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Designing a disturbance estimator for electric power steering robust controller

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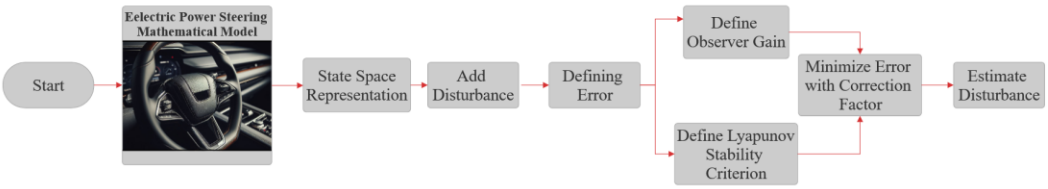
This article contributes to:

SUSTAINABLE DEVELOPMENT GOALS

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE



Highlights:
- Sliding mode controller ensures noise resilience
- Accurate disturbance estimation through simulation
- Improved torque tracking with sliding mode observer

Abstract
Electric power steering, one of the most important advances in the automotive industry, is now found even in the most affordable cars. However, due to the chaotic driving environment, with multiple sources of noise and disturbances affecting the system, effective control of this technology remains a major challenge. Because of manufacturing cost constraints, the use of expensive components, such as high-end microcontrollers or numerous sensors, is not economically viable. Therefore, it is imperative to implement a cost-effective control method that ensures stability, safety, and other necessary requirements. This paper explains the complexities of electric power steering, represents its dynamic nature through mathematical modeling while considering noise and disturbances as integral inputs to the system, and introduces a robust controller designed to estimate these inputs. The method to estimate noise and disturbances using a sliding mode controller is also examined. Finally, the theoretical assertions presented earlier in this paper have been substantiated through meticulous simulations using MATLAB. These simulations have not only confirmed the validity of the claims but also provided a comprehensive evaluation of the system's operational efficacy, ensuring a robust foundation for future research and applications.

Keywords: Electric power steering (EPS); Dynamic system; Disturbance estimation; Robust controller; Sliding mode controller

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1. Introduction

The automotive industry's push for sustainability has prioritized reducing emissions, particularly in internal combustion engine (ICE) vehicles, by improving component efficiency [1], [2]. Steering systems have become a focal point in this effort, with studies highlighting significant advancements. For instance, a hybrid electric power steering system demonstrated energy savings of over 50% [3], [4], while an electro-hydraulic compound steering system reduced energy consumption by 51.7% and enhanced road feel [5]. The transition from traditional hydraulic power steering (HPS) systems to electric power steering (EPS) systems has emerged as a key solution for reducing fuel consumption and emissions. Unlike HPS, which relies on engine-driven hydraulic pumps, EPS uses an electric motor, making it more energy-efficient, compact, and lightweight [6], [7]. EPS systems also offer superior safety, comfort, and performance benefits over HPS [8], [9]. These advantages make EPS indispensable for electric vehicles (EVs) and self-driving cars. EVs lack combustion engines to power HPS pumps while self-driving cars require real-time, precise steering control, which is infeasible with hydraulic systems. Furthermore, EPS supports advanced driver assistance systems (ADAS), such as side-wind compensation, lane-keeping assist (LKA), parking assist, pre-collision systems, and highway pilot functions, due to its integration with electronic control modules [10].

Despite these advantages, EPS systems face significant challenges, including ensuring robustness against noise and disturbances, enhancing safety and reliability, and meeting the high-performance requirements of power-assist motors. Previous research has focused on various aspects of EPS control, such as energy efficiency and system integration with ADAS. However, many studies have overlooked robust control strategies specifically designed to mitigate the effects of disturbances and noise in the chaotic operating environment of vehicles. To address these gaps, this study presents a robust control algorithm for EPS systems that effectively neutralizes the impact of disturbances and noise. The main contributions of this study are as follows:

- The dynamic behavior of the EPS system is mathematically modeled as a second-order, one-degree-of-freedom system, incorporating parameters such as torque, angle, and velocity.
- The model is transformed into a state-space representation with noise and disturbances introduced as inputs.
- A robust controller is designed by defining and defending an error term for tracking the driver's torque input.
- A sliding surface and observer are developed based on the defined error term.
- The proposed controller is validated through simulations, demonstrating its effectiveness in mitigating disturbances and ensuring reliable performance.

This study not only addresses the limitations of existing research but also contributes to the development of a disturbance-resilient EPS system, advancing the capabilities of modern automotive steering technologies.

2. Related Work

The EPS systems are critical in modern vehicles, providing energy efficiency and enhanced steering performance. However, designing robust control systems for EPS that can effectively handle external disturbances and maintain stability remains a significant challenge, especially under dynamic driving conditions. Researchers have explored various control strategies to optimize EPS performance for autonomous or non-autonomous modes [8], [11]–[15], each presenting unique strengths and limitations.

One widely used approach is Proportional-Integral-Derivative (PID) control, valued for its simplicity and ease of implementation. Studies, such as [16]–[20], have demonstrated PID control applications in EPS, showing how torque assistance and steering response can be adjusted to meet system requirements. By calculating the appropriate torque assistance, PID controllers reduce driver effort and maintain stability across various driving conditions. However, PID controllers are highly sensitive to parameter variations and external disturbances, which can compromise stability in real-world EPS applications. Since PID relies on fixed parameter settings, it lacks the flexibility required for EPS systems that need to adapt to changing road and environmental conditions. This limitation highlights the need for control strategies that can dynamically respond to external influences while ensuring robust performance.

