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Design of Robust Control for Vehicle Steer-by-Wire System

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ABSTRACT

This study presented the design of a robust controller based on Integral Sliding Mode Control (ISMC) for controlling the Vehicle Steer-by-Wire (VSbW) system. The dynamic model of the VSbW system is first developed and then the design of ISMC has been conducted via the states of the system. The VSbW system has been described by two terms; one term represents the nominal model, which is free from nonlinearities, and the other term lumps the uncertainties in system parameters. The integral sliding mode controller has been designed for controlling the VSbW system. The control design consists of two parts. The first control part has addressed the nominal term of the system, while the second control part tackles and eliminates the effects of uncertainties and perturbation due to the uncertain term of the system. The numerical simulation has been conducted to show the robustness of ISMC and its capability to reduce the chattering effect in the control signal. In addition, a comparison study in performance has been conducted between the proposed controller and other controllers in the literature. We also carry out bibliometric analysis to see research trends. Based on our analysis, the number of publications regarding the keywords "controller", "steer", and "wire system" changes every year (25 (2018), 56 (2019), 51 (2020), 71 (2021), and 61 (2022)).

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1. INTRODUCTION

Due to the advances in the automotive industry, the technology of drive-by-wire technology played a vital role in this industrial field. The basic principle of this technology is to replace the conventional mechanical mechanism and linkages with a control system and electromechanical actuators (Hoseinnezhad & Bab-Hadiashar, 2005). This technology allows the free design of force transmission characteristics and permits a large space in the steering system of the vehicle (Yih & Gerdes, 2005). Many modern vehicles applied the drive-by-wire mechanism for brakes and throttle valves. Compared to the classic way, this technology could give active steering capability and enhance the vehicle maneuverability and stability, and promote handling behavior during driving. These features in this modern technology have attracted considerable attention from researchers in the field of the automotive industry (Huh & Kim, 2001; Baviskar *et al.*, 2008). Therefore, many researchers have conducted studies in this field. Several control techniques have been developed in the literature to control the VSbW system including an Adaptive non-linear controller (Baviskar *et al.*, 2008), a nonlinear Adaptive Sliding Mode Controller (Kazemi & Janbakhsh, 2010), Linear Active Disturbance Rejection Controller (LADRC) (Qiu *et al.*, 2012), feedback Proportional Integral Derivative (PID) controller, Iterative Learning Control (ILC), Sliding Mode Learning Control (SMLC) (Do *et al.*, 2013), sliding mode control (H. Wang et al.), optimizing PID controller based on Imperialist Competitive Algorithm (ICA), adaptive sliding mode control (Sun *et al.*, 2015), Adaptive Terminal Sliding Mode Control (ATSMC) algorithm (Wang *et al.*, 2016), Sliding Mode-Based Active Disturbance Rejection Control (SMADRC) (Sun *et al.*, 2018), PD-PID control (Tumari *et al.*, 2017), Single Input Fuzzy Logic Control (SIFLC) (Tumari *et al.*, 2018).

The SMC is a robust control design methodology that showed high robustness characteristics when applied in linear and nonlinear systems subjected to uncertainties in their parameters (Husain & MohammadRidha, 2022a; AL-Samarraie *et al.*, 2015). The sliding and reaching phases are the main parts of trajectory motion in sliding mode control design. The reaching phase is sensitive to external disturbances and model uncertainties, while in the sliding phase, the system perturbations have an insignificant effect on dynamic performance. To overcome the problems in classical SMC, integral sliding mode control (ISMC) has been introduced to avoid the reaching phase and to reduce the chattering effect in actuating signals (Pan *et* al., 2017; Husain & Mohammad Ridha, 2022b).

In this study, ISMC is designed to improve the tracking performance and robustness characteristics of the controlled system. Moreover, the performance of ISMC is compared to other control strategies from the literature (Wang *et al.*, 2016; Sun *et al.*, 2018). The contributions of this work can be summarized as the following:

- Design of ISMC to improve the tracking performance and robustness characteristics of controlled VSbW system.
- To reduce the absolute error to a lower limit.
- To reduce the chattering effect in the control signal.

In addition, in this study, we conducted a bibliometric analysis to see research trends based on keywords (Nandiyanto & Al Husaeni, 2022; Nugraha, 2022). The reason for conducting a bibliometric analysis, apart from seeing research trends, is because bibliometrics is a discipline with broad crosses and combinations of philology, information science, mathematics, and statistics in certain areas, and the evolution of certain research directions can be better expressed using bibliometric indicators. One

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way to understand research trends on a large scale and intuitively see the structure and trends of research fields or journals is by analyzing scientific mapping. This bibliometric has been well-documented and applied in many areas (Al Husaeni & Nandiyanto, 2022a; Al Husaeni & Nandiyanto, 2022b; Al Husaeni & Nandiyanto, 2022c; Al Husaeni & Nandiyanto, 2023; Maryanti *et al.*, 2022; Mubaroq *et al.*, 2020; Nandiyanto & Al Husaeni, 2021; Nandiyanto *et al.*, 2023; Nandiyanto *et al.*, 2021; Nandiyanto *et al.*, 2022a; Nandiyanto *et al.*, 2020; Nandiyanto *et al.*, 2020; Nandiyanto *et al.*, 2022b; Nandiyanto *et al.*, 2023; Nandiyanto *et al.*, 2022c; Nandiyanto *et al.*, 2022d; N'diaye *et al.*, 2022; Wiendartun *et al.*, 2022; Yulifar *et al.*, 2021).

2. METHODS

The development of the VSbW system has sparked many control researchers to present their control schemes to control this system. However, the presence of uncertainty is one of the challenging problems encountered the any proposed control strategy. In this study, the ISMC has been proposed as one effective and promising control scheme which can cope with the variation of system parameters. In what follows, the dynamic description of VSbW is first presented and then a detailed design of ISMC has been presented for this application.

2.1. Mathematical Model

Figure 1 shows the conventional vehicle steering system, which is configured with a rack and pinion and is supported by hydraulic power (Humaidi *et al.*, 2019). The VSbW described in **Figure 2** makes use of all the stock components except for the intermediate steering shaft, which is replaced by a brushless dc servomotor to provide steering actuation in place of the hand wheel (Hoseinnezhad & Bab-Hadiashar, 2005).

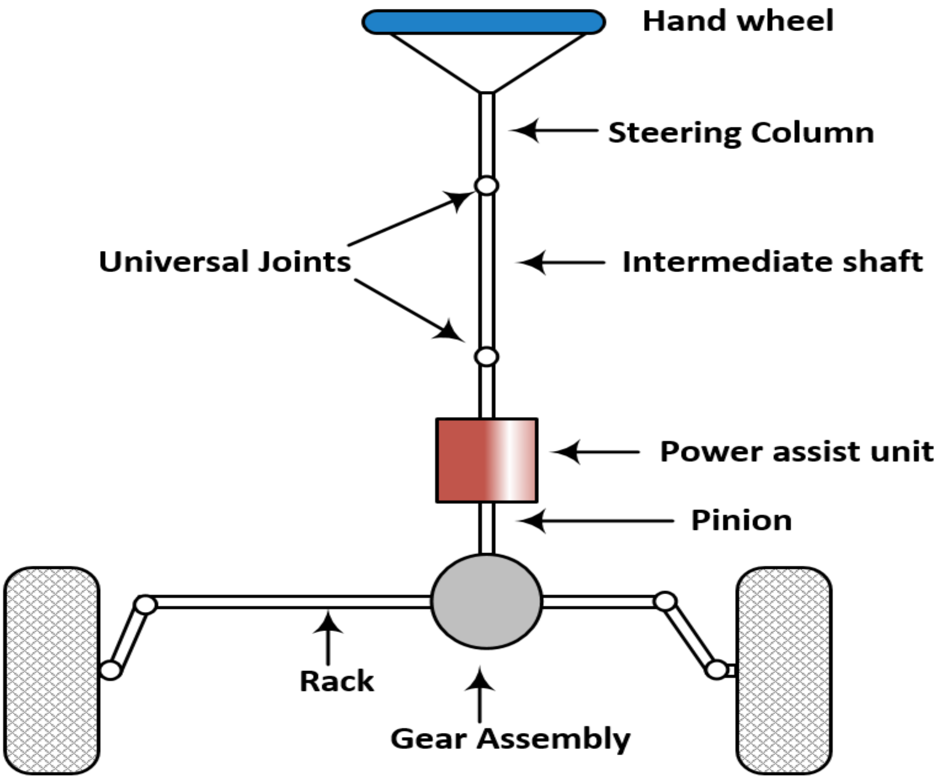

Figure 1. Conventional vehicle steering system.

