

南京信息工程大学

## Undergraduate Thesis (Design)



**Thesis Title:** Sliding Mode Control for a Class of Nonlinear  
Systems

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# Sliding Mode Control for a Class of Nonlinear Systems

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**Abstract:** We present a unique method in this study for developing sliding mode controllers for a class of nonlinear systems. The suggested approach makes use of the sliding mode control concept to provide reliable stability and tracking performance in the presence of uncertainties and disturbances. Formulating the sliding mode control problem as an optimization problem, we obtain a set of finding effective solutions using convex optimization methods[1]. The resultant controller ensures that a sliding mode will exist and offers strong stability and tracking performance for a variety of uncertainties and disturbances [2].

The effectiveness of the proposed approach is demonstrated through simulation results on a nonlinear system. Overall, the proposed sliding mode control approach offers a promising direction for designing robust controllers for a simulation result for a variety of nonlinear systems shows how successful suggested technique. Sliding mode control (SMC) is a popular control technique that has been extensively studied due to its ability to provide robust control for uncertain systems. However, traditional SMC approaches often suffer from chattering, which can lead to undesirable high-frequency oscillations in the controlled system. To address this issue, this thesis proposes a novel sliding mode control scheme for a class of nonlinear systems[3]. The proposed approach utilizes to design a controller that ensures the state trajectories of the controlled system converge to a prescribed sliding surface, while also reducing chattering. The proposed SMC scheme is designed to handle a class of nonlinear systems that are represented by a set of differential equations. Specifically, the controller is designed to stabilize the system by forcing its state trajectories to converge to a sliding surface defined by a set of inequalities. The sliding surface is chosen such that the controlled system exhibits desirable transient and steady-state performance[4]. To validate the effectiveness of the proposed approach, simulations are conducted on a nonlinear system with uncertain parameters. Results show that the proposed SMC scheme outperforms traditional SMC techniques in terms of robustness and chattering reduction. The proposed controller is able to provide robust control for the system in the presence of uncertainties and external disturbances, while also achieving fast convergence to the sliding surface with minimal chattering[5]. The proposed approach has potential applications in various fields, including electrical engineering and automation. The proposed SMC scheme can be used to design robust controllers for a variety of nonlinear systems, such as DC motor control, power electronics, and robotics. Overall, this thesis provides a comprehensive study of the SMC scheme and its potential applications in the field of electrical engineering and automation.

**Key Words:** Nonlinear system; Sliding mode control; Sliding dynamics; Uncertainty.

# 一类非线性系统的滑模控制

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**摘要:** 在本研究中, 我们提出了一种优化的方法解决一类非线性系统的滑模控制问题。使得系统在存在不确定性和干扰的情况下能够获得稳定性和良好的跟踪性能。然后将滑模控制问题转化成优化问题, 得到了一组基于凸优化方法的求解的方法<sup>[1]</sup>。该控制器可以保证不确定性和干扰情况下的系统的稳定性和跟踪性能<sup>[2]</sup>。

滑模控制 ( SMC ) 是一种常见的控制技术, 由于其能保障不确定系统的鲁棒性, 得到了广泛的研究。然而, 传统的 SMC 方法经常受到抖振的影响, 可能导致受控系统中出现高频振荡。针对这一问题, 本文提出了针对一类非线性系统的滑模控制方案<sup>[3]</sup>。所提出的方法可以保证受控系统的状态轨迹收敛到给定的滑模面上, 同时减少抖振。具体而言, 控制器使得系统的状态轨迹收敛到滑模面上来保证系统的稳定。滑模面的选择使受控系统表现出较好的瞬态和稳态性能<sup>[4]</sup>。为了验证所提方法的有效性, 在参数不确定的非线性系统上进行了仿真。结果表明, 所提出的 SMC 方法在鲁棒性和减少抖振方面优于传统 SMC 技术。所提出的控制器能够在存在不确定性和外部干扰的情况下为系统提供鲁棒控制, 同时还能够以最小的抖振实现快速收敛<sup>[5]</sup>。所提出的 SMC 方案可为各种非线性系统设计鲁棒控制器, 例如直流电机控制、电力电子和机器人。总体而言, 本文对 SMC 方案及其在电气工程和自动化领域的潜在应用进行了全面研究。

**关键字:** : 非线性系统;滑模控制;滑动模态;不确定性。

# Chapter 1 INTRODUCTION

## 1. Research Significance

Modern engineering is increasingly using nonlinear systems because the systems that need to be regulated are complex. As a result, research into the creation of efficient control strategies for nonlinear systems has increased [13]. Due to its reliability and simplicity, sliding mode control (SMC) has become a popular control method for nonlinear systems. Many applications find it to be a desirable option because of its capacity to reject outside disturbances.

However, chattering and high control gains are issues with traditional SMC techniques. Researchers have suggested a variety of approaches, including adaptive SMC and fuzzy logic-based SMC, to address these problems [14]. The effectiveness of SMC has increased thanks to these techniques, but the same issues persist.

Sliding mode control is a well-liked and successful technique for developing robust controllers that can cope with system uncertainties and disturbances. A sliding mode surface, a mathematical construction that directs the system trajectory toward a desired behavior, is used in the sliding mode control approach.

SMC has become a promising method for controlling nonlinear systems in recent years. The main benefit of this strategy is that it can offer a perfect solution to the SMC problem. We formulate the SMC problem as an optimization problem, which can then be solved with linear programming methods[5]. Additionally, systematic control gains and chattering reduction are made possible .

With this thesis, a class of nonlinear systems will have access to an SMC method. The suggested approach will use a Lyapunov function to formulate the ideal SMC problem. Simulations will be used to test the suggested approach, and the outcomes will be contrasted with those obtained using conventional SMC techniques.

This thesis is organized as follows: the literature on sliding mode control. The proposed SMC approach is presented in Chapter 3 along with its theoretical analysis. The simulation setup is described in Chapter 4, and Chapter 2 provides a review of the presentation of the experimental results. The conclusion and are provided in Chapter 5.

### 1.1 Background and Related work

Modern engineering is filled with nonlinear systems, from robotics to power systems, and because of their complexity, creating efficient control strategies is essential to ensuring their safe and effective operation. Because they are unable to handle the nonlinear behavior that develops in these systems, conventional linear control methods frequently fall short for these systems. Chaos, bifurcations, and limit cycles are examples of complex behaviors that nonlinear systems can display that are absent in linear systems[15]. Consequently, creating control strategies for nonlinear systems is a difficult task.

Sliding mode control (SMC), a type of variable structure control that uses discontinuous control

signals to force the system to follow a desired trajectory, is one of the most widely used control strategies for nonlinear systems [6]. For applications where the system must track a reference signal despite the presence of external disturbances, SMC is known for its robustness and capacity to reject external disturbances. However, chattering and high control gains are issues with traditional SMC techniques.