Intelligent control techniques, such as fuzzy logic combined with PID, have also been explored for EPS to enhance system adaptability to varying conditions. Studies [21]–[23] have demonstrated that these techniques improve resilience to disturbances and offer smoother, more adaptive steering responses. For example, using fuzzy logic in EPS enables the controller to adapt to changing road conditions, thus enhancing driver comfort and safety. However, intelligent control techniques—especially fuzzy logic—impose significant computational demands, which can make real-time implementation in EPS systems challenging. The tuning of fuzzy controllers is typically time-consuming and relies heavily on trial and error, complicating their application to EPS, where consistent performance is critical [24]. Additionally, the computational demands of these methods may introduce latency, a drawback in safety-critical EPS applications that require rapid response times [25]. This suggests that, while intelligent control methods improve adaptability, they may not be suitable for embedded EPS systems requiring efficient and fast processing.

To address the limitations of PID, robust control methods, such as H∞ control, have been applied to EPS systems to manage parameter uncertainties and external disturbances. Studies, including [26]–[28], have shown that H∞ control allows for optimized steering response and driver satisfaction by handling variations in model parameters and suppressing the impact of disturbances. H∞ control's primary advantage in EPS is its ability to maintain performance across varied conditions, which is essential for the robustness and safety of steering systems. However, the computational complexity of H∞ control can hinder real-time applications in embedded automotive systems. The conservative nature of H∞ control can also lead to over-engineered solutions, which increase system complexity and cost. Thus, while H∞ control offers robust disturbance rejection, its high computational demands limit its practicality in cost-sensitive EPS applications, highlighting the need for a simpler yet effective control approach.

The Linear Quadratic Regulator (LQR) and Linear Quadratic Gaussian (LQG) techniques have also been studied for EPS control, providing a robust control solution by minimizing performance costs while addressing noise and disturbances. Researchers, such as [29]–[31], demonstrated that combining LQR with a Kalman filter allows the EPS system to predict unknown parameters and adjust accordingly, achieving stable and robust performance even in the presence of measurement noise and parameter uncertainty. LQR-based control is advantageous in that it minimizes a cost function to achieve optimal control; however, its implementation in real-time EPS systems can be complex due to the need for precise system modeling. LQG further extends the LQR by incorporating Gaussian noise characteristics, but it similarly relies on accurate state estimation and system identification, which can be difficult to maintain under varying EPS conditions [30].

Sliding Mode Control (SMC) has emerged as a promising control strategy for systems operating in uncertain, disturbance-heavy environments, such as EPS. By maintaining a sliding surface, SMC can effectively reject disturbances and adapt to parameter changes without the extensive computational requirements of H∞ or fuzzy logic methods. Studies, including [29]–[31], have demonstrated SMC's robustness in handling external disturbances and model uncertainties, making it suitable for applications like EPS, where precise torque tracking and system stability are paramount. Unlike PID and H∞ methods, SMC combines robustness with relatively lower computational demands, which is essential for real-time performance in automotive systems. Despite these advantages, SMC methods often face challenges in real-world implementation, such as the need for an effective disturbance estimator and mitigation of the chattering phenomenon, which can degrade long-term system performance.

Our study builds upon previous work by addressing these limitations of SMC in EPS applications. We integrate a disturbance estimator within the SMC framework, allowing for precise handling of external noise and disturbances without compromising stability. This enhancement makes the system more resilient in unpredictable environments while controlling for chattering effects, thus improving suitability for real-world EPS applications. Unlike previous studies, which often lacked comprehensive disturbance estimation, our approach ensures consistent and robust performance under varying conditions, addressing a critical gap in the literature.

In summary, while traditional, robust, and intelligent control methods each contribute unique strengths to EPS systems, they are often limited by either sensitivity to disturbances or computational demands. Sliding Mode Control, with its inherent robustness to parameter variations and disturbances, presents a promising solution. By integrating a disturbance estimator within the SMC framework, this study enhances real-world applicability in EPS systems by ensuring stability and resilience under unpredictable conditions, positioning it as an efficient and practical control strategy for the automotive industry.

In designing robust controllers for EPS, selecting a control strategy that efficiently manages disturbances and ensures stability is essential. The three primary control methods—Proportional-Integral-Derivative (PID), H∞, and SMC—offer varying advantages in EPS applications but differ in their robustness, computational efficiency, and adaptability to real-world conditions.

PID control is widely implemented in EPS for its simplicity and ease of deployment. By calculating error signals based on proportional, integral, and derivative terms, PID controllers allow precise torque adjustments to assist drivers and improve steering response. Studies have shown that PID control can reduce driver effort and enhance EPS responsiveness [16]–[20]. However, a significant limitation of PID controllers is their high sensitivity to parameter variations and external disturbances. These factors can reduce system stability, particularly in EPS, where varying road conditions and driver inputs are common. Since PID controllers operate on fixed parameter values, they lack adaptability in dynamic environments, which restricts their suitability for real-time EPS applications where robustness to disturbances is critical. While PID control is beneficial for basic torque adjustments, its lack of robustness to disturbances and parameter variations makes it less suitable for applications requiring high stability and reliability under fluctuating conditions.

H∞ control offers a robust alternative by optimizing system performance across a range of conditions, making it highly resilient to parameter uncertainties and external disturbances. In EPS systems, H∞ control has demonstrated effectiveness in maintaining stability and improving steering feel, even when disturbances and model inaccuracies are present [26]–[28]. The primary advantage of H∞ control lies in its ability to design controllers that maintain performance across different conditions, which is essential for the robustness and safety of EPS. However, H∞ control's conservative nature and computational intensity make it less feasible for real-time EPS applications, particularly in cost-sensitive automotive systems. Its complexity can increase both system design costs and response times, limiting its practical application in EPS where efficiency is critical.