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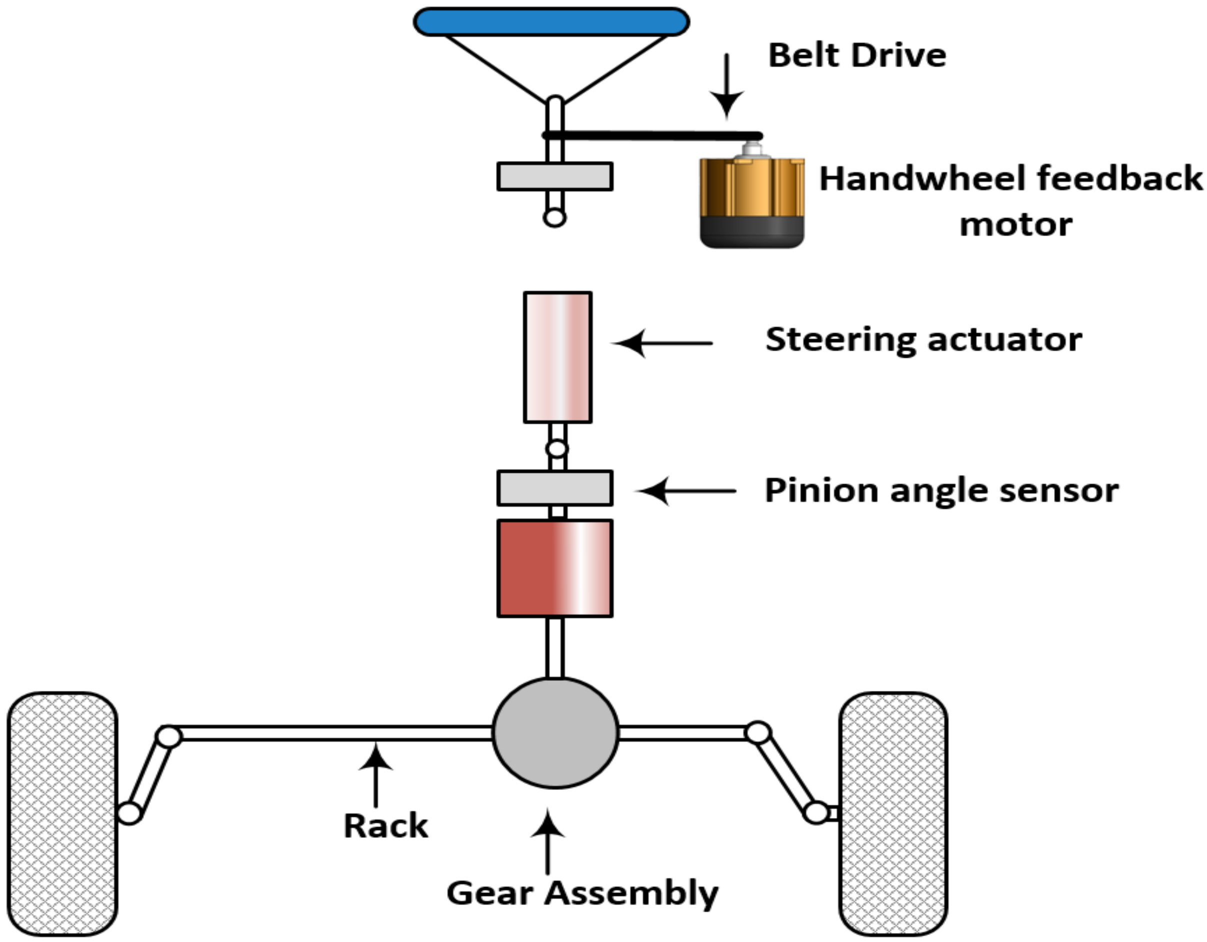

Figure 2. The converted VSbW.

In this study, a simplified vehicle model can be used to describe the mathematical model of VSbW (Wang et *al.,* 2016; Sun et *al.,* 2018),

$$J\ddot{y} + c\,\dot{y} + \rho\, sign(\dot{y}) + \tau = bu \qquad (1)$$

where, J, c, represent the moment of inertia, and the viscosity friction of the steering system, respectively. The angular variable y denotes the orientation of the front wheels. The self-aligning torque applied on the front wheels is denoted by τ. The term $\rho\, sign(\dot{y})$ represents the Coulomb friction with friction constant ρ. The coefficient b is the scaling factor, which accounts for the conversion of steering motor input voltage to output torque, the gear ratio of the gear head, the gear ratio of the system pinion-rack, and the ratio due to transmission from the linear motion of the rack to the steering angle of front wheels.

Assumption 1: The value of b is slightly varying and as such it is constant.

Assumption 2: The parameters J, c, and ρ are uncertain with known upper bounds as follows:

$$|\Delta J| = |J - J_0| \;\le\; J^{\Delta},\;\; |\Delta c| = |c - c| \;\le\; c^{\Delta},\;\; |\Delta\rho| = |\rho - \rho_0| \;\le\; \rho^{\Delta}$$

where J^{Δ}, c^{Δ} and ρ^{Δ} represent the upper bounds of corresponding parameters.

Assumption 3: The front wheels are provided without forward velocity. Therefore, the ground cannot exert real self-aligning torque on the front wheels. Under small slip angles, a hyperbolic tangent signal is used to mimic the self-aligning torque, which can be expressed as (Kazemi & Janbakhsh, 2010):

$$\tau = \xi \tanh(y) \qquad (2)$$

The coefficient ξ is related to road conditions and the $\tanh(.)$ function is the hyperbolic tangent function. According to

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Assumption 2, the system of Equation (1) is into two terms, nominal term and uncertain term.

$$(\Delta J + J_0)\ddot{y} + (\Delta c + c_0)\dot{y} + (\Delta\rho + \rho_0).sign(\dot{y}) + \tau = bu \quad (3)$$

Equation (4) can be rewritten as

$$\ddot{y} = -\frac{c_0}{J_0}\dot{y} - \frac{\rho_0}{J_0} sign(\dot{y}) - \frac{\tau}{J_0} + K u + \Delta \quad (4)$$

where:

$\Delta = \Delta_1/J_0$, $\Delta_1 = -\Delta J\ddot{y} - \Delta c\,\dot{y} - \Delta\rho\, sign(\dot{y})$, $K = b/J_0$

Rewrite the system model of Equation (4) with new state variables ($x_1 = y$ and $x_2 = \dot{y}$), the plant model becomes

$$\dot{x}_1 = x_2 \quad (5)$$

$$\dot{x}_2 = f_n + \Delta + Ku \quad (6)$$

where, f_n represents the nominal part of the model, which is expressed by the following equation:

$$f_n = -\frac{c_0}{J_0}x_2 - \frac{\rho_0}{J_0} sign(x_2) - \frac{\tau}{J_0} \quad (7)$$

For the VSbW model to be more appropriate for control design, one can define the tracking error as the difference between actual and reference signals,

$$e_1 = x_1 - x_d \quad (8)$$

taking the second time derivative of error, one can obtain

$$\dot{e}_2 = f_n + \Delta + Ku - \ddot{x}_d \quad (9)$$

In the next section, an integral sliding mode control strategy will be designed for VSbW and compared with other control schemes from the literature (Wang *et al.*, 2016; Sun *et al.*, 2018).

2.2. Integral Sliding Mode Control Design for Steer-by-Wire System

In this section, the design of ISMC has been developed for the VSbW system. The main two steps of ISMC design are the design of the sliding surface and the control law (F Abd & Al-Samarraie, 2021). The sliding surface is first established according to the following equation:

$$s = e_2 + z \quad (10)$$

where s represents the sliding variable, and $z \in R^1$ denotes the integral term. Taking the derivative of Equation (10) and using Equation (9) to have

$$\dot{s} = f_n + \Delta + Ku - \ddot{x}_d + \dot{z} \quad (11)$$

Based on Equation (12), one can deduce the control

$$u = \frac{1}{K}(u_n + u_d) \quad (12)$$

where, u_n represents the equivalent part which deals with the nominal part for the VSbW system, u_d denotes the discontinuous part that tackles with uncertain part of the model. Using Equation (11) and Equation (12), one can obtain

$$\dot{s} = f_n + \Delta + u_n + u_d - \ddot{x}_d + \dot{z} \quad (13)$$

The derivative part $\dot{z}$ can be designed as

$$\dot{z} = -u_n - f_n + \ddot{x}_d \quad (14)$$

Accordingly, Equation (14) becomes

$$\dot{s} = \Delta + u_d \quad (15)$$

The nominal part u_n and discontinuous part u_d of the controller, u can be respectively expressed as

$$u_n = -f_n + \ddot{x}_d - c_1 e_1 - c_2 e_2 \quad (16)$$

$$u_d = -M.sgn(s) \quad (17)$$

where, M represents the sliding gain, and c_1 and c_2 are design constants.

