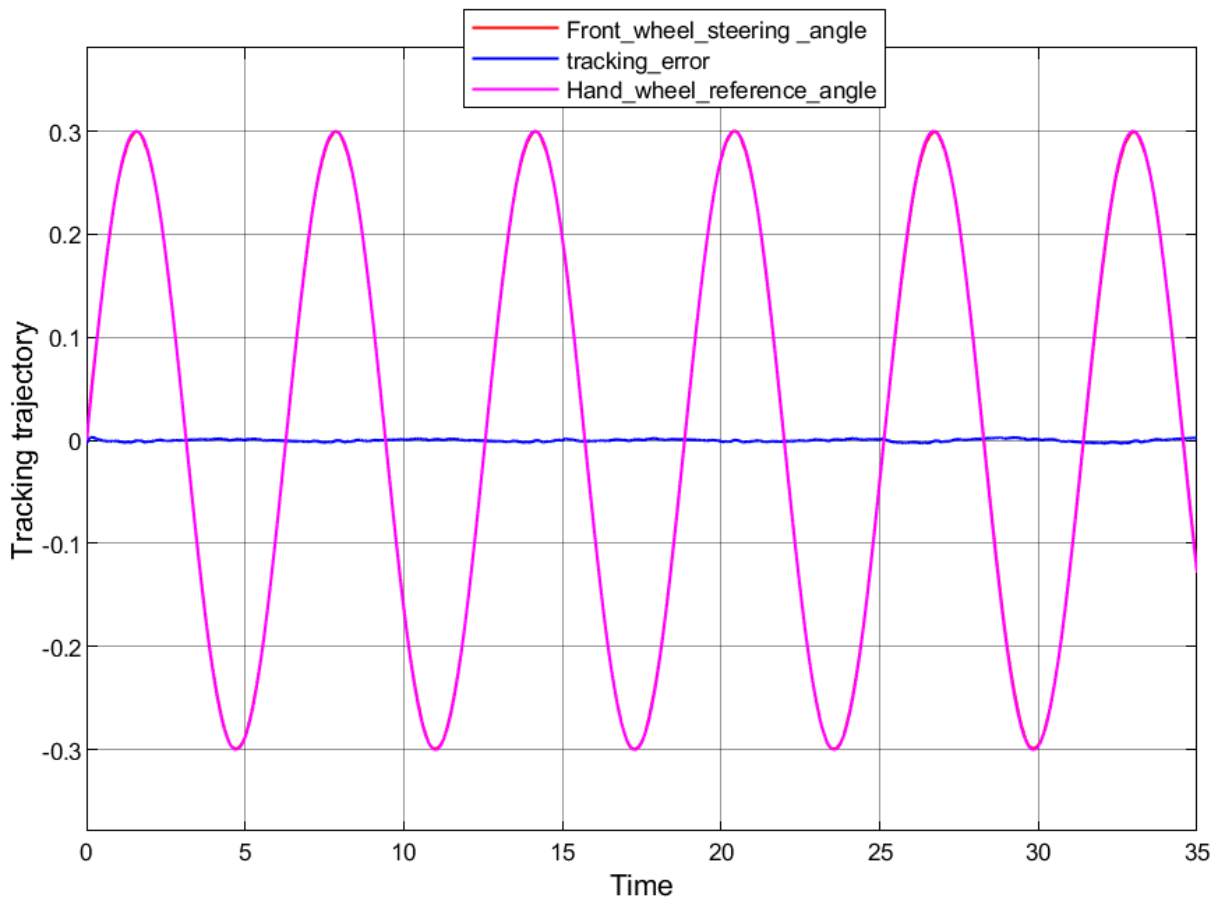


Figure 4. 1: Tracking performance of the proposed system

Figure 4.1 illustrates the tracking performance of the proposed system under various road conditions, including wet asphalt road, snowy road, and dry asphalt road. The figure compares the desired steering input with the actual output to evaluate the system's robustness and accuracy. The system demonstrates high robustness in following the desired trajectory regardless of the road surface type. Despite varying friction coefficients on wet asphalt, snowy, and dry asphalt roads, the proposed controller maintains stable and accurate steering control. The integral sliding mode controller effectively compensates for bounded matched uncertainties as well as the external disturbances associated with different road conditions. Furthermore, the inclusion of a boundary layer in the switching control ensures smooth performance, even on slippery surfaces like snowy roads. This performance analysis confirms the capability of the proposed system to deliver reliable steering control in diverse and challenging driving environments.