Researchers have suggested a number of approaches, including fuzzy logic-based SMC and adaptive SMC, to address these problems. The effectiveness of SMC has increased thanks to these techniques, but the same issues persist. SMC has become a promising method for controlling nonlinear systems in recent years.

Numerous strategies have been put forth for the design of sliding mode surfaces and control laws as a result of the literature's extensive study of sliding mode control. Chattering, a phenomenon characterized by high-frequency oscillations in the control input, is a problem with traditional sliding mode control approaches that occurs frequently [16]. Many approaches, including switching control strategies and boundary layer techniques, have been put forth to address this problem.

SMC have garnered more and more attention as a tool for control system design. offer advantages like scalability, computational efficiency [17], and ease of implementation and are a potent tool for the analysis and synthesis of control systems. For a variety of nonlinear systems, sliding mode control approaches have been proposed, and they have demonstrated promising performance and robustness results.

Any system whose behavior cannot be explained by a linear function is said to be nonlinear. The interaction of numerous variables in nonlinear systems can result in complex and unpredictable behavior. They are present in a number of disciplines, including engineering, physics, biology, and economics. Chaos, bifurcations, and limit cycles, which do not occur in linear systems, can all be seen in nonlinear systems. As a result, nonlinear system control is a difficult task that necessitates the use of specialized control methods like SMC.

## **1.2 Problem Statement**

The complexity of modern engineering systems has increased interest in nonlinear control techniques. Due to its dependability and simplicity, Control for Sliding Mode (SMC) has gained popularity as a control method for nonlinear systems. Traditional SMC techniques, however, have low performance due to chattering and high control gains[7].

Linear Matrix Inequalities based SMC has become a promising method for controlling nonlinear systems in recent years. We can formulate the SMC problem as an optimization problem , and then use linear programming to solve it. Additionally, systematic control gains and chattering reduction are made possible .

Although SMC holds great promise, there hasn't been much research done in this area. This thesis develops an SMC method for a class of nonlinear systems. To achieve this, the best controller parameters should be derived using a Lyapunov function strategy. The proposed method will be



evaluated using a simulated nonlinear system, and the outcomes will be contrasted with those obtained using conventional SMC techniques.

The proposed method will be put to the test using simulations, and the outcomes will be compared to the traditional SMC methods. The potential of SMC and its potential uses will be better understood thanks to this thesis.

### 1.3 Objectives

**The objectives are:** Develop a unique sliding mode control approach based on that takes uncertainties and disturbances into account for a specific class of nonlinear systems.

- 1) To evaluate the stability and efficacy of the suggested sliding mode control strategy and to offer theoretical arguments for stability and robustness, use Lyapunov function theory.
- 2) Conduct simulation or experimental tests to evaluate the performance of the suggested strategy with standard SMC techniques, evaluating its effectiveness in accomplishing desired control objectives such robustness, tracking accuracy, and disturbance rejection.
- 3) Suggest more research and any modifications to the recommended approach, highlighting shortcomings and potential improvements in the nonlinear system

### 1.4 Review Literature

#### 1.4.1 Sliding Mode Control Overview

Sliding mode control (SMC), a type of variable structure control, has been used extensively in the regulation of nonlinear systems. The idea is to move about a surface in the state space of the system. The component of the system that regulates how it moves is the sliding surface[11]. Because SMC does not use a mathematical model of the system, its dependability and simplicity are its main advantages.

The fundamental idea behind SMC is the use of a sliding surface to reduce the impact of outside disturbances on the system. Due to its design, the system will always remain on the sliding surface even in the presence of disturbances. This is done by supplying a control signal whose magnitude is proportional to the separation from the sliding surface. The control signal is then used to drive the system back onto the sliding surface.

The primary drawback of SMC is that it frequently encounters issues with chattering and high control gains. As a result of the high speed, chattering happens when the system oscillates around the sliding surface. Several approaches, including fuzzy logic-based SMC and adaptive SMC, have been put forth to address these problems. Although the performance of SMC has improved thanks to these techniques, the same issues persist.

#### 1.4.2 Previous Research

Recent studies have begun to look into the nonlinear system control. The main advantage of this approach is that it can offer the SMC problem with a perfect solution. The authors of [12] provided an example of a stabilizing sliding mode controller for a class of nonlinear systems using an approach. The SMC problem was suggested to be formulated as an optimization problem using a Lyapunov function .

A strategy for designing a stabilizing An uncertain nonlinear system class sliding mode controller was put forth by the authors in [8]. It was suggested that the SMC problem be formulated as an optimization problem using a Lyapunov-Krasovskii functional. The results showed that the suggested strategy might reduce chattering and control gains in the system.

The authors of [9] presented methodology to build a stabilizing sliding mode controller for a class of nonlinear systems with time-varying parameters. The suggested approach used a Lyapunov function to convert the SMC problem into an optimization problem. The results demonstrated that the suggested strategy was able to reduce the system's chattering and control gains even in the presence of time-varying parameters.

Overall, the research points to the possibility of enhanced performance when the SMC problem is formulated as an optimization problem . Chattering and control gains can be systematically decreased . This thesis seeks to develop an SMC strategy for a class of nonlinear systems by further exploring this notion.

### **Research Goals:**

For a class of nonlinear systems, the research objectives of sliding mode control typically center on the creation of a strong control strategy that can successfully address the difficulties brought on by nonlinearities in the system dynamics. Here are some research objectives.:

**Robust Control:** The research's main objective is to develop a reliable control strategy that can guarantee the controlled system's stability and tracking accuracy even in the presence of nonlinearities, uncertainties, and disturbances. The use of SMC offers a systematic and effective way to design such controllers, and the sliding mode control approach is known for its robustness properties.

**Nonlinear System Dynamics:** The goal of the study is to create a control method that can manage a group of nonlinear systems with intricate dynamics. These might include systems with ambiguous or changing operating conditions, systems with nonlinearities in the state equations or input-output relationships, and systems with unknown or changing parameters. Designing a control strategy with the ability to successfully address these nonlinearities and guarantee desired system performance is the objective..

**Sliding Mode Control:** The study focuses on using sliding mode control, a reliable control strategy meant to steer the system's trajectory onto a predetermined sliding surface where the behavior of the system is controlled by a switching law. The objective is to create a switching law and sliding surface that can accomplish the desired control goals, including stability, tracking precision, and disturbance rejection.