Lemma: Consider the controlled VSbW system defined by Equation (1) subjected to uncertain parameters. The components of control law u_n and u_d resulting from ISMC and described by Equation (16) and Equation (17) lead to asymptotic convergence of tracking error**.**

Proof: The Lyapunov function can be chosen as:

$$V = \frac{1}{2}s^2 \quad (18)$$

The time-derivative of Equation (18) gives

$$\dot{V} = s\,\dot{s} \quad (19)$$

To guarantee an attractive sliding manifold, the condition below has to be satisfied (Hameed *et al.*, 2019; Husain & MohammadRidha, 2022c).

$$s\,\dot{s} < 0 \quad (20)$$

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Using Equation (20) and Equation (15) one can obtain

$$s\,\dot{s} = s.(\Delta - M.sgn(s)) \quad (21)$$

Using the upper-bound concept, one can get the inequality

$$s\,\dot{s} < -|s|(M - |\Delta|) \quad (22)$$

To satisfy the condition of Equation (22), the design parameter M has to be chosen such that

$$M \geq |\Delta| + \varepsilon \quad (23)$$

where ε is a very small positive value. At the sliding phase, where $s = \dot{s} = 0$, the discontinuous control part is responsible for compensating for the uncertainties in system parameters; that is,

$$[u_d]_{eq} = -\Delta \quad (24)$$

Substituting Equation (24) and Equation (16) into Equation (9), the error dynamics of the system can be deduced,

$$\dot{e}_1 = e_2 \quad (25)$$

$$\dot{e}_2 = -c_1 e_1 - c_2 e_2 \quad (26)$$

It is clear that the ISMC lead to error dynamics described by Equation(26) and Equation(27) which have stability characteristics dedicated by design constants c_1 and c_2.

2.3. Analysis Bibliometric

The bibliometric analysis process has 4 steps (see **Figure 3**), namely: data collection using the Publish or Perish application, data processing using Ms. Excel, mapping data using the VOSviewer application, and finally analyzing the data that has been mapped. In the data collection process, we used three keywords, namely "controller, "steer", and "wire system". For the article data used in this study, research data has been published in Google Scholar-indexed journals with a range of 2018-2022. the results of data collection using Publish or Perish we get 264 relevant articles. The articles that have been collected are then saved in *.ris and *.csv (Comma Separated Values) formats. *.ris format is used for data mapping using VOSviewer while *.csv format is used for data processing using Ms. Excel. We mapped article data from prepared database sources. Data mapping consists of three types, namely network, density, and visualization overlay. When making a bibliometric map, the frequency of keywords is set to at least 5 times found or appear in the database in addition, we also filter the terms that will be included in the web mapping visualization and VOSviewer. Detailed information on how to do bibliometric analysis is reported elsewhere (Al Husaeni & Nandiyanto, 2022).

3. RESULTS AND DISCUSSION

3.1. Analysis Bibliometric

Based on the results of the bibliometric analysis, it was found that the development of research on "controller, steer", and "wire system" changes every year. Based on **Figure 4**, in 2018 the number of publications regarding keywords used was 25 (9.47%) articles, this number increased in the following year to 56 (21.21%) articles (in 2019). However, in 2020 it decreased again to 51 (19.32%) articles, and the other way around, namely in 2021 it increased to 71 (26.89%) articles. Then, in 2022 it will decrease to 61 (23.11%) articles. On average, the number of publications over the last 5 years, namely in 2018 – 2022, was 52.80 or 53 articles.

3.1.1. Progression Map Based on Keywords

We use the VOSviewer application to map article data that is considered relevant. There are three forms of visualization used in this study, namely network visualization, overlay visualization, and density visualization. The network visualization shown in **Figure 5** shows the relationship between terms commonly used in research regarding the keywords used. From the network visualization, we can see the clusters along with the terms associated with the keywords. The clusters shown from this visualization form have 6 clusters as shown in **Table 1**.

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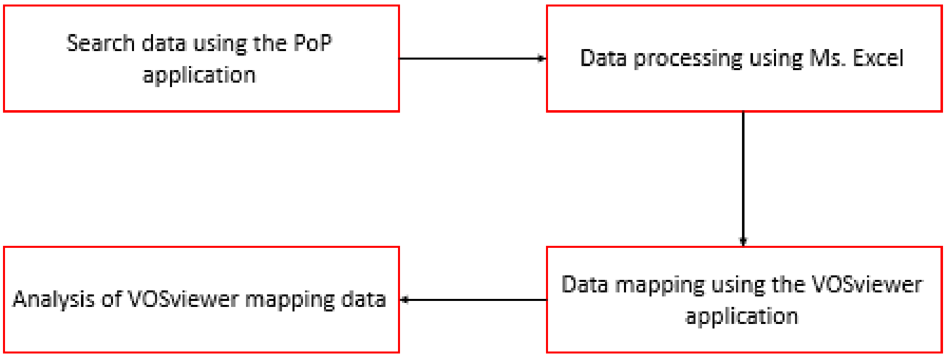

Figure 3. Stages of bibliometric analysis.

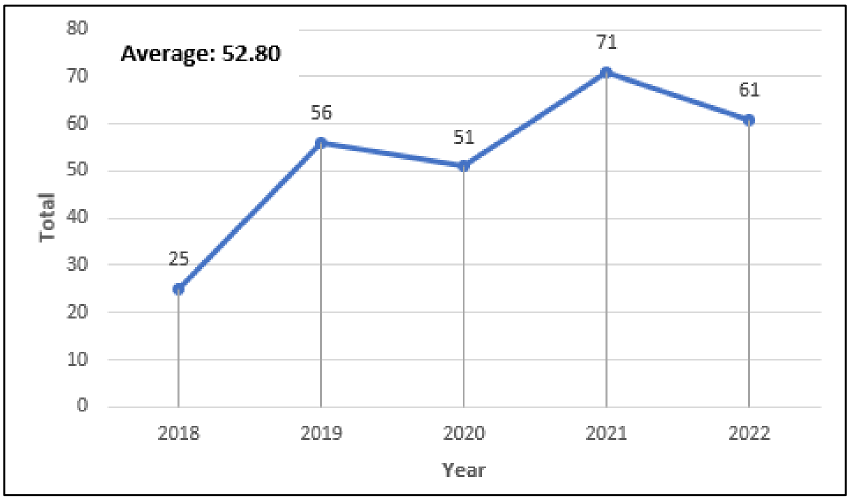

Figure 4. Development of research on "controller, "steer", and "wire system" in 2018-2022.

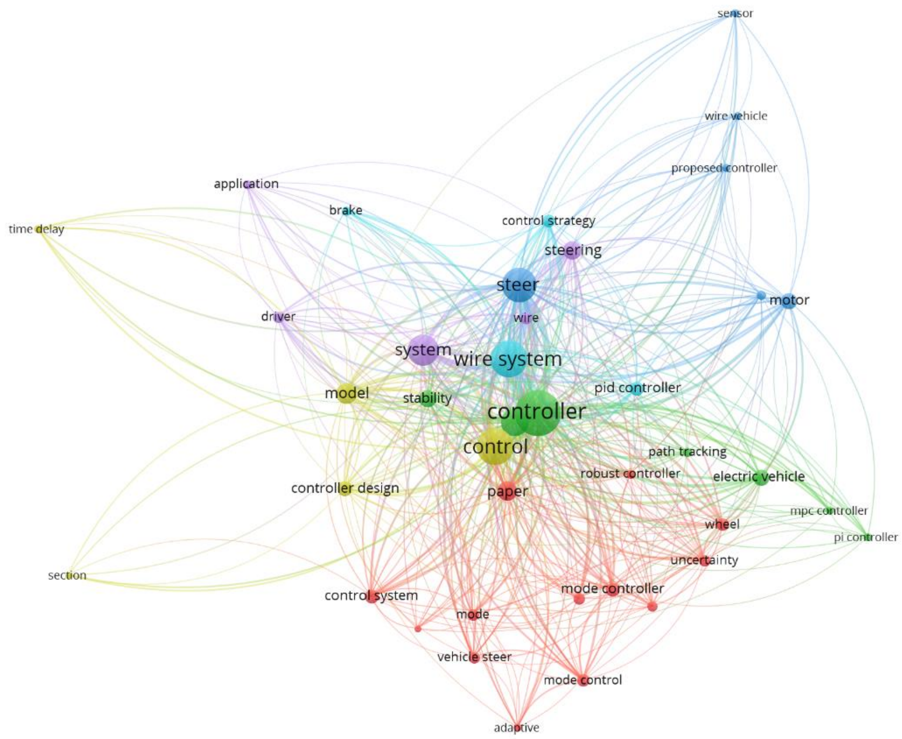

Figure 5. Network visualization based on keywords**.**

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Table 1. Clusters based on the results of the keyword visualization.