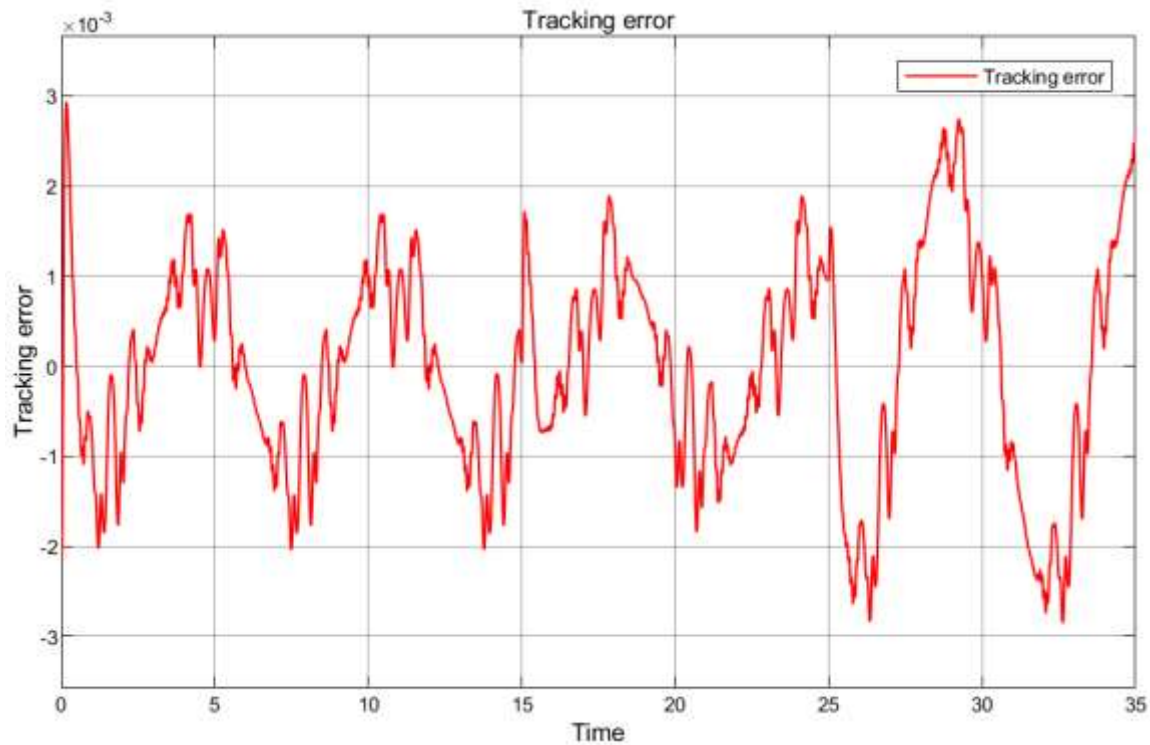


Figure 4. 2: Tracking error of the proposed system

Figure 4.2 shows the tracking error of the proposed system, depicting the difference between the desired driver's command and the actual steering response across various road conditions, including wet asphalt, snowy, and dry asphalt roads. The figure highlights the system's ability to minimize tracking error and maintain precise control, even in the presence of external disturbances and road surface variations. The tracking error remains small, indicating that the integral sliding mode controller effectively compensates for model uncertainties and road-induced disturbances. The performance under different road conditions demonstrates the robustness of the proposed system in achieving accurate and stable steering, with the tracking error being well-controlled across all scenarios.

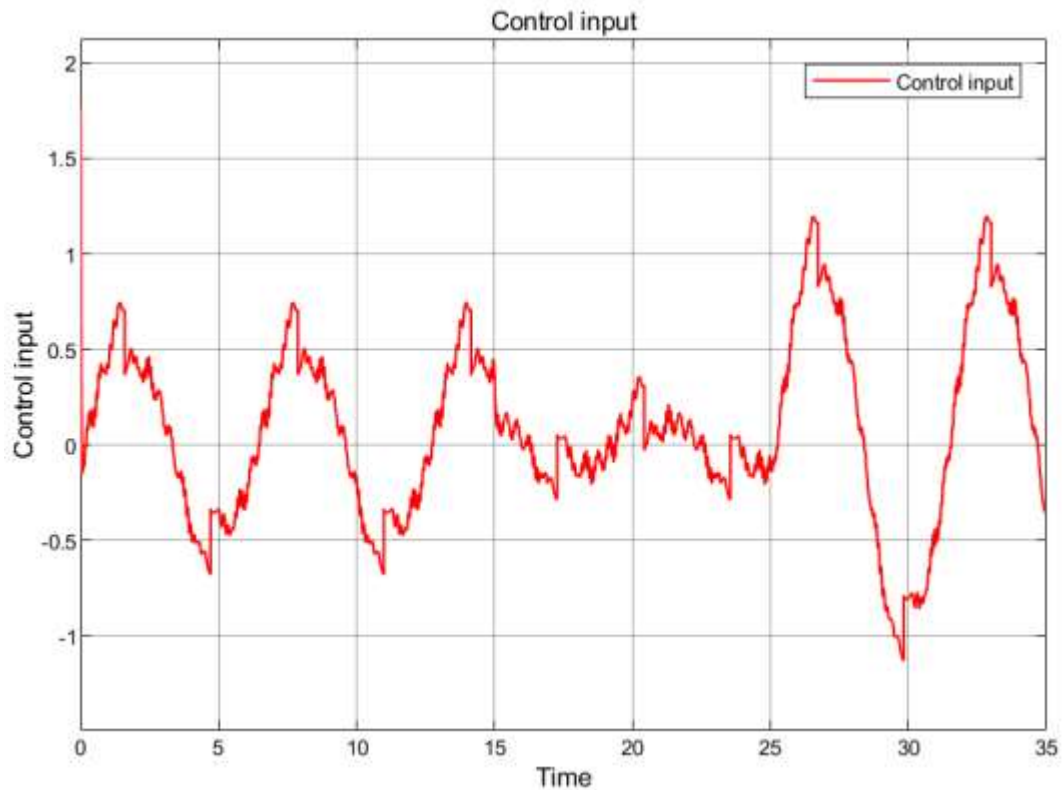


Figure 4. 3: Control torque of the proposed system

Figure 4.3 presents the control torque of the proposed system, which represents the input generated by the integral sliding mode controller to drive the steer-by-wire system. The figure illustrates how the control torque responds to the desired steering command across various road conditions, including wet asphalt, snowy, and dry asphalt roads. The control torque profile shows the necessary input required to achieve precise tracking, with the torque being adjusted to account for disturbances, uncertainties, and variations in road conditions. The inclusion of the boundary layer in the switching control ensures that the torque is smoothly applied, reducing the risk of chattering while maintaining effective disturbance rejection. The results demonstrate the controller's capability to provide the required torque for stable and robust steering control in different driving environments.