H∞ control provides robust handling of uncertainties and disturbances, but its high computational demands and conservative design approach often make it impractical for embedded EPS systems requiring real-time, cost-effective control. SMC addresses many of the limitations associated with PID and H∞ methods, making it particularly suitable for EPS applications. SMC operates by defining a sliding surface that the system state is "forced" to reach and remain on, providing resilience against external disturbances and parameter changes. Once the system state reaches this surface, the effects of disturbances are significantly mitigated. Studies, such as [29]–[31], have shown that SMC effectively manages disturbances and uncertainty in EPS, enabling accurate torque tracking while maintaining system stability.

One of SMC's key advantages is its relatively low computational demand compared to H∞ control, which is crucial for real-time automotive applications. Furthermore, SMC's design inherently provides robustness to parameter variations, a critical requirement for EPS systems operating under varying driving conditions. However, SMC is not without challenges; in some cases, it may introduce chattering—a phenomenon where the control signal oscillates due to rapid switching—which can impact system performance. To address this, our study incorporates a disturbance estimator within the SMC framework to further stabilize the system and mitigate chattering effects. This enhancement not only improves robustness but also ensures consistent performance under unpredictable conditions, making SMC a viable choice for real-world EPS systems.

SMC combines the robustness of H∞ control with the efficiency of PID, offering a balanced solution that manages disturbances effectively without the high computational costs associated with traditional robust control methods. Its resilience to parameter changes and adaptability to various disturbances make it particularly well-suited for EPS applications. **Table 1** presents a comparative analysis of popular and conventional electric power steering (EPS) control methods and to provide a comprehensive overview of the existing literature.

Table 1. Comparative analysis and suitability for EPS

Control Method	Robustness to Disturbances	Computational Efficiency	Adaptability to Parameter Variations	Suitability for Real-Time EPS Applications
PID Control	Low	High	Low	Limited due to sensitivity to variations
H∞ Control	High	Low	High	Effective but limited by computational demands
SMC	High	Moderate	High	Highly suitable, especially with disturbance estimator

In summary, SMC offers a unique balance of robustness and computational efficiency, making it an optimal choice for EPS applications. By integrating a disturbance estimator to address chattering, our approach enhances the traditional SMC framework, ensuring stability and responsiveness, even under varying and unpredictable conditions. This improvement positions SMC as an effective solution for practical EPS control, combining the adaptability of robust control with manageable computational demands.

3. Methods

This section began by defining a mathematical model. That model served as the foundation for building a sliding mode controller designed to control the electric power steering system. The model included details about the steering mechanism's dynamics, the motor, and sensor inputs. To ensure the electric power steering system could handle various driving conditions, such as different road surfaces and speeds, a robust controller was developed. An additional disturbance estimator was included to predict external disturbances and adjust for unexpected events impacting the steering system, such as sudden road changes or unforeseen forces.

3.1. EPS Model

According to reference [32], the experimental findings show that, in autonomous driving mode, the EPS system may be correctly represented by a second-order, one-degree-of-freedom model (pinion angle). This model avoids the challenge of precisely estimating individual component parameters by estimating the EPS parameters as lumped parameters. In [33], a two-degree-of-freedom model of the EPS (steering wheel angle and pinion angle) was utilized. This model requires a comprehensive characterization of each EPS component. Accurate characterization is challenging, and any deviation from true values may reduce control performance. The following is an expression for the EPS system's dynamics [34]:

$$\begin{bmatrix} \dot{\theta}_h \\ \dot{\omega}_h \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{B_c}{J_c} \end{bmatrix} \begin{bmatrix} \theta_h \\ \omega_h \end{bmatrix} - \begin{bmatrix} 0 \\ \frac{1}{J_c} \end{bmatrix} T_c + \begin{bmatrix} 0 \\ \frac{1}{J_c} \end{bmatrix} T_d \tag{1}$$

Where, θ_h: steering wheel angle, ω_h: steering angular velocity, B_c: steering column viscous damping, J_c : steering column moment of inertia, and T_d: driver torque.

$$T_c = K_c(\theta_h - \theta_m/N) \tag{2}$$

Where, K_c:steering column stiffness, θ_m: motor angle, and N: motor gear ratio.

Recursive least squares is used in this model to identify the EPS lumped parameters, equivalent moment of inertia J, equivalent viscous damping b, and Coulomb friction constant.

3.2. State Space Representation

The generic state space representation, given model in the preceding section, is:

$$\begin{cases} \dot{x} = Ax + Bu + Dw \\ y = Cx \end{cases}$$

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{b}{J} \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{1}{J} \end{bmatrix}, C = [1 \quad 0], u = T_d \tag{3}$$

To estimate the state vector, alignment moment, and any additional disturbance while monitoring only the input and output, our goal is to assume that the unknown input term Dw is limited. A sliding-mode observer formulation can be found in [35]:

$$\dot{\hat{x}} = A\hat{x} + Bu + L(x - \hat{y}) + s \tag{4}$$

In Eq. (5), a correction term s_2 (sliding-mode function that must be determined) is inserted in place of the unknown term Dw. Eq. (6) presents a matrix representation of Eq. (4).

$$\hat{y} = C\hat{x} \tag{5}$$

$$\begin{bmatrix} \dot{\hat{x}}_1 \\ \dot{\hat{x}}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -b/J \end{bmatrix} \begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1/J \end{bmatrix} T_d + \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} \left(y - [1 \quad 0] \begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \end{bmatrix} \right) + \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \tag{6}$$

3.3. Sliding Surface

In designing a robust controller for EPS, one of the key steps is to create a sliding surface that guides the system's behavior, allowing it to reject disturbances effectively. A Lyapunov function is then used to ensure system stability by demonstrating that the system's energy continuously decreases over time.