Cluster	Color	Items
1	red	adaptive, autonomous vehicle, control system, disturbance, mode, mode control, mode controller, mode predictive controller, paper, robust controller, uncertainty, vehicle steer, and wheel.
2	green	controller, electric vehicle, MPC controller, path tracking, pi controller, stability, and vehicle.
3	blue	motor, order, proposed controller, sensor, steer, and wire vehicle.
4	yellow	control, controller design, model, section, and time delay.
5	purple	application, driver, steering, system, and wire.
6	light blue	brake, control strategy, PID controller, and wire system.

Based on **Table 1**, the term used is the keyword "controller" in cluster 1 which is marked in red. The term controller is also connected with other terms such as control originating from cluster 4, control system originating from cluster 1, wire system originating from cluster 6, system originating from cluster 5, and other terms as indicated by **Figure 6**. As for the other two terms, namely "steer" and "wire system", they are in cluster 3 and cluster 6 respectively. The term steer is connected with 7 terms (see **Figure 7**), while the term wire system is connected with 34 terms (see **Figure 8**).

Based on the Overlay visualization shown in **Figure 9**, we can see the number of years the term was studied. Based on **Figure 9**, the terms "controller", "steer" and "wire system" have been widely researched in 2020. Meanwhile, based on **Figure 10**, we can see how often these terms are researched, the darker the color produced, the more often the term is researched. Based on **Figure 10**, of the three terms used as keywords the term "controller" is the most frequently used and researched by researchers.

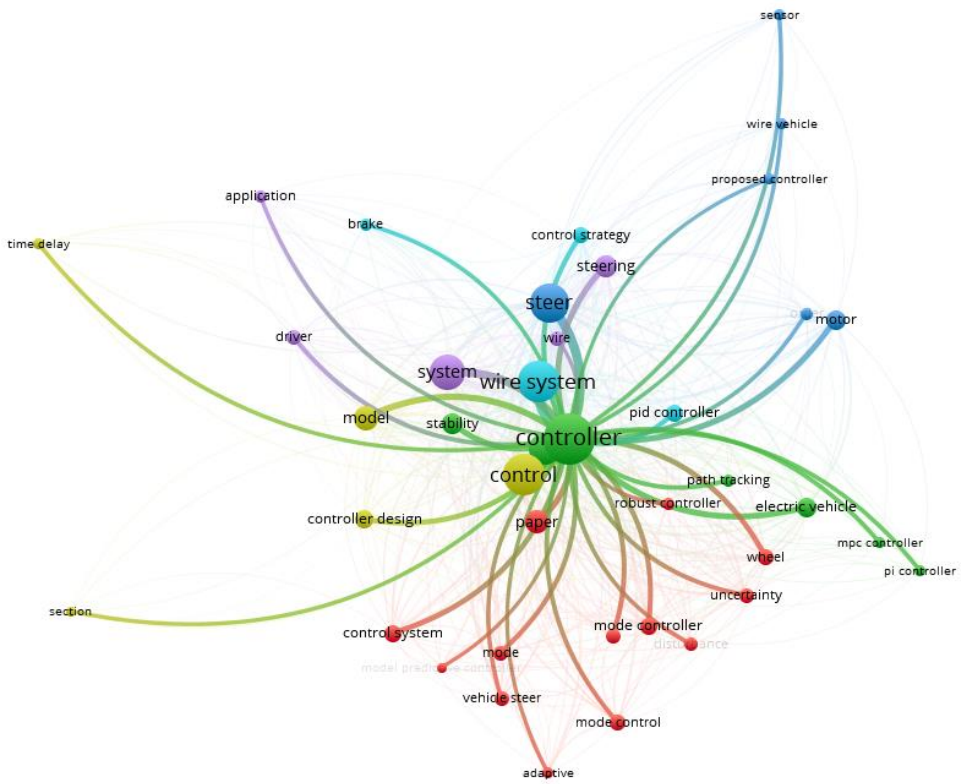

Figure 6. Network Visualization of controller terms.

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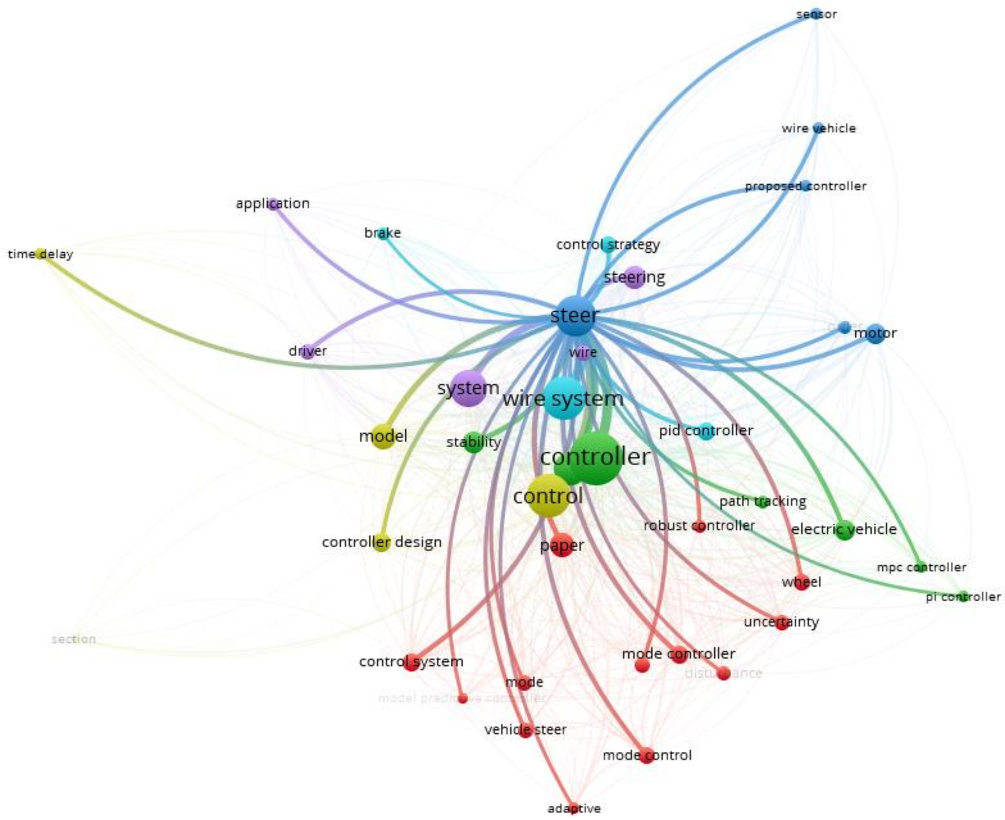

Figure 7. Network Visualization of the term steer.