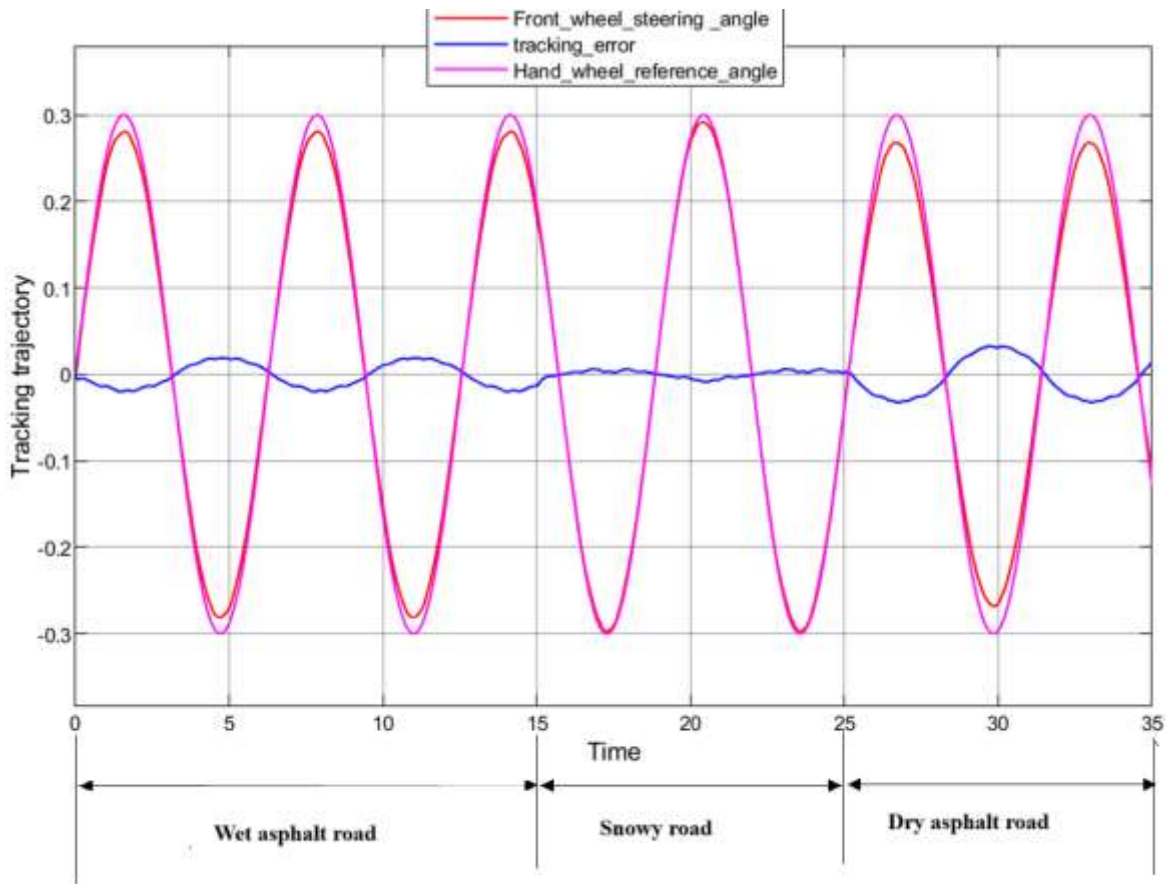


Figure 4. 4: Tracking performance using SMC

Figure 4.4 illustrates the tracking performance of the system using conventional Sliding Mode Control (SMC) as a benchmark. The figure compares the desired steering input (driver's command) with the actual steering response across different road conditions, including wet asphalt, snowy, and dry asphalt roads. The conventional SMC demonstrates lower tracking performance, especially on dry asphalt, where the tracking error is noticeably higher. This is attributed to the higher chattering and reduced disturbance rejection capability of the conventional SMC, which struggles more in scenarios with lower friction and varying road conditions. In contrast, the proposed integral sliding mode controller shows superior performance, with reduced chattering and improved tracking accuracy, particularly under challenging road conditions. This comparison highlights the benefits of the proposed system in providing more precise and stable steering control.