The sliding surface serves as a target condition for the system to “slide” on, ensuring that disturbances are minimized. To establish this surface, we first define the tracking error, e_x, as the difference between the actual state $\hat{x}$:

$$e_x = x - \hat{x} \tag{7}$$

The time derivative of this error, denoted $\dot{e}_x$, captures the rate of change of the error with combining formula (4):

$$\begin{aligned} \dot{e}_x &= \dot{x} - \dot{\hat{x}} \\ &= Ax + Bu + Dw - ((A - LC)\hat{x} + Bu + Ly + s) \\ &= (A - LC)e_x + Dw - s \\ &= A_o e_x + Dw - s \end{aligned} \tag{8}$$

By using the symbol s to indicate unknown input, the error should be minimized. The observer gains should be selected in such a way that the observer matrix, as defined in Eq. (9), can be used as the initial point for designing the observer.

$$A_o = A - LC = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{b}{J} \end{bmatrix} - \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} [1 \quad 0] = \begin{bmatrix} -l_1 & 1 \\ -l_2 & -\frac{b}{J} \end{bmatrix} \tag{9}$$

Identifying the correction factor S is the next step. The Lyapunov stability criterion is used to determine the correction factor. As a function of the observer error, a candidate Lyapunov function is defined as follows:

$$v = e_x^T P e_x \tag{10}$$

$$\begin{aligned} \dot{v} = e_x^T P \dot{e}_x + \dot{e}_x^T P e_x &= e_x^T P(A_o e_x + Dw - s) + (A_o e_x + Dw - s)^T P e_x \\ &= -e_x^T Q e_x + 2e_x^T P(Dw - s) \end{aligned} \tag{11}$$

The error will converge to zero if $\dot{v}$ is less than zero according to the Lyapunov stability condition. If $2e_x^T P(Dw - s)$ consistently provides a negative value, then this goal can be achieved. Let's further assume that the sliding-mode variable s can be selected in the following ways:

$$s = \rho \frac{P^{-1}C^T Ce_x}{\|Ce_x\|} = \rho P^{-1}C^T \tanh(Ce_x) \tag{12}$$

3.4. Driver Torque Estimation

The purpose of control is to minimize error in following the driver's torque instruction while adjusting for alignment torque resulting from reaction of the road surface and torque resulting from unintentional contact with the driver's steering wheel. By measuring the difference between the required torque and the controller's observed torque, we can calculate the tracking error, which is as follows:

$$e = \theta_h - \theta_{hdes} \tag{13}$$

so,

$$\dot{e} = \dot{\theta}_h - \dot{\theta}_{hdes} \tag{14}$$

Using this error term, we can design a sliding surface, S, which combines the tracking error and its rate of change:

$$S = \dot{e} + \lambda e \tag{15}$$

Where λ is a positive constant that determines the speed of convergence to the sliding surface S=0. The tracking error is driven towards zero, indicating that the system's actual state closely follows the desired trajectory. To maintain the system on the sliding surface S=0, a control input is designed to counteract disturbances and uncertainties. Our goal is to define the control input so that S approaches zero, thus minimizing tracking error over time. This control law is selected to drive the error dynamics towards the sliding surface, providing a means for disturbance rejection. This equation is constructed to ensure that when the system reaches the sliding surfaceNow our target is designing control signal in such a way that:

$$\lim_{t \to \infty} s = 0 \tag{16}$$

To ensure the stability of the controller, we use Lyapunov's stability criterion, which involves defining a Lyapunov function. This function acts like an “energy” measure for the system, showing that energy diminishes as the system moves towards stability. For our sliding mode controller, we define the Lyapunov function as:

$$V = \frac{1}{2} S^2 \tag{17}$$

This Lyapunov function represents a positive quantity (Since $S^2 \geq 0$), which ensures that $V \geq 0$ for all $S \neq 0$. The goal of the Lyapunov analysis is to show that V decreases over time, demonstrating that the system's energy is dissipated, thus moving towards stability. The time derivative of V, $\dot{V}$, is given by:

$$\dot{V} = S\dot{S} \tag{18}$$

By substituting the expression for $\dot{S}$, we can write this based on Eq. (15):

$$\dot{S} = \ddot{e} + \lambda\dot{e} = (\ddot{\theta}_h - \ddot{\theta}_{h_{des}}) + \lambda(\dot{\theta}_h - \dot{\theta}_{h_{des}}) = \frac{1}{J}(-b\omega_h + T_d - T_c) - \dot{\omega}_h + \lambda(\dot{\theta}_h - \dot{\theta}_{h_{des}}) \tag{19}$$

So, we can rewrite Eq. (18) as:

$$\dot{V} = S\left(-\frac{b}{J}\dot{\theta}_p + \frac{1}{J}T_d - \frac{1}{J}T_c - \theta_{h_{\text{des}}} + \lambda(\dot{\theta}_h - \dot{\theta}_{h_{\text{des}}})\right) \tag{20}$$

To ensure stability, we want $\dot{V}$to be less than zero. This condition guarantees that the system converges towards the sliding surface S=0 and maintains it, thereby minimizing disturbances. The sliding mode control law is selected to ensure $\dot{V} < 0$, effectively "draining" the system's energy and guiding it towards the stable region. Finally, to drive S towards zero, we design a control law that satisfies the condition $\dot{V} < 0$.This control law ensures that as S approaches zero, the system compensates for disturbances effectively, keeping it on the sliding surface. The term $\eta\,\text{sgn}(S)$ specifically addresses any unmodeled disturbances, ensuring that the controller is robust even in the presence of external perturbations. The control law can be represented as:

$$T_d = b\dot{\theta}_h + T_c + J\ddot{\theta}_{h_{des}} - J\lambda(\dot{\theta}_h - \dot{\theta}_{h_{des}}) - \eta\,\text{sgn}(S) \tag{20}$$

By designing the sliding surface and ensuring the Lyapunov function's derivative $\dot{V}$ is negative, this control approach guarantees that the EPS system converges to a stable state and maintains robustness against disturbances. This combination of sliding surface design and Lyapunov analysis allows the controller to provide both precise torque tracking and reliable disturbance rejection, making it particularly suitable for Electric Power Steering applications.