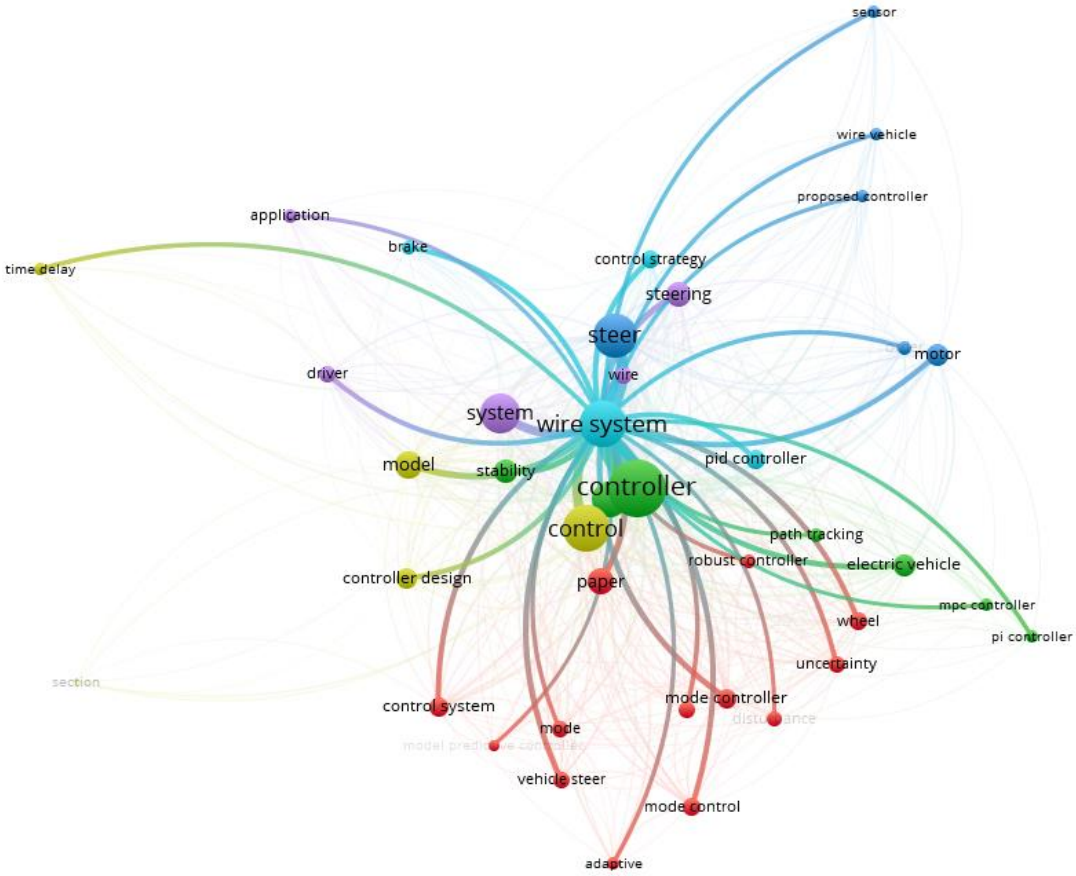

Figure 8. Network Visualization of the term wire system.

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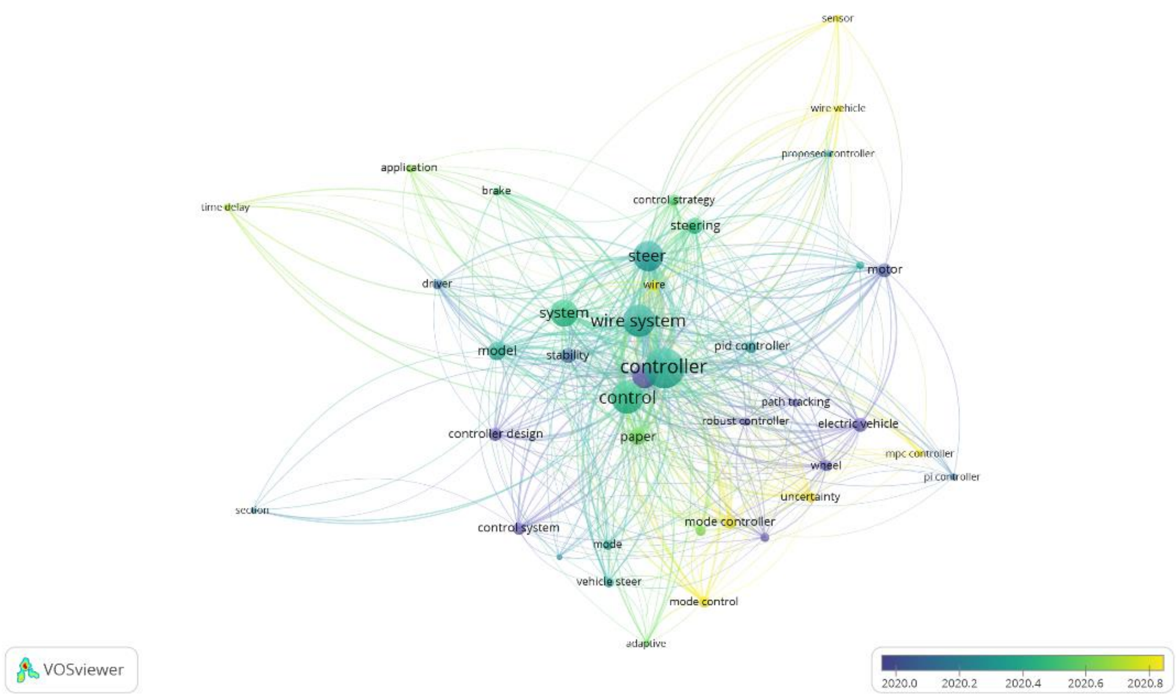

Figure 9. Overlay visualization based on keywords.

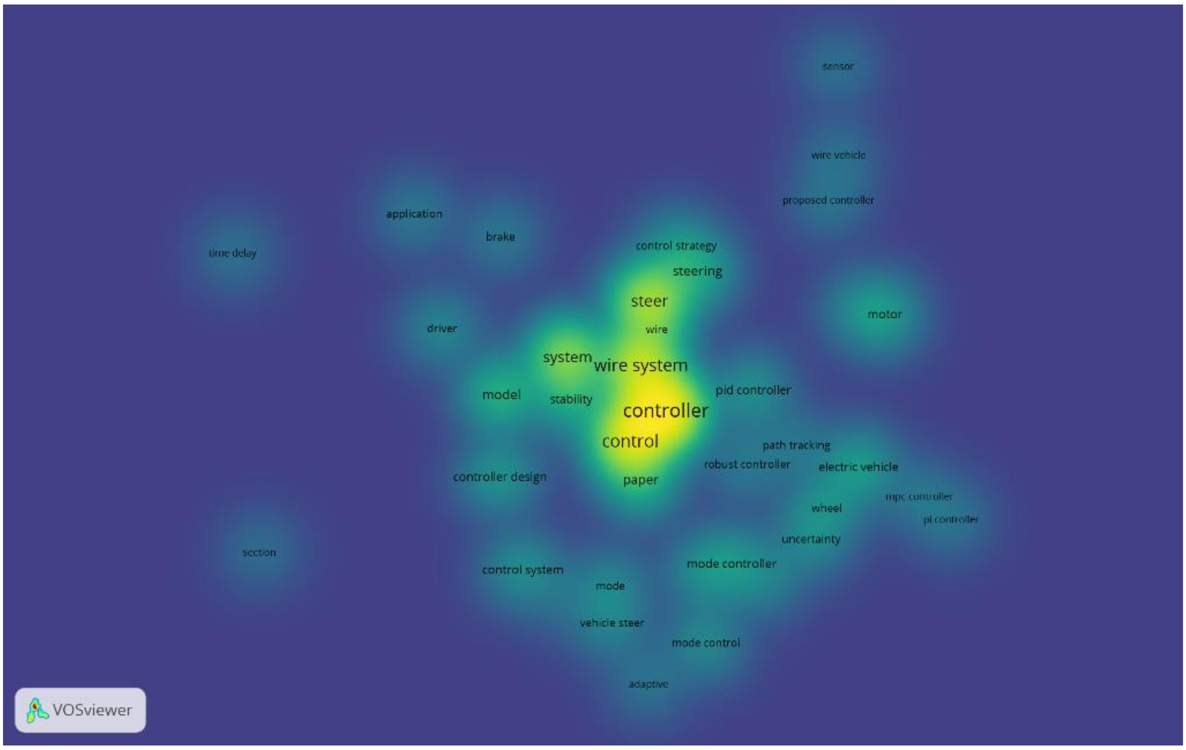

Figure 10. Density visualization based on keywords.

3.1.2. Developmental Map by the Author

Figure 11 shows the mapping results in the form of a network visualization from several authors who often research the keywords used. Based on **Figure 11**, there are 4 clusters with different colors and terms. The following is a breakdown of these clusters.

(i) Cluster 1 marked in red has 5 terms namely Chen, X., Li, C., Li, I., Wang, X., Wu, X.

(ii) Cluster 2 marked in green has 4 terms

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namely Hu, J., Li, H., Wang, Y., Zhang, J.

(iii) Cluster 3 marked in blue has 3 terms namely Du, H., Li, Y., Zhang, Z.

(iv) Cluster 4 marked in yellow has 3 terms namely Ma, B., Wang, J., Wang, Z.