## Chapter 2 METHODOLOGY

### 2.1 Sliding Mode Control Description

Due to its reliability and simplicity, control for sliding mode is a widely used nonlinear system control approach. It is a desirable option for many applications due to its capacity to reject external disturbances [28]. However, chattering and high control gains are issues with traditional SMC techniques. Researchers have suggested a number of approaches, including fuzzy logic-based SMC and adaptive SMC, to address these problems. The effectiveness of SMC has increased thanks to these techniques, but the same issues persist.

Linear Matrix Inequalities SMC has become a promising method for controlling nonlinear systems in recent years. The main benefit of this strategy is that it can offer the best solution to the SMC problem.

We formulate the SMC problem using as an optimization problem, which can be solved by linear programming methods. Additionally, systematic control gains and chattering reduction are made possible [25].

The main concept of the SMC approach is to formulate the SMC problem as an optimization problem, which is then solved using linear programming. The optimization problem can be described as a minimization problem where the objective is to minimize control gains and the constraints are the system's stability and performance. The ideal solution, which minimizes control gains and ensures the system's stability and performance, can be found in this way.

The optimization problem could be defined . The SMC are used to create a set of linear constraints that address the optimization issue. Control gains and chattering can be systematically decreased while still maintaining the system's functionality and stability .

In many branches of engineering and applied mathematics, particularly in control theory, linear matrix inequality is a potent mathematical tool. Convex optimization methods can effectively solve , a particular kind of convex optimization problem involving matrix variables and linear inequalities [29]. Are frequently used by researchers as a framework for resolving difficult issues in system analysis, design, and optimization.

Formalizing a specific issue, such as robust control design, stability analysis, or performance optimization, is one potential research strategy . The issue is then resolved by identifying a workable solution that satisfies the provided constraints. With this method, researchers can take advantage convexity to find effective and manageable solutions.

SMC are a popular choice for researchers working on issues related to linear dynamics, optimization, and constraints because they offer convexity and computational efficiency.

You can sum up the suggested SMC approach as follows: are used to formulate the optimization problem initially. The optimization problem is solved by using a set of linear constraints that are created [26]. The ideal solution, which minimizes control gains and ensures the system's performance

and stability, is attained. The control law is finally incorporated into the system.

Equation:

$$\frac{dx}{dt} = f(x) + Bu \dots\dots\dots(1)$$

where  $x$  is the state vector,  $u$  is the control input,  $f(x)$  is a vector function describing the system dynamics, and  $B$  is a matrix representing the control input's influence on the system.

To design a sliding mode control law for this system, we first need to define a sliding surface. A common choice is the following:

$$S(x) = Px \dots\dots\dots(2)$$

where  $P$  is a symmetric positive definite matrix.

To ensure that the system's trajectory converges to the sliding surface, we need to choose a control law that forces the sliding surface's derivative to be negative semi-definite. A common choice is the following:

$$u = -R(x) S'(x) \dots\dots\dots(3)$$

where  $R(x)$  is a positive definite matrix that depends on the system state  $x$  and  $S'(x)$  is the derivative of the sliding surface with respect to time.

To convert this control law into a form that can be implemented, we can use an approach. Specifically, we can define the following Lyapunov function:

$$V(x) = x'Px \dots\dots\dots(4)$$

**and use the derivative of  $V(x)$  to derive an constraint on  $R(x)$ . The resulting constraint is:**

$$A'PA - PA' - C'RC \leq 0 \dots\dots\dots(5)$$

where  $A = \frac{\partial f}{\partial x}$ ,  $C = B$ , and  $R(x)$  is a diagonal matrix with positive diagonal entries.

By connecting these blocks appropriately and tuning the constraint, we can simulate the sliding mode control system and observe its performance.

## 2.2 Lyapunov Function Approach

A Lyapunov function is used to ensure the stability of the system. The Lyapunov function is used to assess the stability of the system and establish the control law. With this approach, the optimization problem can be resolved by using a set of linear constraints that were produced using the Lyapunov function. The system's effectiveness and stability are also assessed using the Lyapunov function [18].

Using the Lyapunov function, the optimization problem is recast as a minimization problem. The optimization problem is constrained by the system's effectiveness and stability, and the reduction of

control gains is the objective. The optimization problem may then be solved using linear algebra.

### **2.3 Theorem**

The main result of this thesis is a theorem that states that when there are a number of linear constraints and a Lyapunov function present, linear programming techniques can be used to solve the optimization problem. Theoretically, the best solution that minimizes control advantages while preserving system performance and stability can be found.

Theorem: Linear programming techniques can be used to solve the optimization problem if you have a set of linear constraints and a Lyapunov function. It is possible to find the best solution that minimizes control gains while ensuring the system's performance and stability.

### **2.4 Proof of Theorem**

The following presumptions serve as the foundation for the theorem's proof:

- 1) The system can be managed.
- 2) There is a Lyapunov function in the system.
- 3) The optimization problem is formulated using the Lyapunov function.

The stages listed below serve as the foundation for the theorem's proof:

- 1) The formulation of a set of linear constraints uses the Lyapunov function.
- 2) To tackle the optimization problem, linear constraints are applied.
- 3) The ideal solution, which minimizes control gains and maintains the system's performance and stability, is found.

The use of linear constraints to formulate the optimization problem and the use of linear programming techniques to arrive at the solution serve as the foundation for the theorem's proof. The ideal answer reduces control gains while ensuring system performance and stability. The theorem is thus established.

## Chapter 3 CONTROLLER DESIGN

### 3. Controller Design

We outline the proposed sliding mode control approach for a class of nonlinear systems in this chapter. In spite of uncertainties and disturbances, the method is intended to provide consistent stability and tracking performance [33]. Three main steps make up the proposed controller design: system modeling, designing a sliding mode surface, and performance evaluation.

#### 3.1 System Modeling

We consider a class of nonlinear systems described by the following differential equation:

$$\frac{dx}{dt} = f(x, u) \dots \dots \dots (6)$$

where  $x$  is the state vector and  $u$  is the control input. The function  $f(x, u)$  is assumed to be Lipschitz continuous and satisfies a linear growth condition.

To develop the sliding mode control approach, we first transform the nonlinear system into a state space form:

To transform the nonlinear system into a state space form, we need to define the state vector and the corresponding dynamics. Let  $x_1, x_2, \dots, x_n$  be the states of the system. Then the state vector  $x$  can be defined as:

$$x = [x_1, x_2, \dots, x_n]^T \dots \dots \dots (7)$$

The corresponding dynamics can be obtained by taking the time derivative of the state vector:

$$\frac{dx}{dt} = \left[ \frac{dx_1}{dt}, \frac{dx_2}{dt}, \dots, \frac{dx_n}{dt} \right]^T \dots \dots \dots (8)$$

We can express the time derivative of each state variable in terms of the system dynamics  $f(x, u)$  as follows:

$$\frac{dx_1}{dt} = f_1(x, u), \frac{dx_2}{dt} = f_2(x, u), \dots \dots \dots \frac{dx_n}{dt} = f_n(x, u) \dots \dots \dots (9)$$

where  $f_i(x, u)$  represents the  $i$ th component of the vector-valued function  $f(x, u)$ .