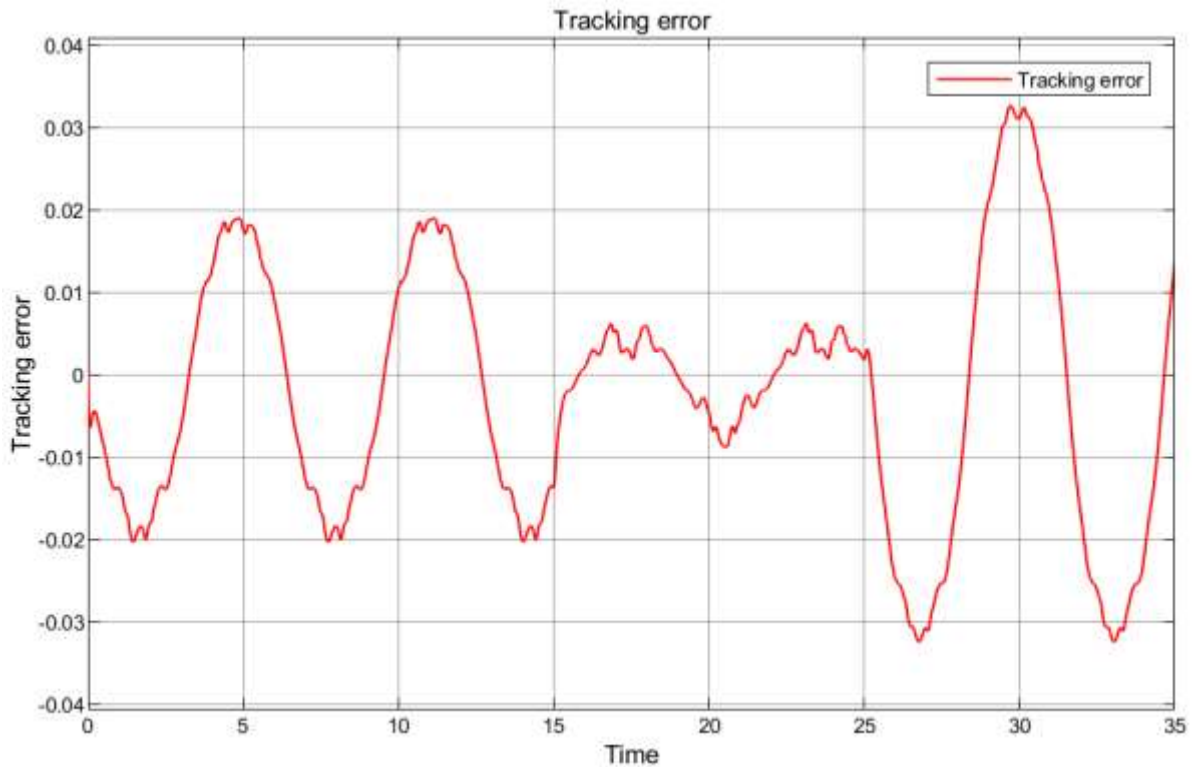


Figure 4. 5: Tracking error using SMC

Figure 4.5 shows the tracking error of the system using conventional Sliding Mode Control (SMC). The figure depicts the difference between the desired steering input (driver's command) and the actual steering response across different road conditions, including wet asphalt, snowy, and dry asphalt roads. The conventional SMC exhibits higher tracking errors, particularly on dry asphalt, where the system struggles to accurately follow the desired trajectory. The increased chattering and insufficient disturbance rejection capabilities of the conventional SMC contribute to these higher errors, especially when road conditions induce significant uncertainties. This figure underscores the limitations of conventional SMC in providing precise and stable steering performance, especially in environments with varying road surfaces.

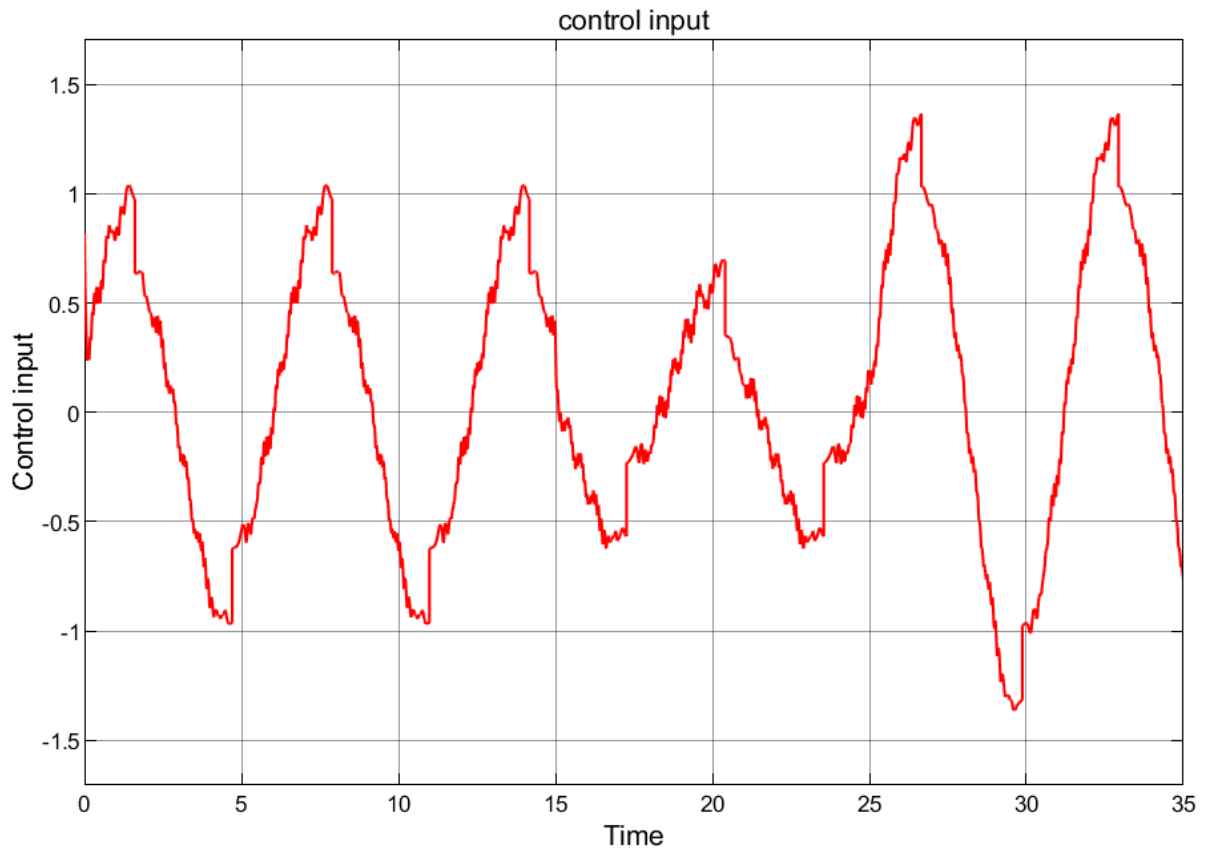


Figure 4. 6: Control torque using SMC

Figure 4.6 shows the control torque of the system using conventional Sliding Mode Control (SMC). The figure illustrates the control input generated by the conventional SMC to achieve the desired steering response across different road conditions, including wet asphalt, snowy, and dry asphalt roads. The control torque profile demonstrates that the conventional SMC demands higher torque from the steering motor, particularly on dry asphalt. This is due to the increased chattering and oscillations inherent in the traditional sliding mode control approach, which requires more aggressive corrective action to handle disturbances and uncertainties. These higher torque demands can lead to inefficiencies and excessive wear on the steering motor, highlighting a key limitation of the conventional SMC, especially in road conditions with varying friction.