In **Figure 11** it can be seen that the author who produces a lot of publications regarding keywords is Wang, Y., who is in cluster 4. Wang, Y., connected with 6 other authors namely Zhang, J., Ma, B., Hu, J., Li, H., Wang, Z., Wu, X. Some authors are in the same cluster and some are different, such as Zhang, J., Hu, J., and Li, H. (who are in Cluster 2), Ma, B. and Wang, Z. (who are in Cluster 4) and Wu, X. (who is in Cluster 1). Further explanation can be seen in **Figure 12**.

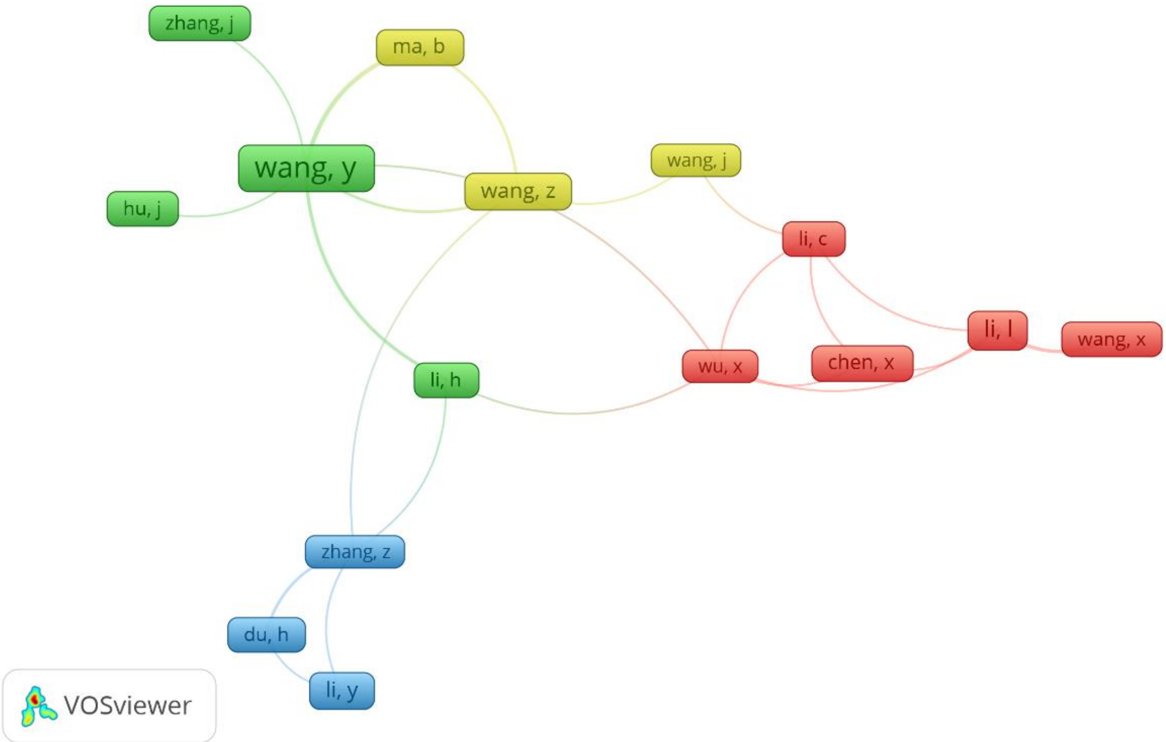

Figure 11. Network visualization by author.

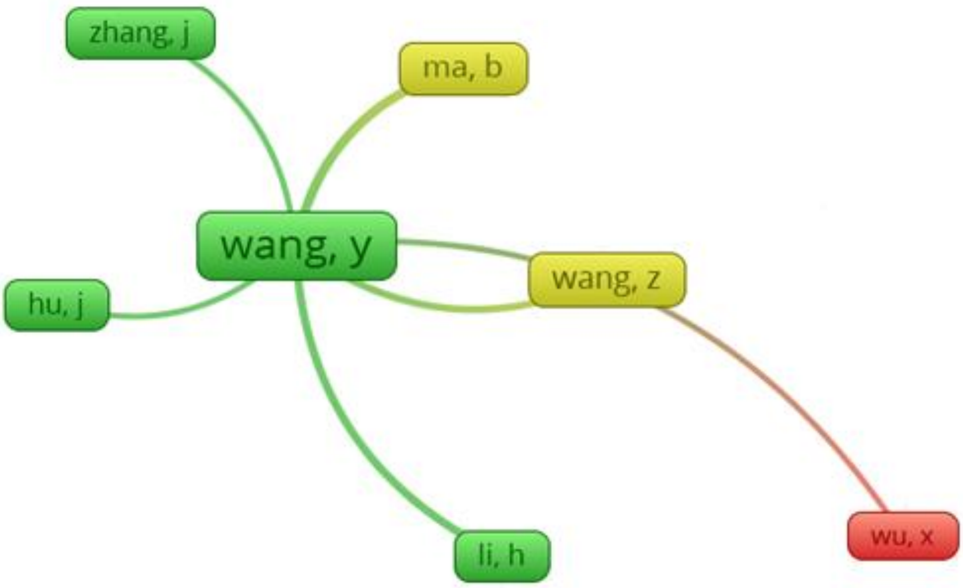

Figure 12. Network visualization from the author Wang, Y.

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In this part, the performance of ISMC has been assessed via computer simulation. The numerical simulation of a controlled VSbW system has been conducted within a MATLAB environment. The evaluation of the proposed controller has been tested based on three scenarios that address real situations. Then, the performance of the proposed controller is compared to other control techniques in the literature (Wang *et al.,* 2016; Sun *et al.*, 2018). To reduce the chattering effect in the control signal due to discontinuous part u_d, the following approximation is used instead of the hard signum function:

$$sgn(s) \approx \frac{s}{|s|+\varepsilon_1} \quad (27)$$

where ε_1 is a very small positive constant.

Table 2 lists the parameters of the VSbW system and the design parameters of the proposed controller (ISMC). In the first scenario (Scenario I), the vehicle is controlled to follow a reference sinusoidal path (Slalom path). In addition, the coefficient ξ in Equation (3) has been varied to mimic three real conditions: snowy road, wet asphalt road, and dry asphalt road. The three conditions have been applied respectively to the system during the three-time intervals $0 < t \leq 20$ s, 20 s $< t \leq 40$, and 40 s $< t \leq 60$ s as indicated in **Figure 13.**

Figure 14 shows the behaviors of steering angle, tracking error, and control effort under different road conditions. The ISMC could give good performance under uncertain parameters of the system.

In scenario II, the performance of ISMC has been tested by commanding the vehicle along a sharp or curved road path. The vehicle is first forced to move along a straight line and then it has to follow a circular path. This desired and commanded path will be generated by steering the wheel of the vehicle within 15 s of vehicle movement. In this scenario, the coefficient ξ has been set to value ξ = 950. The performance of ISMC is illustrated in **Figure 15**, which shows the responses of steering angle, tracking error, and control effort.

In scenario III, a sudden shock disturbance is applied to mimic a bump or a brick in the way of the vehicle. In this case, the vehicle is commanded to follow the straight path. The nominal reaction of the vehicle in the presence of sudden change is to return the front wheels to their original situation in an active and fast manner. The objective of the designed controller is to compensate and reject this exerted load such as to have fast convergence of tracking error during the time of load change.

This real situation has been simulated numerically by applying shock disturbance for 10 s. The reference input is set to zero. To exclude the interference of road conditions the coefficient ξ of the self-aligning torque is set to ξ = 150 to represent an invariable snowy road. Accordingly, the t performance of ISMC is illustrated in **Figure 16**, which shows the responses of steering angle, tracking error, and control effort.

Table 2. Parameters of VSbW system and ISMC controller (Wang *et al.,* 2016).