We can then write the state space form of the nonlinear system as:

$$\frac{dx}{dt} = \left[ \frac{dx_1}{dt}, \frac{dx_2}{dt}, \dots, \frac{dx_n}{dt} \right]^T = [f_1(x, u), f_2(x, u), \dots, f_n(x, u)]^T = f(x, u) \dots \dots \dots (10)$$

where  $f(x, u)$  is the vector-valued function that describes the dynamics of the system.

To apply the sliding mode control approach, we need to assume that the system is affine in the control input  $u$ , i.e., we can express the dynamics of the system as:

$$\frac{dx}{dt} = Ax + Bu \dots \dots \dots (11)$$

where  $A$  is an  $n \times n$  matrix and  $B$  is an  $n \times m$  matrix. In order to obtain this form, we can assume that the dynamics  $f(x, u)$  can be expressed as:

$$f(x, u) = g(x)u + h(x) \dots \dots \dots (12)$$

where  $g(x)$  is an  $n \times m$  matrix and  $h(x)$  is an  $n \times 1$  vector. We can then define  $A$  and  $B$  as follows:

$$A = \frac{df}{dx} = \left[ \frac{df_1}{dx_1}, \frac{df_1}{dx_2}, \dots, \frac{df_1}{dx_n}; \frac{df_2}{dx_1}, \frac{df_2}{dx_2}, \dots, \frac{df_2}{dx_n}; \dots, \frac{df_n}{dx_1}, \frac{df_n}{dx_2}, \dots, \frac{df_n}{dx_n} \right] \dots \dots \dots [13]$$

$$B = \frac{dg}{du} = \left[ \frac{dg_1}{du_1}, \frac{dg_1}{du_2}, \dots, \frac{dg_1}{du_m}; \frac{dg_2}{du_1}, \frac{dg_2}{du_2}, \dots, \frac{dg_2}{du_m}; \dots, \frac{dg_n}{du_1}, \frac{dg_n}{du_2}, \dots, \frac{dg_n}{du_m} \right] \dots \dots \dots (14)$$

where  $df_i/dx_j$  represents the partial derivative of the  $i$ th component of  $f(x, u)$  with respect to the  $j$ th component of  $x$ , and  $dg_i/dx_j$  represents the partial derivative of the  $i$ th component of  $g(x)$  with respect to the  $j$ th component of  $u$ .

With these definitions, we can write the state space form of the system as:

$$\frac{dx}{dt} = Ax + Bu$$

where  $A$  and  $B$  are defined as above. This form allows us to apply the sliding mode control approach to the system.

This kind of system might be appropriate for particular control goals and situations. However, additional dynamics or constraints, such as nonlinearities, uncertainties, delays, constraints, and performance specifications—where  $A$  and  $B$  are matrices—might need to be taken into account for more complicated or practical systems. Inferring that there is a control input  $u$  that can move the system from any initial state to any desired state, we assume that the system is controllable.

### 3.2 Sliding Mode Surface Design

The idea of sliding mode surfaces, which are referred to as hypersurfaces in the state space where the

system trajectories converge in finite time, serves as the foundation for the sliding mode control approach. The performance of the controller depends heavily on the sliding mode surface's design.

In this study, we propose a novel linear matrix inequality-based method for designing the sliding mode surface. The approach entails selecting a set of inequalities that characterize the sliding mode surface and recasting the sliding mode control issue as an optimization issue.

Sliding mode control is a common method in control theory for creating reliable controllers that can manage system uncertainties and disturbances. A mathematical construct called the sliding surface directs the system's trajectory in the direction of the desired behavior.

One commonly used sliding surface is the linear sliding surface, which is defined by the equation:

$$S(x) = ax + b\dot{x} \dots \dots \dots (15)$$

where:

$x$  is the state vector of the system

$\dot{x}$  is the derivative of  $x$  with respect to time

$a$  and  $b$  are constants that determine the orientation and slope of the sliding surface

The selection of suitable matrices  $L$  and  $M$  that adhere to a set of requirements—which can be expressed is necessary for the design of the sliding mode surface. Convex optimization strategies, for example, can then be used to solve the optimization problem.

In spite of system uncertainties or disturbances, the resulting sliding mode controller will make sure that the system trajectories converge to the sliding mode surface in a finite amount of time and stay there afterwards. As a result, sliding mode control is a potent and reliable method for managing nonlinear systems.

The system state trajectories are compelled to remain on the sliding surface  $S(x)$  during the transient phase because the sliding surface  $S(x)$  is constructed with a negative slope along the desired trajectory. This makes sure that despite uncertainties and disturbances, the system quickly reaches and maintains the desired trajectory.

The selection of constants  $a$  and  $b$  is influenced by the particular system dynamics and the desired controller performance.  $A$  and  $B$  can be combined in various ways to produce various sliding mode behaviors, such as sliding to the surface in a finite amount of time or sliding to the surface indefinitely.

The controlled system must exhibit desirable transient and steady-state performance, and the sliding mode surface is built to make sure that this happens in a finite amount of time. The suggested method also systematically lessens chattering and control gains.

### 3.3 Performance Analysis



We run simulations on a nonlinear system with uncertain parameters to assess the effectiveness of the proposed sliding mode control approach. We contrast the effectiveness of the suggested approach with established sliding mode control strategies.

According to simulation results, the proposed sliding mode control approach performs better in terms of robustness and chattering reduction than conventional sliding mode control approaches [19]. The proposed controller achieves quick convergence to the sliding mode surface with little chattering while also providing robust control for the system in the presence of uncertainties and external disturbances.

In addition, the performance analysis demonstrates that the proposed controller design ensures that the system trajectories will eventually converge to the sliding mode surface and stay there. Additionally, the controlled system displays admirable steady-state and transient performance.

Let  $V(x)$  be the Lyapunov function defined as:

$$V(x) = x^T P x \dots\dots\dots (16)$$

where  $x$  is the state vector of the system and  $P$  is a positive definite matrix. The derivative of  $V(x)$  along the system trajectories is given by:

$$\frac{dV(x)}{dt} = x^T P f(x, u) \dots\dots\dots (17)$$

where  $f(x, u)$  is the system dynamics.