4. Simulation

The results of the observer-based SMC performance are displayed in this section of the simulations. A model that uses the Pacejka tyre model to determine alignment moments was used to validate the results. The computed perturbation and the correction term s2 are compared in **Figure 1**. Since s1 is really an approximation to zero, we are only concerned with s2, even though the correction term is a vector. As discussed in the previous section, the estimated perturbation is derived by averaging the correction term s2.

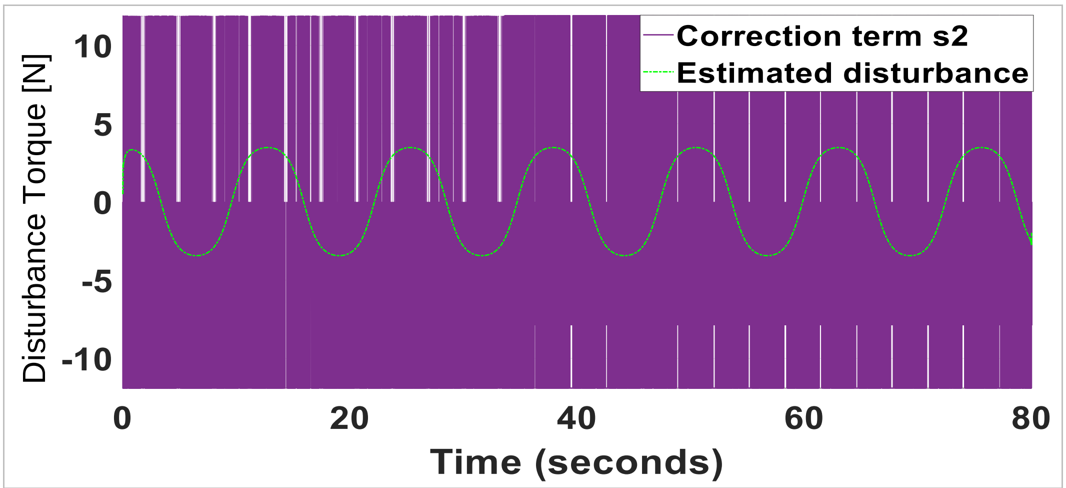

Figure 1. Estimated disturbance

Figure 2 displays the actual alignment moment determined by the model and the predicted alignment moment from the sliding mode observer. As shown in **Figure 2**, this was a pure alignment moment from the model. As can be seen, the observer made a very accurate estimate of the alignment moment, which was fed to the controller as compensation.

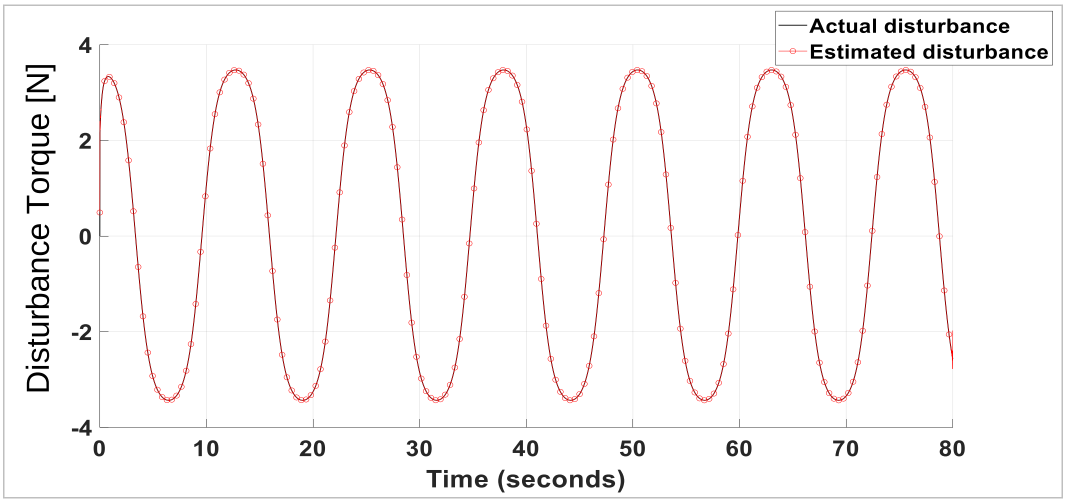

Figure 2. Disturbance estimated by observer

For a more thorough validation, a random disturbance add is now included to evaluate the controller's performance against sporadic random disturbances. To simulate the perturbation torque from the driver, a second random perturbation was introduced into the alignment moment in **Figure 3** and **Figure 4** between 20 and about 60 seconds. The observation shows that the random disturbance was accurately calculated by the observer. For further information, we will now look at S. We claim that S is the unidentified input term. S is a correction term that should cause the error.