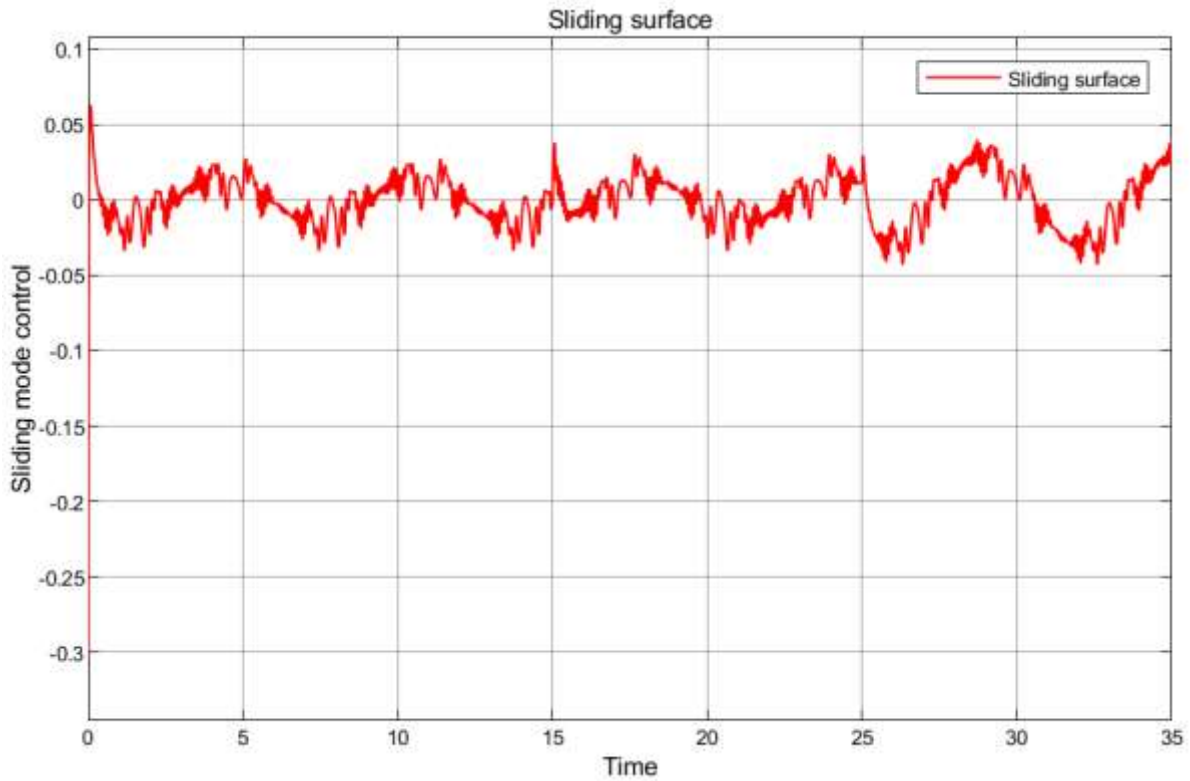


Figure 4. 7: Sliding surface for ISMC

Figure 4.7 shows the sliding surface of the proposed system, which is a key component of the integral sliding mode controller. The figure illustrates how the sliding surface evolves over time as the system state (tracking error) approaches and stays on the surface. The sliding surface is defined based on the error between the desired and actual steering inputs, with the integral of the error providing additional robustness and faster convergence to the desired trajectory. As the system enters the sliding mode, the error is minimized, and the system reaches a stable equilibrium, indicating effective disturbance rejection and accurate tracking. The smooth evolution of the sliding surface in the proposed system demonstrates the effectiveness of the boundary layer in reducing chattering and ensuring a more stable control action compared to conventional sliding mode control.