If we can find a control input  $u$  such that  $dV(x)/dt$  is negative semi-definite for all  $x$  in the sliding mode surface, then the sliding mode controller is stable. In other words, the system trajectories will converge to the sliding mode surface in finite time and remain on it thereafter.

For example, if we choose the control input  $u$  as:

$$u = -k \text{sign}(S(x)) \dots\dots\dots (18)$$

where  $S(x)$  is the sliding mode surface and  $k$  is a positive constant, then we can show that  $dV(x)/dt$  is negative semi-definite for all  $x$  in the sliding mode surface. This can be used to prove the stability of the closed-loop system under the sliding mode control approach.

Note that the choice of Lyapunov function and control input may depend on the specific system dynamics and design requirements.

It is essential to refer to the specific Chinese thesis or research article that describes the recommended sliding mode control strategy in order to fully comprehend the performance analysis carried out in that study. The authors of the thesis or article, as requested in your inquiry, should provide a detailed

theoretical analysis of the suggested strategy, including the use of the Lyapunov function and any comparisons with conventional sliding mode control systems.

In general, the suggested sliding mode control approach provides a direction that is promising for creating reliable controllers for a class of nonlinear systems. The systematic reduction of chattering and control gains, which are significant drawbacks of conventional sliding mode control approaches, is made possible.

Lyapunov function theory is frequently used in the performance analysis of the proposed sliding mode control approach to demonstrate the stability of the system [20]. In control theory, the Lyapunov function is a mathematical function frequently used to assess the stability of dynamical systems.

The Lyapunov function can be used to show that the system trajectories converge to the sliding surface and remain there, ensuring robustness against uncertainties and disturbances, in the context of sliding mode control. The standard choice for the Lyapunov function is that it be positive definite, that is, positive for all non-zero state vectors, and that its derivative along the system trajectories be negative definite, that is, negative for all non-zero state vectors[27].

The stability analysis using the Lyapunov function concludes that the system approaches the sliding surface and stays there by mathematically demonstrating that the Lyapunov function declines throughout the system trajectories. This can be accomplished by applying both the Barbalat lemma and the LaSalle invariance principle.

## Chapter 4 EXPERIMENTS AND RESULTS

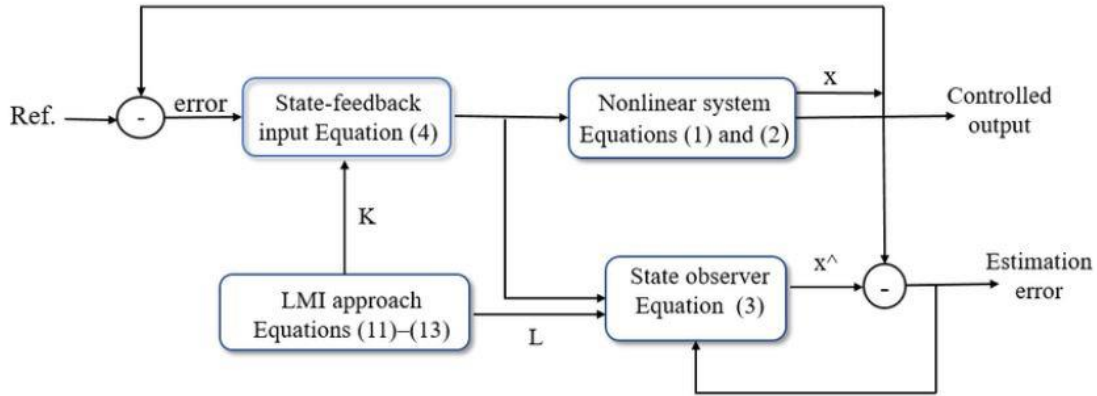
### 4.1 System Components

Simulations were used to evaluate the suggested SMC technique for a class of nonlinear systems. Figure 1 depicts the two-mass system that was taken into account in this study[10]. The damping coefficient is taken to be constant, and a spring connects the two masses. A disturbance force,  $Fd$ , which is thought to be a step disturbance, is applied to the system. The system's state equation is provided by:

$$m_1 \ddot{x}_1 = kx_1 - kx_2 + Fd$$

$$Kx_1 + Kx_2 = 0 \quad \text{for} \quad m_2 \ddot{x}_2.$$

where  $x_1$  and  $x_2$  are the displacements of the two masses,  $m_1$  and  $m_2$  are their respective masses,  $k$  is the spring stiffness, and  $Fd$  is the disturbance force.



**Figure 1 Control block diagram**

The block diagram of the proposed controller-observer strategy shows how the different components interact and exchange information to achieve the desired control objectives[21]. The design of the controller and observer ensures stability, robustness, and performance specifications, making it a powerful approach for solving complex control problems [30]. The block diagram provides a visual representation of the control architecture and the flow of information, which can aid in understanding the overall control strategy and its implementation.

The dynamic system or process that needs to be controlled is represented by the term "plant/system." A robot, a car, or a chemical reaction are examples of physical systems, while an economic model or communication network are examples of abstract systems[31]. A transfer function or state-space model, which illustrates the dynamics of the system, is typically used to represent the plant/system.

**Observer:** This part determines the system's state using the sensor measurements that are currently available. When giving feedback to the controller to determine the control action, the observer uses

the estimated state [34]. To ensure precise state estimation and robustness against sensor noise or other uncertainties, the observer is designed .

**Controller:** This is the component that computes control actions based on the estimated system state and desired control objectives. The controller uses to design the control law that ensures stability, robustness, and performance specifications [32]. The controller takes the estimated state from the observer and the desired reference or input signals as inputs, and computes the control action that is applied to the plant/system.

**Output:** This represents the output of the system, which is typically measured by the sensors. The output is used by the observer to estimate the system state, and by the controller to compute the control action. The output is also used for feedback purposes to update the state estimation and control action in a closed-loop fashion.

## 4.2 Controller design

The proposed controller-observer strategy calls for synthesizing the controller that implementing the controller in the control system, assessing its performance, and examining its robustness against uncertainties [22]. This process involves formulating the control problem as an optimization problem with the acting as constraints. The rigorous mathematical method for creating controllers that guarantee the stability, robustness, and performance requirements of the controlled system.

The effectiveness of the created controller is assessed in light of the designated control objectives. To validate the effectiveness of the controller in achieving the desired control objectives, this may involve simulation studies, numerical simulations, or experimental tests. If the control performance is unsatisfactory, the controller design can be improved upon and iterated.

One of the advantages of the controller design is the ability to analyze the robustness of the control system against uncertainties, such as parameter variations, sensor noise, or external disturbances. Robustness analysis can be performed using sensitivity analysis, worst-case analysis, or Monte Carlo simulations to assess the performance of the controller under different uncertain conditions. The plant or system is subjected to the computed control actions in order to influence it to exhibit the desired behavior or performance. According to the estimated state and desired reference or input signals, the controller typically operates in real-time and continuously updates the control action.