Parameter	Value
$J_0, c_0, and\ \rho_0$	86 kgm^2, 220 Nms/rad, 4.2 Nm
J^Δ, c^Δ and ρ^Δ	9, 22, 0.4
ρ_1, ε, ε_1, b	100, 0.005, 0.001, 275

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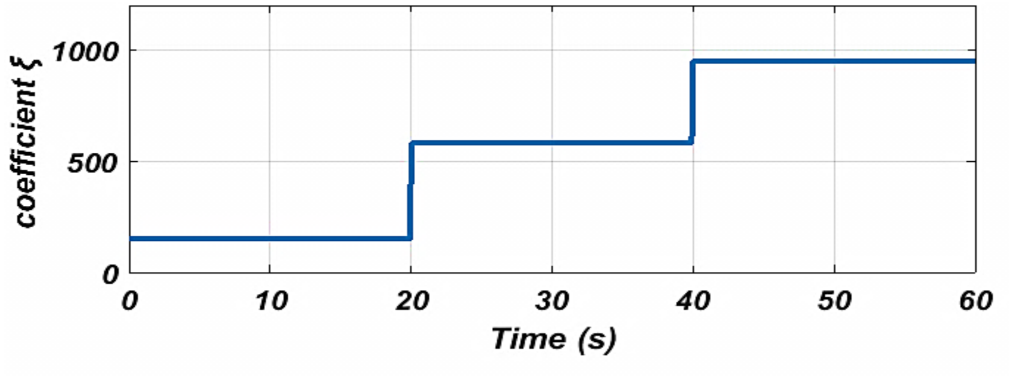
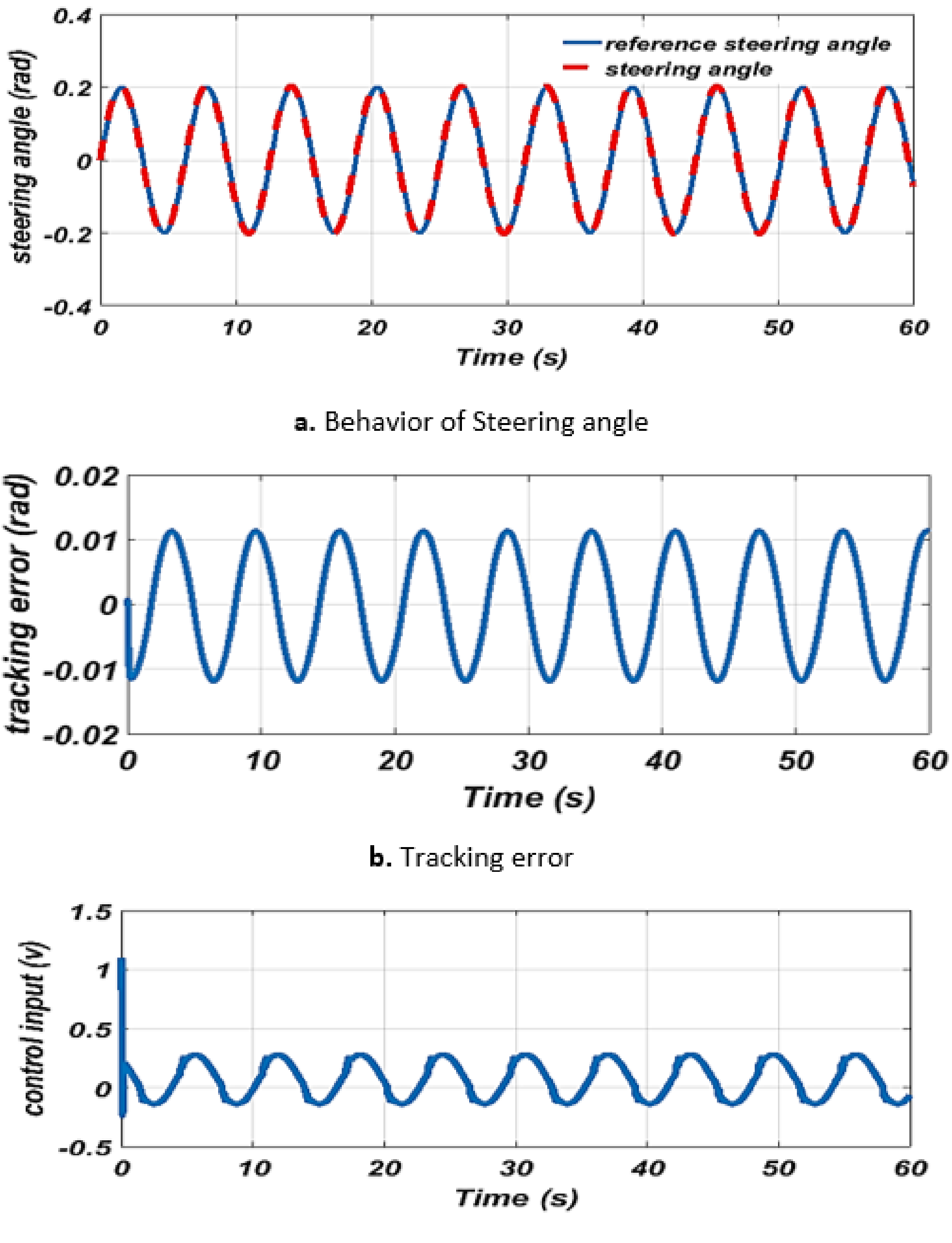


Figure 13. The variations of coefficient ξ (road conditions).

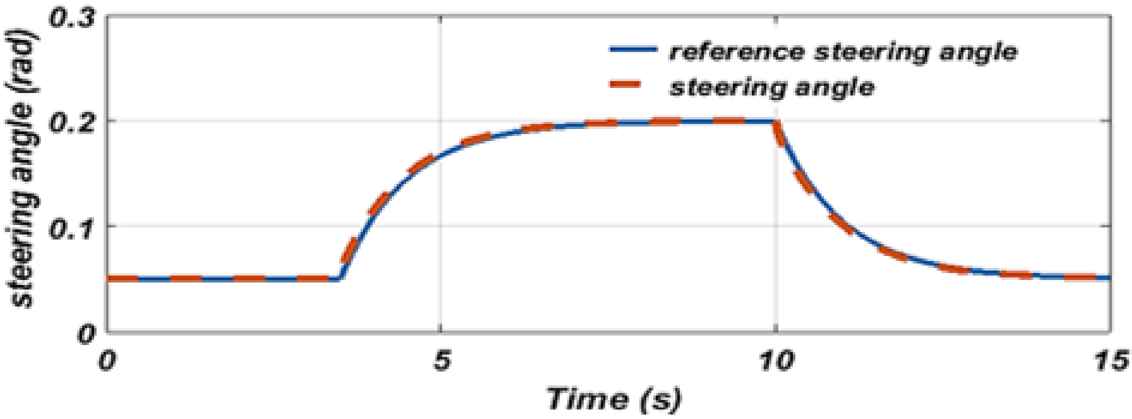


a. Behavior of Steering angle

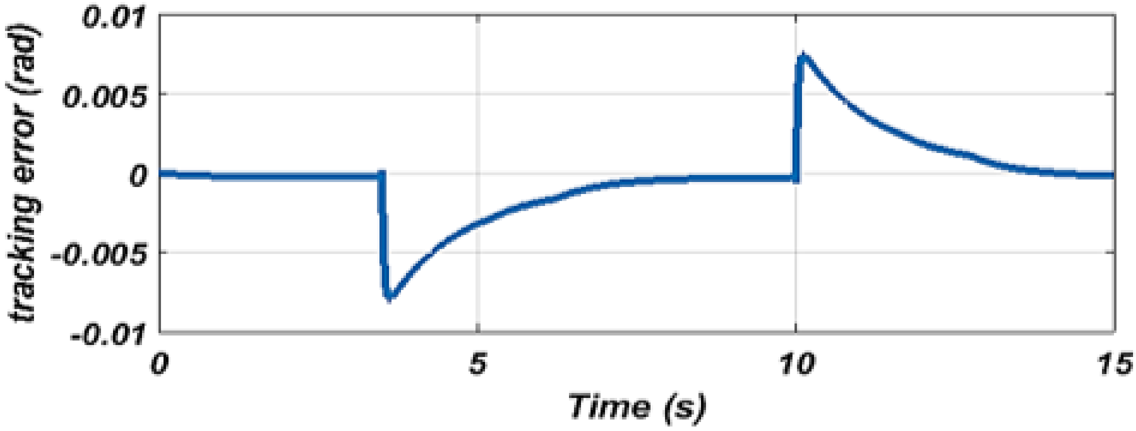
b. Tracking error

c. Control effort

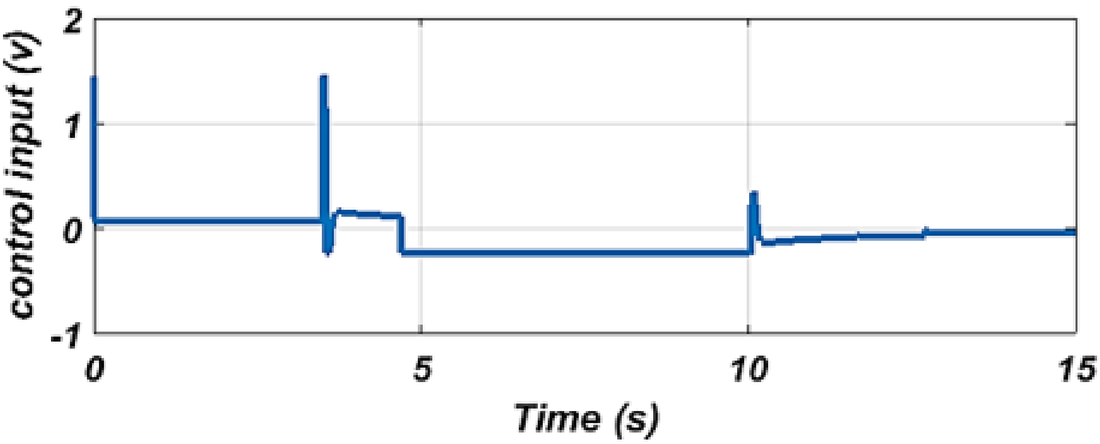
Figure 14. Tracking performance of ISMC with Scenario I.