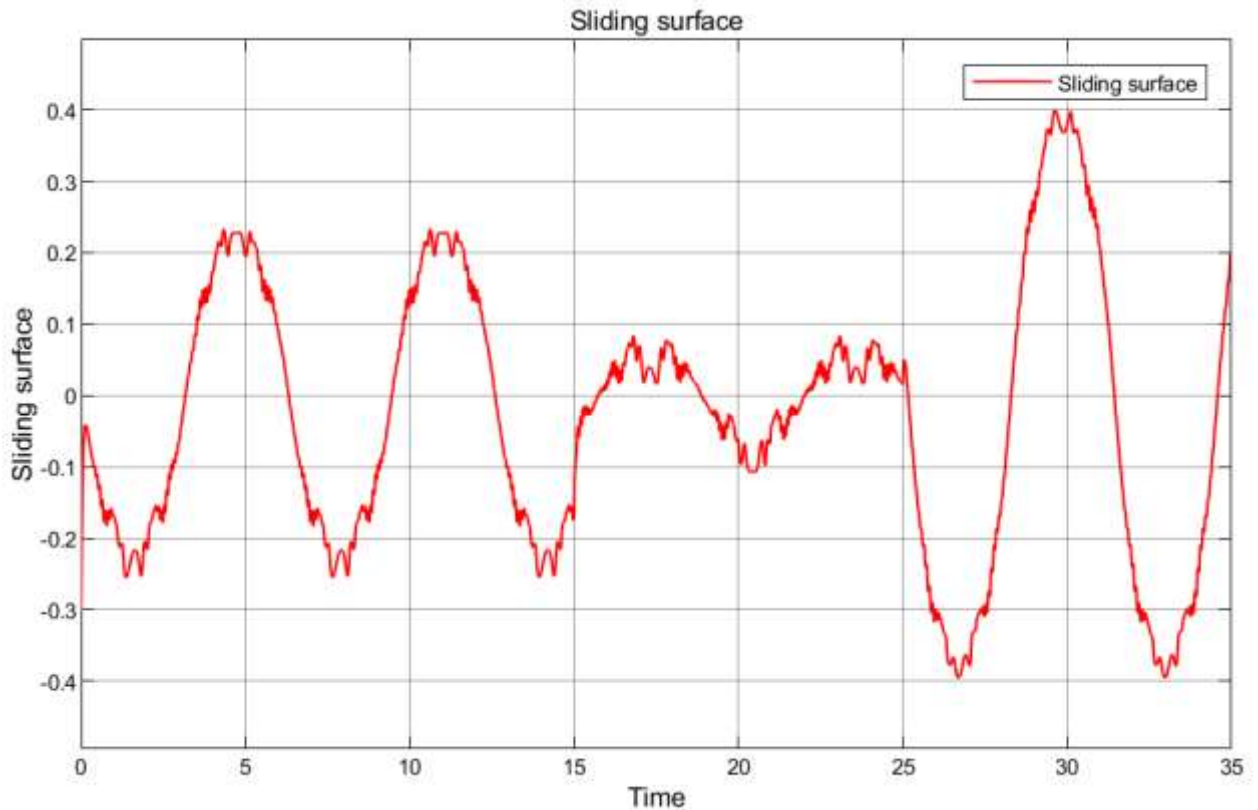


Figure 4. 8: Sliding surface for SMC

Figure 4.8 shows the sliding surface for the system using conventional Sliding Mode Control (SMC). The figure illustrates how the system state (tracking error) behaves as it approaches the sliding surface and attempts to remain on it. Unlike the proposed system, the sliding surface in the conventional SMC exhibits more oscillatory behavior, primarily due to the chattering effect that occurs as the system switches between states. This results in higher tracking errors and less smooth transitions compared to the integral sliding mode controller. The figure highlights the limitations of conventional SMC in maintaining a stable, continuous path along the sliding surface, particularly in the presence of disturbances and road surface variations. The increased fluctuations on the sliding surface demonstrate the drawbacks of conventional SMC, including higher control effort and less efficient disturbance rejection.

The simulation results, depicted in Figures 4.1 through 4.6, illustrate the tracking performance, tracking error, input control torque, and sliding variable for each controller.

Table 4.1 supplements these findings by presenting key metrics, maximum tracking error, RMS tracking error, maximum input control torque, and RMS input control torque for each controller.

Upon analysis of the simulation data, it becomes evident that the Integral Sliding Mode Controller (ISMC) demonstrate superior tracking performance in comparison to the Conventional Sliding Mode Controller.

Despite the marked improvement in tracking performance achieved by the novel controllers when compared to the conventional Sliding Mode Controller, it is noteworthy that there is no discernible disparity in the input control torques across the different controllers. This observation suggests that while the tracking objectives are significantly enhanced with the adoption of advanced control strategies, the control effort required remains relatively consistent across the board.

Table 4. 1: Performance Comparison of Controllers

Controller	Maximum tracking error (rad)		RMS tracking error (rad)	Maximum Control Torque (Nm)	RMS Control Torque (Nm)
CSMC	0.021720		0.011000	1.1110	0.4182
ISMC	0.002933		0.001192	1.7630	0.4292

Chapter Six

CONCLUSION AND RECOMMENDATION

Conclusion

This thesis presents the design and implementation of an Integral Sliding Mode Controller (ISMC) for a Steer-by-Wire (SBW) system, aimed at achieving robust and precise steering control under varying road conditions and uncertainties. The proposed ISMC integrates a sliding surface with an integral action, improving disturbance rejection and transient performance. The system was developed to address the challenges of external disturbances, model uncertainties, and road surface variations that can affect the performance of SBW systems.

Through detailed modeling and simulations, the ISMC was compared with Conventional Sliding Mode Control (SMC), demonstrating superior performance in terms of tracking accuracy, robustness, and disturbance rejection. The inclusion of a boundary layer in the switching control action effectively mitigated chattering, ensuring smoother and more efficient control. The system's performance was evaluated under diverse road conditions, such as wet asphalt, snowy, and dry asphalt roads, using MATLAB Simulink simulations. The results validated the effectiveness of the proposed ISMC in providing reliable and efficient steering control.

Furthermore, the asymptotic stability of the SBW system was verified using Lyapunov stability theory, confirming the reliability and robustness of the proposed control strategy. The proposed ISMC proves to be an effective solution for modern automotive applications, offering enhanced safety, performance, and adaptability to varying driving conditions.

In conclusion, the ISMC for the SBW system represents a significant advancement in steering control technology, and future work may involve hardware implementation and further optimization of the control strategy to handle additional real-world challenges.

Future Work and Recommendations

To further enhance the performance and applicability of the proposed Integral Sliding Mode Controller (ISMC) for the Steer-by-Wire (SBW) system, the following future work and recommendations are suggested:

Implementing Optimization Techniques:

Employ optimization algorithms such as Genetic Algorithm (GA) or Particle Swarm Optimization (PSO) to determine the optimal gain matrix for the ISMC. These techniques can enhance the tuning process by finding the optimal balance between tracking accuracy, robustness, and energy efficiency. Such methods would also improve the adaptability of the control strategy to varying system dynamics and road conditions.

Prototype Development:

Build a physical prototype of the SBW system to validate the effectiveness of the ISMC in a real-world scenario. This includes designing and assembling the hardware components, such as actuators, sensors, and a real-time control unit, and integrating the proposed control algorithm into the prototype for experimental testing.

Integration of Optimization and Real-Time Implementation:

Combine the optimized gain matrices obtained through GA or PSO with real-time implementation on the prototype system. This would ensure that the optimized parameters translate into practical benefits during operation under various uncertainties

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APPENDIX

Appendix A: MATLAB function

```
clear
```

```
clc
```

```
close all
```

```
% nominal SBW system parameters
```

```
a_o = 0.064
```

```
b_o = 0.16
```

```
Fs_o = 3.04
```

```
Kr_o = 18
```

```
Jh = 0.0791
```

```
Bh = 0.15
```

```
Ch = 0.2
```

```
N_theta = 12
```

```
% parameters of implimented controller and differentiators
```

```
K1 = -80
```

```
K2 = -15.5
```

```
lambda = 12
```

```
lambda_2 = 12
```

```
lambda_3 = 12
```

```
lambda_4 = 12
```

```
lambda_5 = 12
```

```
lambda_6 = 12
```

```
q1 = 0.5
```

```
q2 = 0.01
```

```
q3 = 0.5
```

```
q4 = 0.5
```

```
q5 = 0.5
```

```
q6 = 0.5
```