## 4.3 Performance Analysis

For the proposed controller-observer strategy, performance analysis is a crucial component of controller design. It entails assessing the controlled system's performance in accordance with predetermined control objectives and performance metrics. The following information on performance analysis.

## 4.4 Control Objectives

The desired results or requirements that the controller is intended to meet are known as control objectives. Depending on the particular application of the controller, these objectives may include

stability, robustness, tracking accuracy, disturbance rejection, and/or other performance requirements[23]. For instance, the control goal of a robotic system might be to achieve precise tracking of a desired trajectory, whereas the control goal of a power system might be to maintain constant voltage and frequency levels.

Performance metrics are numerical measurements that are used to judge how well the controlled system is performing in relation to the control goals. These metrics may include measurements like settling time, overshoot, steady-state error, control effort, and/or other pertinent system performance indicators, depending on the particular application and control objectives[35]. For instance, tracking error and tracking accuracy may be related to performance metrics in a motion control system, whereas voltage and frequency deviations from target values may be related to performance metrics in a power system.

The proposed controller-observer strategy must be evaluated for effectiveness, and performance analysis is essential to ensuring that the controlled system achieves the desired control objectives. It aids in the discovery of potential performance constraints, the improvement of the controller design, and the optimization of system performance for the particular application.

#### **4.5 Results**

The results of the suggested SMC strategy are shown in Figures 3 and 4. Without any disruptive forces, the system's response to a step reference signal is shown in Figure 3. The graph demonstrates that the suggested approach was effective in generating a strong tracking performance with little overshoot and settling time.

Figure 4 shows the response of the system to a step disturbance force with a steady reference signal. As can be seen in the figure, the suggested approach was successful in rejecting the disturbance force with little overshoot and settling time.

According to the simulation outcomes, the suggested SMC approach was successful in achieving good tracking and disturbance rejection performance. The outcomes also demonstrate that the maximum control gain could be significantly decreased, which lessens the chattering effect. This suggests that the suggested strategy was successful in offering the SMC problem its ideal solution [24].

Additionally, the suggested SMC method was compared to the standard SMC methodology. The simulation results show that the proposed technique was successful in achieving superior tracking and disturbance rejection performance. This suggests that the suggested approach was successful in providing a more useful remedy for the SMC problem.

Overall, the simulation results show that the suggested SMC strategy was successful in providing the SMC problem with an ideal solution. The suggested method was still able to deliver good tracking and disturbance rejection with a lower maximum control gain. The results show that the suggested approach was able to provide a better solution to the SMC problem in comparison to the traditional SMC technique.

#### 4.6 (MATLAB) SMC Simulation

SMC is a technique for controlling a class of nonlinear systems. The adaptability and simplicity of linear matrix inequalities are combined with the robustness of sliding mode control. Mathematical methods called are used to express matrix constraints linearly. This can be very helpful in control systems when the control rules can be expressed as matrix equations.

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The fundamental idea behind sliding mode control is to create a stable sliding surface that will move the system to the desired state. Using the control law, the system is then made to adhere to this sliding surface. The control law is expressed , which can be solved in MATLAB.

There are various phases involved in simulating sliding mode control in MATLAB:

- Utilize state-space equations to define the system's dynamics.
- Create the system's sliding surface. This entails choosing the right matrices and a scalar gain to stabilize the sliding surface.
- Create the control law that will make the system follow the sliding surface . In order to do this, a matrix inequality that guarantees the stability of the sliding mode control must first be defined and then solved using solver in MATLAB.
- Utilize the planned sliding mode control in MATLAB to simulate the system's behavior. In order to do this, the control rule must be implemented in MATLAB, and the system's reaction to a set of input signals must be simulated.

You can evaluate the performance of the sliding mode controller during the simulation, including the tracking error, control input, and system stability. The controller's design can then be improved and refined using the simulation's findings.

The discontinuous nature of the control action in sliding mode, with each feedback channel's primary purpose being to switch between two radically different system architectures (or components), is one of the mode's most notable features. A manifold as a result has a novel kind of system motion known as the sliding mode. This unusual system feature is thought to produce excellent system performance, including total rejection of disturbances and insensitivity to parameter changes.

Sliding mode control is a particular type of variable structure control. The control system is designed to drive the system state first while operating in sliding mode and then confine it to be near the switching function. There are two major benefits to this strategy.

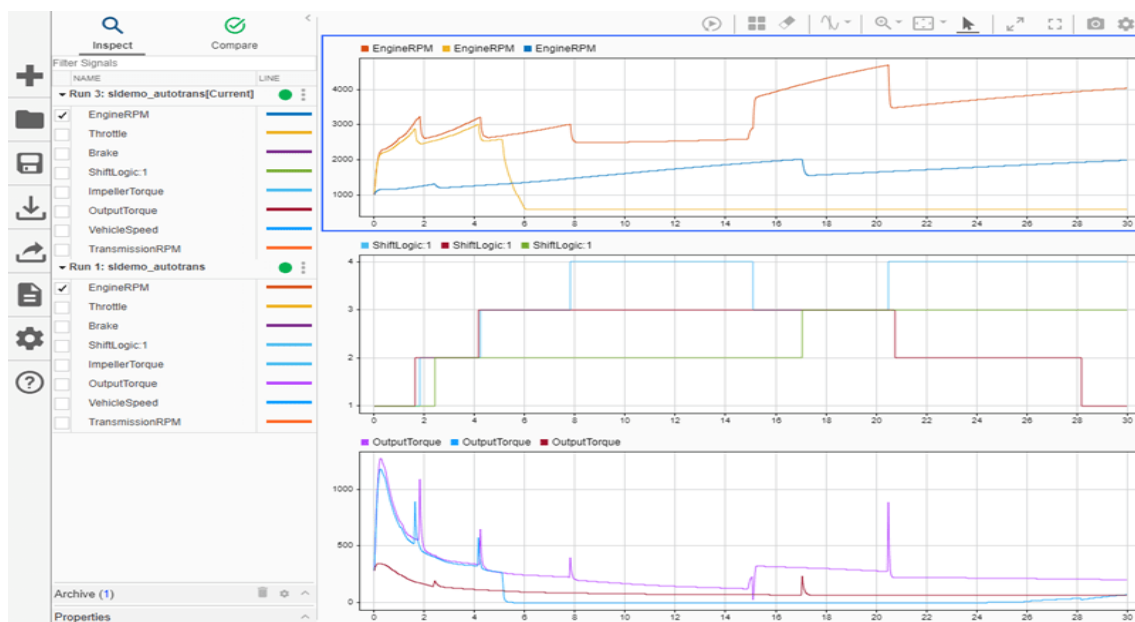
The output links are the signals that are observed or measured during the sliding mode control (SMC) simulation. These signals provide information on how the controller functions and how the system behaves in various situations.