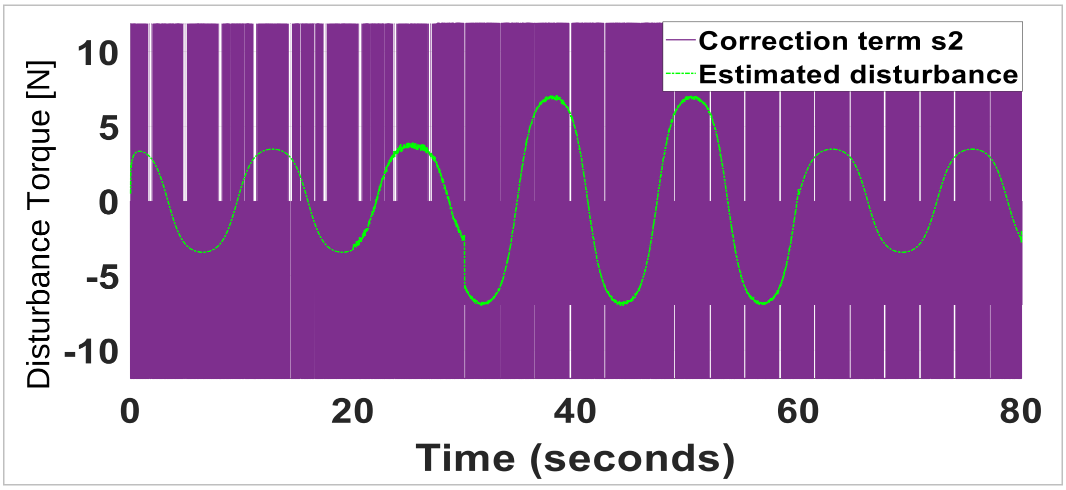

Figure 3. Estimated sporadic random disturbance

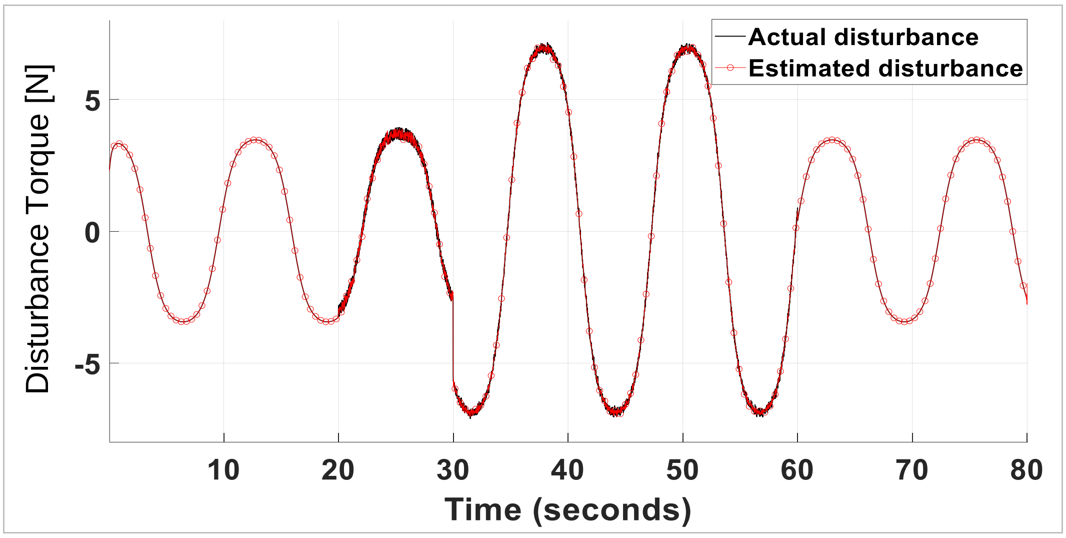

Figure 4. Estimated sporadic random disturbance

Figure 5 is magnified part of Figure 4. The square wave S has rising edges that are separated by a short period, as you can see. Furthermore, there are variations in both frequency and duty cycle.

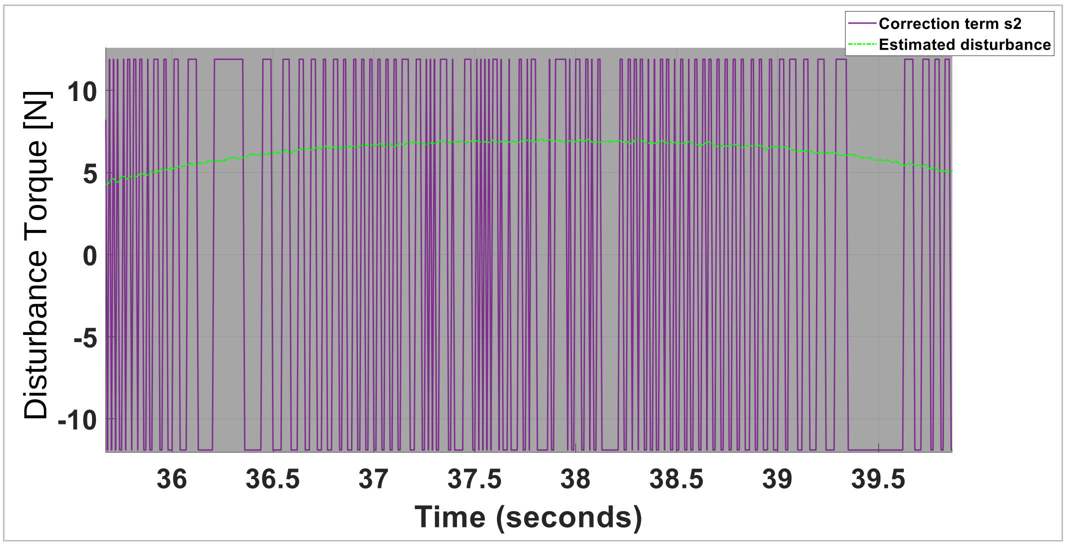

Figure 5. Behaviour of correction term s2

Figure 6 shows an enlarged view of part of Figure 4. The approximator is still able to estimate the noise with a reasonable degree of accuracy at the locations where the noise peaks and causes the most interference.