a. Behavior of Steering angle



b. Tracking error.



c. Control effort

Figure 15. Tracking performance of ISMC with Scenario II.

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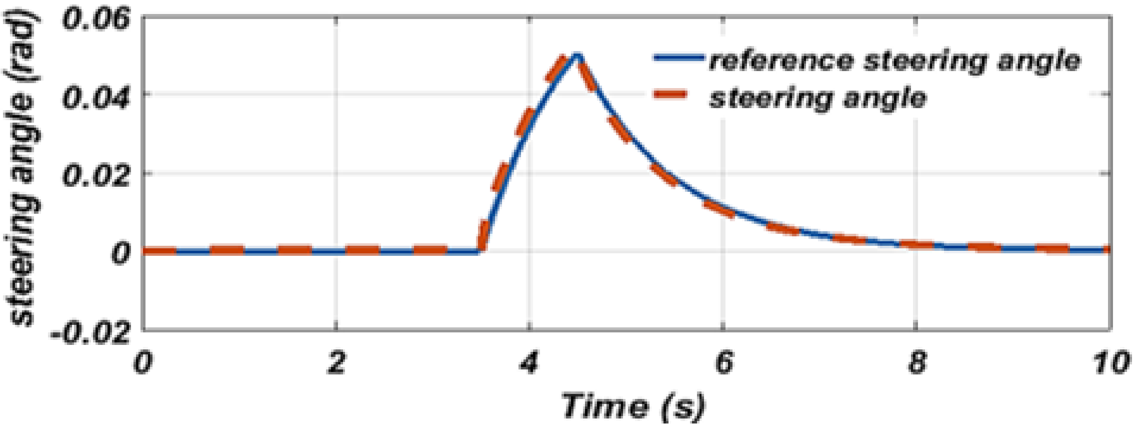
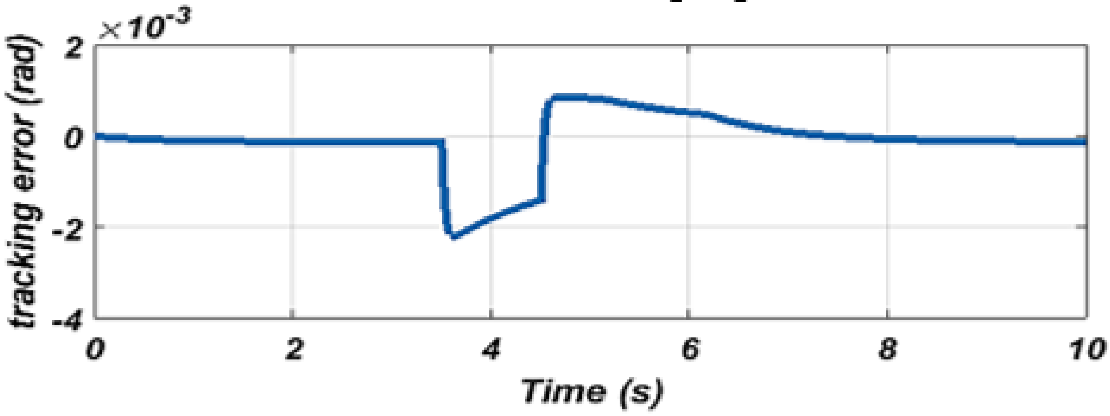
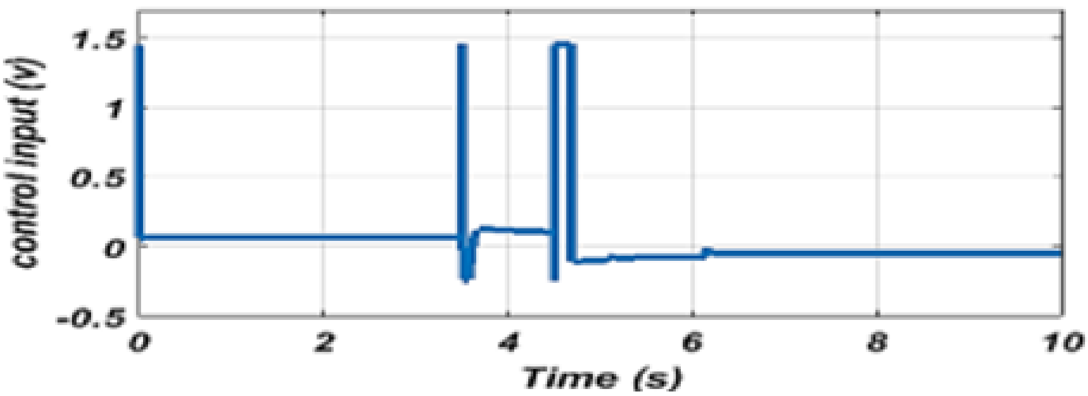


a. Behavior of Steering angle



b. Tracking error.



c. Control effort

Figure 16. Tracking performance of ISMC with Scenario III.

To show the effectiveness of the proposed ISMC strategy concerning other control schemes in the literature, a comparison in performance has been made with previous control studies such as ASMC (Sun *et al.*, 2018), PDADRC, and SMC (Wang *et al.*, 2016). **Table 3** reports the performances of both proposed and suggested controllers subjected to three conditions (Scenarios). The maximum value of error and control efforts are the indices used to evaluate these controllers. According to the performance table, one can deduce that the proposed ISMC has better tracking performances and lower control efforts as compared to other competitive control schemes.

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Table 3. Reports the performances of controllers.

	Control strategy	Max tracking error (rad)	Max control input (v)
		Scenario I	
1	ASMC	0.028	1.4
2	PDADRC	0.029	1.5
3	SMC	0.055	1.2
4	ISMC	0.012	1.1
		Scenario II	
1	ASMC	0.05	1
2	PDADRC	0.032	1.7
3	SMC	0.041	1.5
4	ISMC	0.0075	1.45
		Scenario III	
1	ASMC	-	-
2	PDADRC	0.022	1.3
3	SMC	0.082	1.5
4	ISMC	0.0022	1.45

4. CONCLUSION

In this study, a robust controller based on ISMC to control the vehicle steer-by-wire system. Based on observations of numerical simulation, one can conclude that the ISMC can give better robustness characteristics against bounded uncertain parameters as compared to other control techniques. The ISMC could considerably reduce the effect of the perturbation term and makes the controlled system behaves like a nominal system. This is the salient feature of control design based on ISMC. Also, the ISMC could prove better tracking errors for the three considered scenarios. In addition, the simulated results showed that the ISMC could reduce the chattering effect in the control signal to a large extent.

One can extend this study by suggesting other control techniques such as active disturbance rejection control (Alawad *et al.*, 2022), Finite-time control (Al-Qassar *et al.*, 2021), adaptive control (Humaidi, & Hameed, 2019), robust control (Abood *et al.*, 2023), and nonlinear PD control (Humaidi & Abdulkareem, 2019). A comparison study may be conducted between these suggested control methods and the proposed ISMC. Another future work can utilize different modern optimization algorithms to enhance the performance of ISMC by optimal tuning of its design parameters (Al-Qassar *et al.*, 2021a; Abdul-Kareem *et al.*, 2022). In addition, the proposed ISMC can be implemented in a real-time environment by conducting embedded system design using advanced hardware technologies (Al-Obaidi *et al.*, 2021; Hassan *et al.*, 2022).

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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