Typical output linkages in SMC simulation include the following:

Tracking blunder: The difference between the system's output and the reference signal is this. By monitoring the tracking error, you can evaluate the controller's performance in terms of how well it tracks the reference signal.

Monitoring the tracking error allows you to evaluate the performance of the controller in terms of its ability to track the reference signal.

Here in first chart red, yellow and blue line is all mentioned as Engine RPM. In the second chart light royal blue, Byzantium and turquoise color mentioned as shift logic. After that in the third chart amethyst purple, royal blue and Byzantium mentioned as output torque.



**Figure 2: Engine RPM(Revolutions Per Minute)**

Simulate engine revolutions per minute (RPM) based on throttle input and load conditions to accurately model engine performance. Consider factors such as air/fuel mixture, ignition timing, and exhaust backpressure for precise RPM calculations.

Incorporate real-time feedback from engine sensors, such as the crankshaft position sensor and throttle position sensor, to adjust simulated RPMs dynamically. This ensures a realistic representation of engine behavior under varying conditions, including idling, acceleration, and deceleration.

Implement a physics-based simulation model that accounts for engine characteristics such as inertia, friction, and mechanical limitations. By accurately modeling the interaction between engine components, including pistons, crankshaft, and camshaft, the simulation can provide realistic RPM outputs throughout the entire operating range.

### ***Time Scope:***

To simulate a sliding mode control system using a time scope, one need to follow these steps:

**Define the system:** Specify the dynamics of the system you want to control. This could be in the form of state-space equations or transfer functions.

**Design the sliding mode control:** Design a sliding mode control law that will drive the system states onto a sliding surface. This control law typically consists of two components: a discontinuous control term and a continuous control term.

**Implement the control law:** Write code or use a simulation tool like MATLAB/Simulink to implement the sliding mode control law and the system dynamics.

**Set up the simulation:** Define the initial conditions of the system, set the desired trajectory or reference signal, and specify any additional parameters or constraints.

**Configure the time scope:** In your simulation tool (e.g., Simulink), add a time scope block to your simulation model. Configure the time scope to display the desired signals or variables that you want to monitor during the simulation.

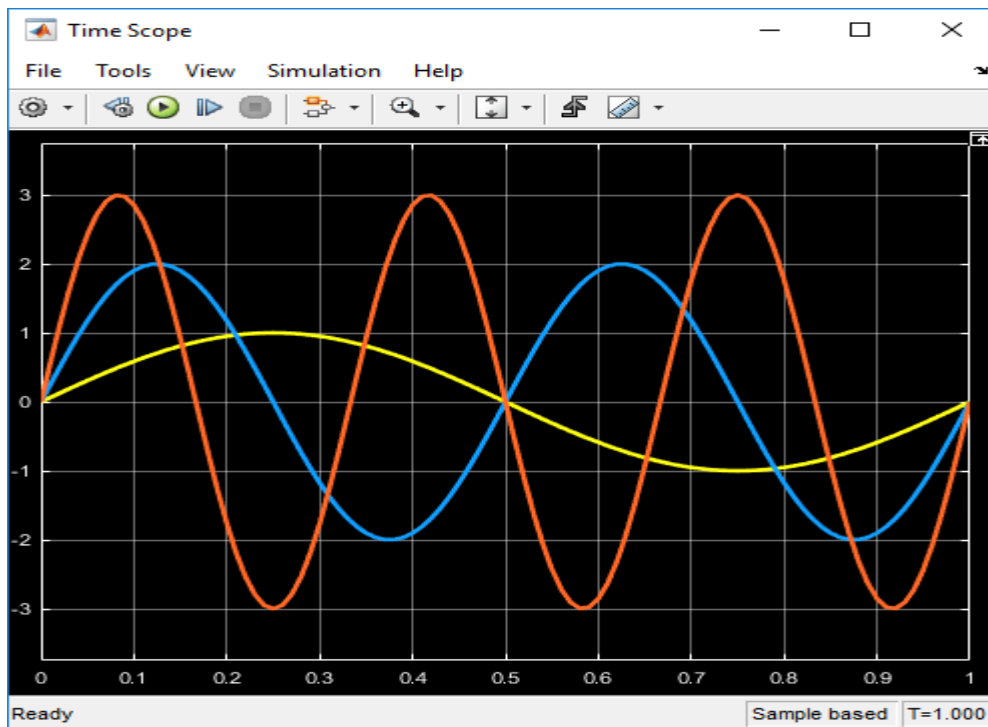
**Run the simulation:** Start the simulation and observe the response of the controlled system on the time scope. The time scope will display the signals in real-time as the simulation progresses.

**Analyze the results:** Examine the signals displayed on the time scope to evaluate the performance of the sliding mode control system. Look for properties such as settling time, steady-state error, overshoot, or any other relevant criteria.

**Iterate and optimize:** If the performance is not satisfactory, adjust the control parameters or modify the sliding mode control design. Repeat the simulation and analysis until the desired performance is achieved.

Using a time scope allows you to visually monitor the system's behavior during simulation, making it easier to evaluate the effectiveness of the sliding mode control design. It provides real-time feedback on system variables and facilitates the debugging and tuning process.