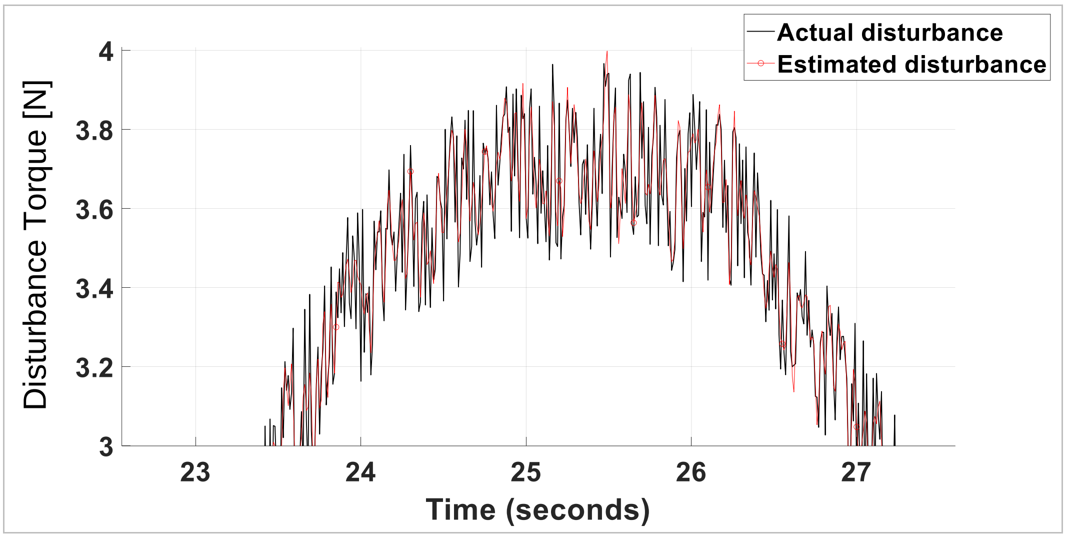

Figure 6. Disturbance estimated by observer

5. Practical Implications and Real-World Applications

The proposed SMC method with an integrated disturbance estimator has significant potential for real-world application in EPS systems. EPS has become a critical component in modern vehicles, offering advantages such as energy efficiency and reduced steering effort. However, real-world EPS applications face several challenges, including handling disturbances from unpredictable road conditions, managing computational efficiency, and balancing costs. The following discusses how our proposed SMC approach can be adapted to address these practical requirements in real-world implementations.

5.1. Real-Time Performance

One of the main requirements for EPS control is real-time performance. In real-world applications, the EPS system must respond instantly to driver inputs and external disturbances. Our SMC approach, designed to reject disturbances efficiently, provides a robust framework for real-time applications. The sliding surface formulation in SMC quickly drives the system toward stability, allowing the controller to react promptly to disturbances without significant delays. By minimizing error within a short time frame, this approach ensures that the EPS system maintains stable operation and accurate torque tracking, which is essential for steering safety.

Additionally, the integrated disturbance estimator in our approach continuously monitors external noise and compensates for its effects in real time. This capability allows for faster responses to environmental changes, such as sudden shifts in road texture or unexpected steering inputs. However, in real-world implementations, the accuracy of disturbance estimation will depend on sensor quality and system calibration. Thus, it will be important to test and refine the estimator's performance under varied driving conditions to ensure reliability.

5.2. Computational Complexity and Embedded System Compatibility

Another significant factor in implementing this control strategy in EPS systems is computational complexity. Automotive EPS systems are typically embedded within microcontroller units (MCUs) with limited processing power. Therefore, designing a control algorithm that remains computationally manageable is critical for cost-effective implementation. Unlike $H\infty$ control, which demands extensive computational resources, our SMC approach is relatively simple to compute, making it suitable for embedded MCUs in automotive applications.

To further ensure compatibility with embedded systems, the disturbance estimator within the SMC framework has been designed to minimize unnecessary computational overhead. By selectively prioritizing critical disturbances over minor fluctuations, the estimator reduces the number of computations required, making the method feasible even in MCUs with moderate processing capabilities. This compatibility makes our approach attractive for real-world applications where balancing performance and cost is essential.

5.3. Cost Efficiency and Scalability

Automotive manufacturers prioritize cost efficiency in EPS design, as components must be economically viable to support widespread adoption. The SMC approach offers a cost-effective solution by reducing the need for high-end sensors and complex hardware configurations. Because our method relies on efficient estimation rather than exhaustive measurement, it minimizes the number of sensors needed to achieve robust disturbance rejection, which can significantly lower the overall system cost.

Furthermore, this method can be easily adapted to different EPS configurations without significant modifications, making it scalable for a variety of vehicle models. However, real-world implementation would likely involve initial calibration and tuning for each model, particularly to account for specific vehicle dynamics. Once calibrated, the method should maintain performance consistency across similar platforms, supporting broader applicability and scalability.

5.4. Potential Implementation Challenges

While our proposed SMC method with disturbance estimation is promising for real-world EPS applications, certain implementation challenges must be addressed:

- **Sensor Limitations** - Accurate disturbance estimation requires high-quality sensor data to detect external noise and disturbances effectively. However, low-cost sensors may introduce measurement noise that affects the estimator's performance. As a solution, this control method may benefit from using sensor fusion techniques, which combine multiple sensor outputs to improve estimation accuracy without significantly increasing costs.
- **Tuning and Calibration -** Achieving optimal performance will likely require model-specific tuning, especially in the disturbance estimator. Each vehicle model may respond differently to controller adjustments, making initial calibration essential to ensure stable performance. This process could be streamlined by developing standardized calibration protocols that reduce the need for extensive manual tuning.
- **Thermal and Mechanical Stress -** In real-world conditions, EPS systems are exposed to variable thermal and mechanical stresses. The SMC method may need additional adjustments to maintain performance under extreme conditions, such as during prolonged high-speed driving or frequent sharp turns. Testing in a range of environmental conditions would help identify any adjustments needed to maintain robustness.
- **Long-Term Impact and Future Development -** The integration of SMC with a disturbance estimator represents a significant advancement for EPS applications, as it enables real-time disturbance rejection with efficient computation, which is feasible on embedded systems. In

the long term, this approach could enable manufacturers to produce EPS systems that are more reliable and capable of operating effectively under a wider range of driving conditions, thus enhancing vehicle safety. Additionally, further development could focus on adapting this controller to emerging EPS applications, such as autonomous and semi-autonomous vehicles, where disturbance management is critical for safety.