$q7 = 0.5$

$\delta = 0.1$

% The uncertain bound parameters

$c_0 = 1.0$

$c_1 = 0.3$

$c_2 = 0.1$

$\gamma_0 = 6$

$\gamma_1 = 2.8$

$\gamma_2 = 2.2$

% terminal sliding surface

$p = 3$

$q = 5$

% parameters for self aligning torque

$\rho_0 = 300$ % nominal tire dependent parameter

% $\rho_1 = 520$ % representing wet asphalt

% $\rho_2 = 150$ % representing snowy road

% $\rho_3 = 950$ % representing dry asphalt road

$X = 273.5$ % the ratio between the actual self-aligning

% torque and the input voltage of the servo driver

Appendix B: Simulink model of Conventional Sliding Mode Control

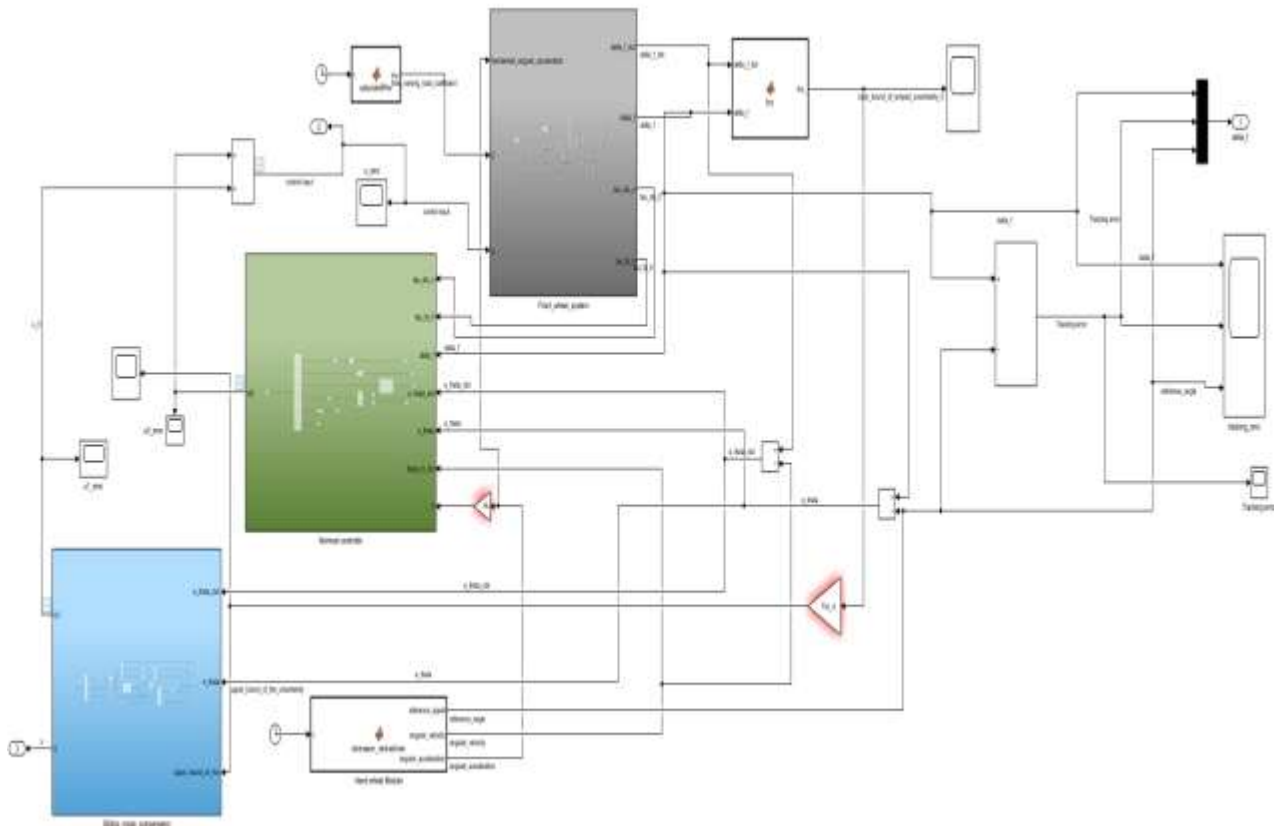


Figure A. 1: Overall conventional sliding model control of SBW System

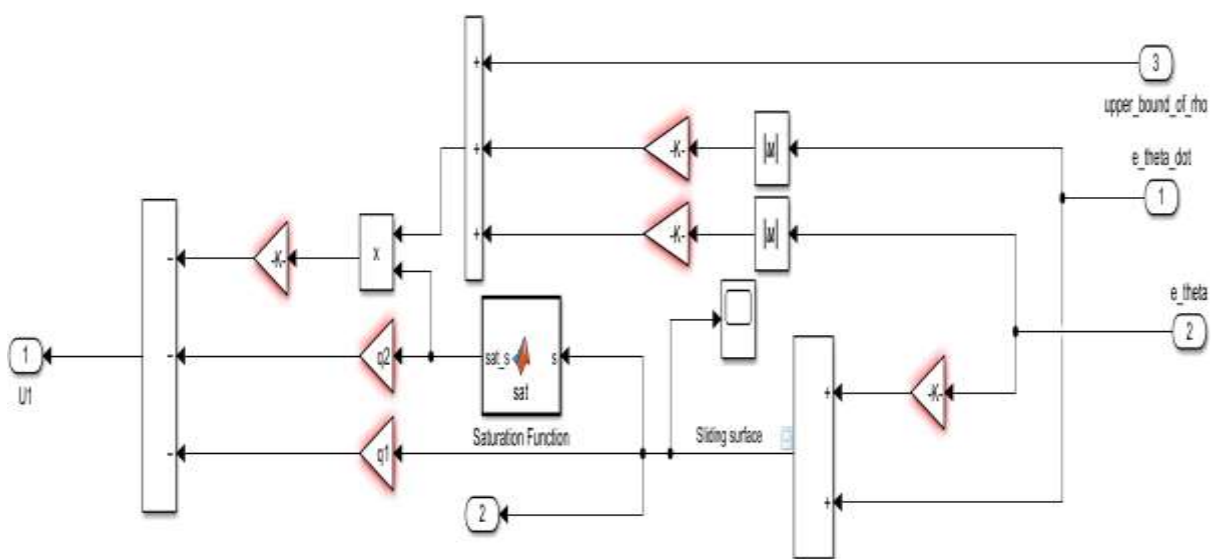


Figure A. 2: Smulink model of switching control input

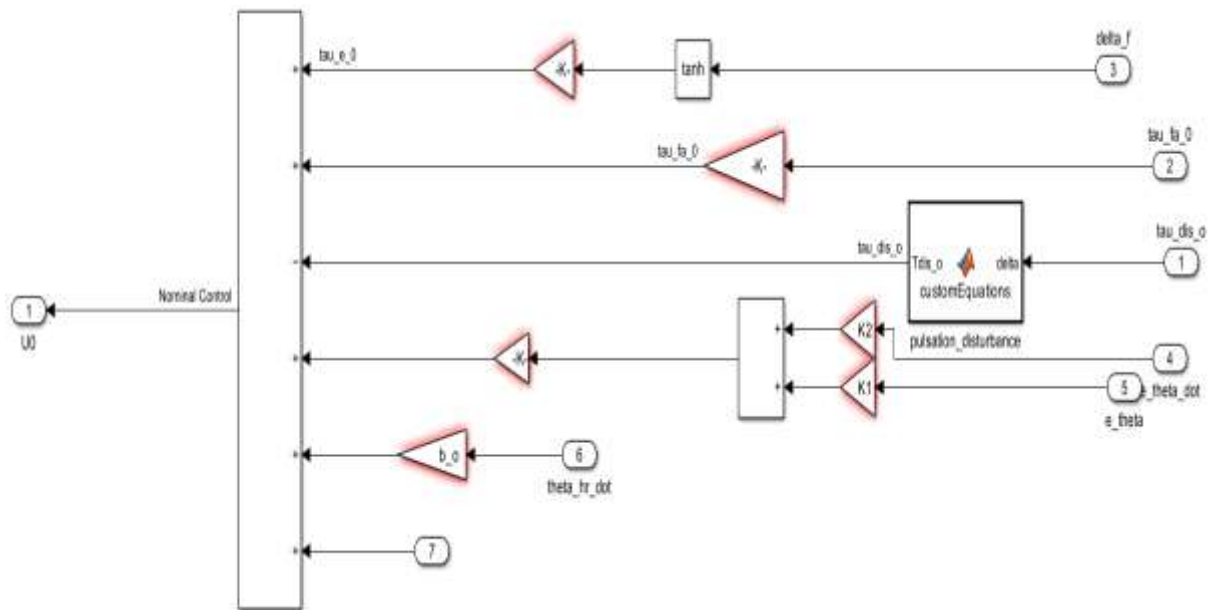


Figure A. 3: Smulink model of nominal control input

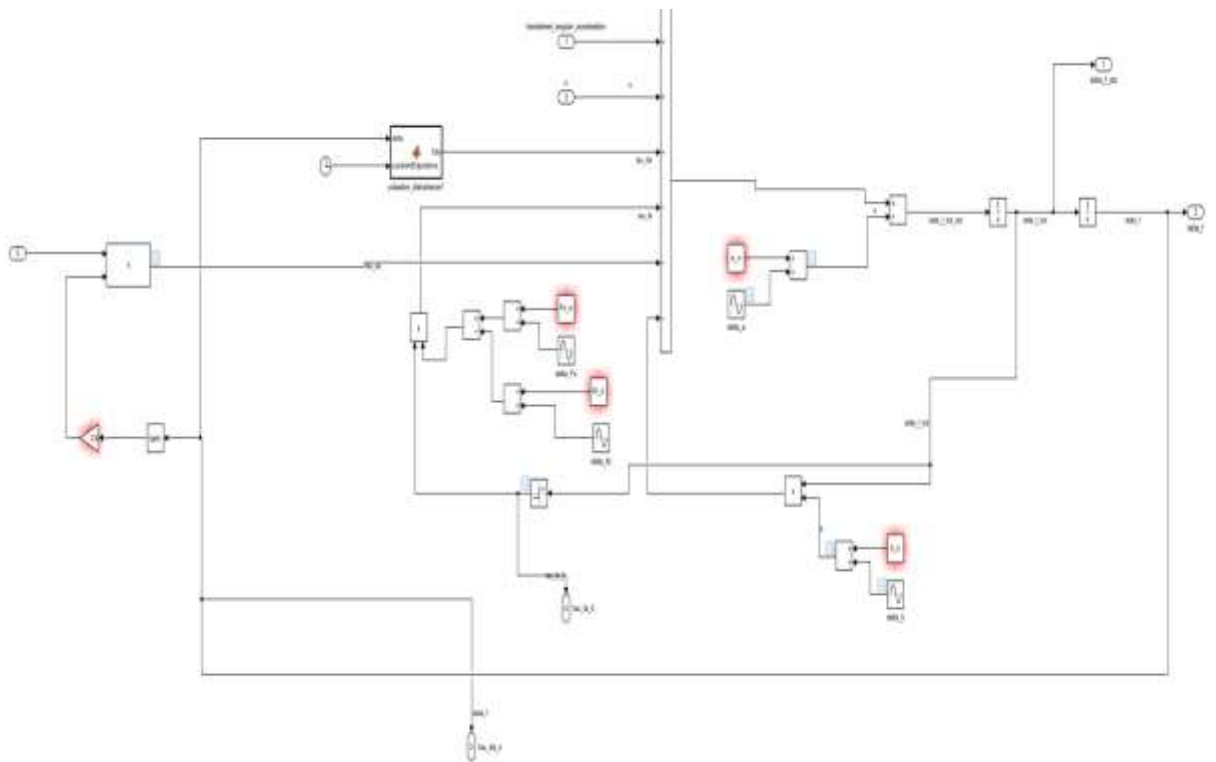


Figure A. 4: Dynamic model of SBW system