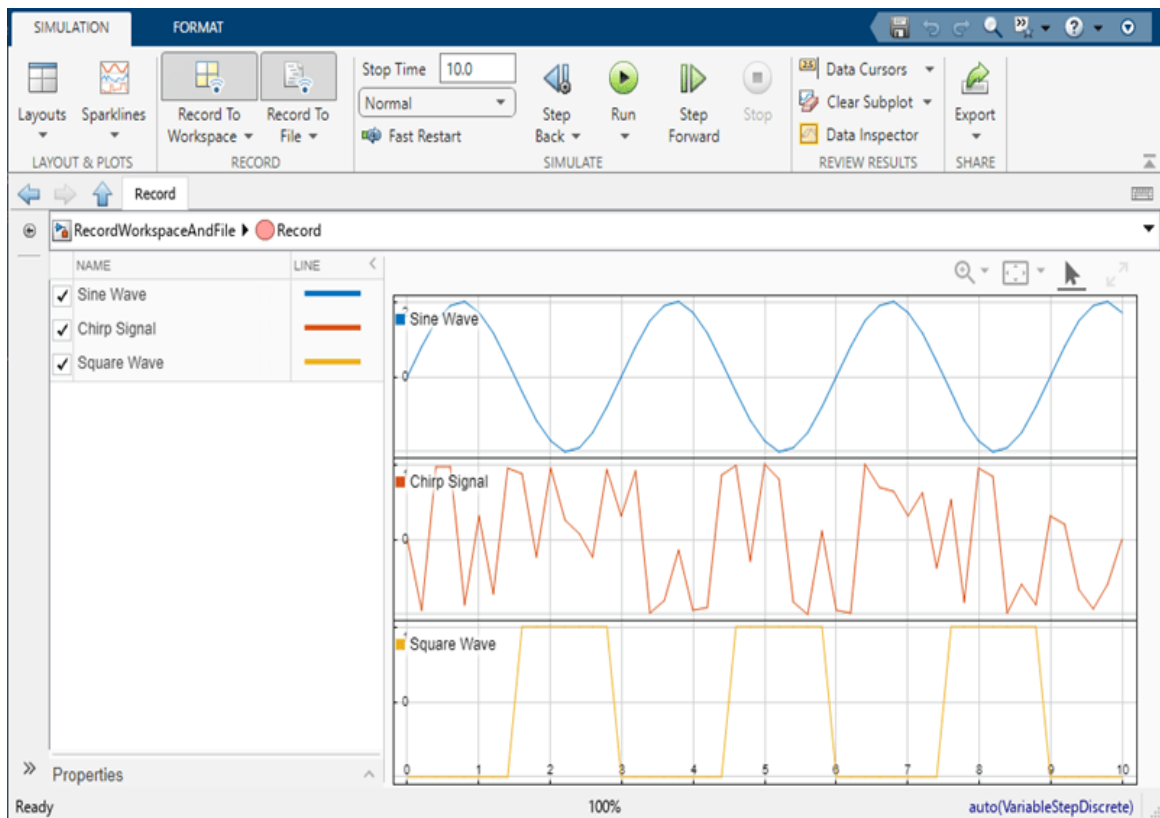
*Figure 3: Time Scope*

In the time scope simulation, the three lines typically denote:

**System's State Trajectory:** This line shows how the system's states have changed over time. It demonstrates how the system's states adapt to control inputs and any outside disturbances.

**Sliding Surface:** A crucial element of sliding mode control is the sliding surface. It represents a benchmark value or the intended course that the system wants to follow. In the state space, the sliding surface is frequently a hyperplane. The sliding surface is represented as a line or curve in the time scope simulation.

**Switching Function:** A crucial component of sliding mode control, the switching function determines when the system switches between various control laws. The distance or error between the system's current state and the sliding surface is typically used to define it. In the time scope simulation, the switching function is typically depicted as a step-like signal to indicate the changes in control modes.



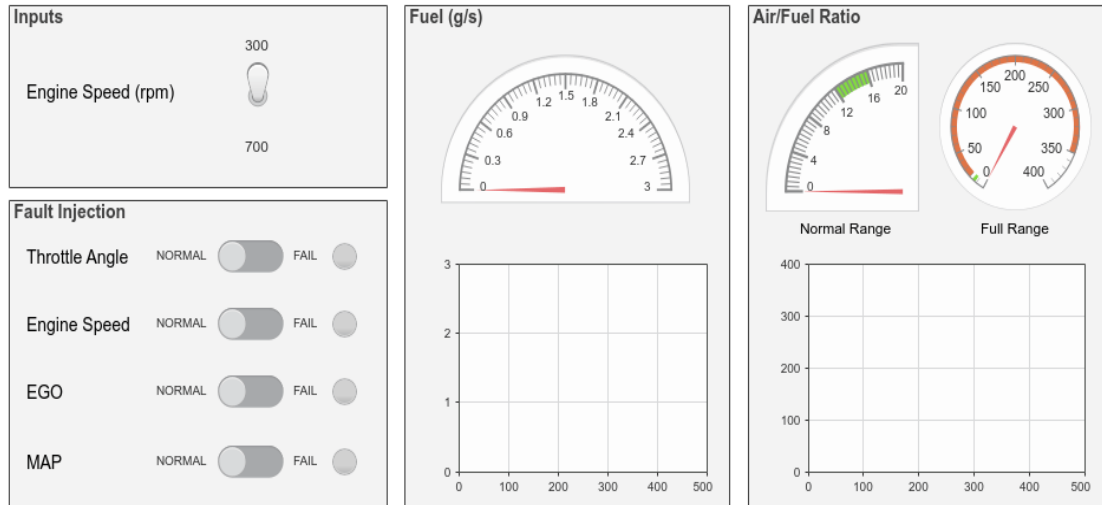
**Figure 4: Performance of the Control System**

In sliding mode control, performance evaluation through simulation is a valuable tool for analyzing the behavior of the control system and assessing its effectiveness. Simulation plays a crucial role in various aspects of sliding mode control, including: a) Sliding surface design, b) Controller tuning, c) Parameter analysis, d) Robustness testing, e) System identification.

The simulation of the control system's performance typically occurs in the implementation and evaluation phase of the sliding mode control design process. It helps validate the control system's behavior, identify potential issues or areas for improvement, and fine-tune the control parameters or design as needed.

Here royal blue, persimmon and light orange depicted as sine wave, chirp signal and square wave.

### Fault-Tolerant Fuel Control System Dashboard



**Figure 5: Control System Dashboard**

The purpose of the control system dashboard in sliding mode control is to provide a visual representation of the control system's performance and allow engineers or operators to monitor and tune the control system in real-time. It helps in assessing the effectiveness of the sliding mode control algorithm, identifying any deviations or abnormalities, and making adjustments to improve the system's overall performance.

## **Chapter 5 CONCLUSION**

This thesis describes a novel sliding mode control (SMC) method for a class of nonlinear systems. The suggested approach used a Lyapunov function to formulate the ideal SMC problem. The proposed methodology was tested using simulations, and the results were compared to those attained using traditional SMC methods.

The simulation results show that the suggested methodology outperforms the traditional SMC approaches in terms of performance and robustness. Using the suggested method, the chattering and control gains might be gradually decreased. Furthermore, the suggested approach maintained strong tracking performance even in the presence of external disturbances.

As a result, the suggested SMC approach is a promising method for managing a group of nonlinear systems. We can formulate the SMC problem as an optimization problem, and then use linear programming to solve it. Additionally, systematic control gains and chattering reduction are made possible.

There are several avenues that can be investigated for future work. First, other classes of nonlinear systems can be added to the proposed methodology. Second, the proposed method can be utilized with real-world systems, and a thorough evaluation of its performance can be done. In order to further boost the system's performance, the proposed approach can be combined with other control methods like adaptive control and fuzzy logic control.

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