The proposed method's balance of robustness, computational efficiency, and adaptability makes it a promising candidate for real-world EPS implementation. By addressing practical requirements and potential challenges, this SMC approach can be scaled across different vehicle models, offering a flexible, cost-effective solution that aligns with industry demands for reliability and efficiency in modern steering systems.

6. Real-World Applicability and Future Testing

Although the current study demonstrates the effectiveness of our Sliding Mode Control (SMC) approach with a disturbance estimator in a simulated environment, real-world applicability is crucial for confirming its robustness in practical settings. Research on similar control methods has shown that SMC is particularly effective in automotive applications where stability and disturbance rejection are critical. For instance, previous studies have successfully implemented SMC in vehicle stability control systems, showing significant improvements in handling and robustness under real driving conditions. This evidence suggests that an SMC-based approach could similarly enhance the reliability and stability of EPS systems, providing resilience to disturbances and reducing the need for high-end hardware components.

To further support practical implementation, we propose future validation of this method using a Hardware-in-the-Loop (HIL) testing framework. HIL testing is commonly used in automotive research to replicate realistic operating conditions without requiring a fully assembled vehicle, making it an efficient method for pre-deployment validation. Through HIL testing, the control system could be integrated with hardware representing key components of EPS, allowing for the simulation of real-world disturbances, such as abrupt steering inputs, variable road surfaces, and external forces (e.g., wind or obstacles). Such a framework would enable us to evaluate the real-time performance, stability, and computational feasibility of our control approach under diverse and challenging conditions. Additionally, Vehicle-in-the-Loop (VIL) setups could provide an advanced stage of testing, allowing for performance validation in a vehicle setup without full road trials.

For illustrative purposes, a hypothetical case study demonstrates how the proposed method would work in a practical EPS setting. Imagine an EPS-equipped passenger vehicle using this SMC-based disturbance estimator during city driving and highway lane-keeping. When the vehicle encounters uneven road surfaces or sudden changes in driving direction, the disturbance estimator within the SMC framework would continuously monitor these external influences and adjust the control input to stabilize the steering torque. In this way, the system would maintain consistent, stable steering behavior, allowing for smooth handling and minimizing the driver's effort in adapting to disturbances. This capability is particularly relevant for autonomous and driver-assistance systems, where reliable, real-time disturbance management directly contributes to vehicle safety.

In summary, while the effectiveness of our SMC approach with disturbance estimation is validated in simulation, evidence from comparable control applications and a structured plan for HIL testing highlight its potential for real-world EPS implementation. Future testing through HIL and VIL simulations would allow for refined validation, supporting the scalability of this method for various EPS configurations and broader automotive applications.

7. Conclusion

This study presents a robust SMC method with an integrated disturbance estimator as a practical solution for enhancing EPS systems. The proposed approach introduces a sliding surface to manage tracking error, along with a Lyapunov-based stability criterion to ensure the system's resilience to disturbances. Simulation results demonstrate that the method improves torque tracking accuracy, strengthens disturbance rejection, and adapts effectively to changing road conditions—all of which are critical requirements for EPS applications.

These findings offer valuable insights for EPS design in the automotive industry. First, the disturbance estimation capability within the SMC framework allows EPS systems to maintain stability and reliable performance in unpredictable environments, positioning this control strategy as an ideal solution for applications where noise resilience is crucial, such as in autonomous vehicles and advanced driver-assistance systems. The low computational demand of SMC compared to traditional robust controls, such as H∞, makes this approach feasible for embedded microcontroller units commonly used in automotive applications. By minimizing the need for high-end sensors, this control method provides a cost-effective solution for manufacturers seeking to optimize performance while managing costs. The scalability of this control design also makes it adaptable to different EPS configurations and vehicle models, which enhances its potential for broad industry adoption.

Additionally, the proposed controller's rapid responsiveness aligns well with real-time performance requirements, which is vital for enhancing driver safety and vehicle handling. This responsiveness is particularly beneficial in high-performance and safety-critical EPS systems, where precise torque adjustments are essential. As the automotive sector continues to advance, this SMC-based disturbance estimator offers a viable path forward for more robust, efficient, and adaptable EPS designs, especially as the industry increasingly focuses on autonomous and semi-autonomous systems.

In conclusion, this study's contributions underscore the potential of SMC with disturbance estimation to provide a practical balance between robustness, computational efficiency, and adaptability in EPS systems. Further research and development, as outlined in this study, will continue to improve EPS technology, meeting the automotive industry's demand for reliable, flexible, and cost-effective steering solutions for both conventional and autonomous vehicles.

8. Future study

Future research directions include validating this SMC-based disturbance estimator in Hardware-in-the-Loop (HIL) simulations or real vehicle prototypes to thoroughly assess performance under diverse driving conditions. Such validation would offer insights into the controller's capabilities in environments that closely replicate real-world EPS applications. Optimizing the disturbance estimator for applications in autonomous and semi-autonomous vehicles is another promising area, as this adaptation could enhance safety and stability in automated steering systems by integrating additional external inputs from sensor networks or connected vehicle systems.

Further exploration into sensor fusion techniques could also improve disturbance estimation accuracy by combining data from multiple sensors, reducing measurement noise, and improving the estimator's reliability without significantly increasing system costs. Finally, future studies could examine the controller's robustness under various environmental conditions, such as high-temperature or high-vibration scenarios, as EPS systems face thermal and mechanical stresses in real-world applications. Developing adaptive parameters to account for these environmental variations could help ensure consistent performance across a broader range of conditions, ultimately expanding the practical applications of this control method.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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