Development and Application of Steer-By-Wire (SBW) with Linear Sensors to a Small Electric Vehicle

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Abstract

A steer-by-wire (SBW) system with linear sensors has been developed and implemented on a small electric vehicle (EV). This system comprises a steering wheel, an angle and torque sensor, a wheel angle feedback sensor, an electric motor actuator, linkages, and a controller. It is specifically designed to electrically control the wheel angles without utilizing a conventional steering gearbox. The electric actuator motor is mounted on the steering mechanism and directly connected to the left and right wheel knuckles via linkages. Two linear sensors are employed: one located on the steering wheel to generate steering wheel angle signal θ_1, and the other installed on the wheel knuckle mechanism to produce front wheel angle feedback signal θ_2. When the driver rotates the steering wheel, the controller calculates the pitch error based on inputs from the two linear sensors and subsequently adjusts the wheel angles by powering the electric motor actuator. Experimental testing revealed a response time of 0.3 seconds, with the pitch error maintained within an angle of less than 3° during straight-motion tests. During cornering motion tests, the measured backlash was approximately 0.06 rad, demonstrating the system's responsive performance. This SBW technology with linear sensors is anticipated to reduce system complexity while enhancing precision, accuracy, and response speed of wheel angle adjustments to steering inputs, effectively meeting driving requirements.

Keywords: *steer-by-wire, linear sensor, small electric vehicle, straight and cornering test motions.*

Abstrak

Sistem steer-by-wire (SBW) dengan sensor linear telah dikembangkan dan diterapkan pada kendaraan listrik (EV) kecil. Sistem ini terdiri dari setir, sensor sudut dan torsi, sensor umpan balik sudut roda, aktuator motor listrik, penghubung, dan pengontrol. Sistem ini dirancang khusus untuk mengontrol sudut roda secara elektrik tanpa menggunakan gearbox kemudi konvensional. Motor aktuator listrik dipasang pada mekanisme kemudi dan dihubungkan langsung ke sambungan knuckle roda kiri dan kanan melalui penghubung. Dua sensor linear digunakan: satu terletak pada setir untuk menghasilkan sinyal sudut kemudi θ_1, dan yang lainnya dipasang pada mekanisme knuckle roda untuk menghasilkan sinyal umpan balik sudut roda depan θ_2. Ketika pengemudi memutar setir, pengontrol menghitung kesalahan pitch berdasarkan input dari kedua sensor linear tersebut dan kemudian menyesuaikan sudut roda dengan mengaktifkan motor aktuator listrik. Pengujian eksperimental menunjukkan waktu respons sebesar 0,3 detik, dengan kesalahan pitch dipertahankan dalam sudut kurang dari 3° selama pengujian gerakan lurus. Pada pengujian gerakan berbelok, backlash yang terukur adalah sekitar 0,06 rad, yang menunjukkan kinerja sistem yang responsif. Teknologi SBW dengan sensor linear ini diharapkan dapat mengurangi kompleksitas sistem sekaligus meningkatkan presisi, akurasi, dan kecepatan respons dalam penyesuaian sudut roda terhadap input kemudi, sehingga secara efektif memenuhi kebutuhan berkendara.

Kata kunci: *steer-by-wire,* sensor linear, kendaraan listrik (EV) kecil, pengujian jalan lurus dan belok

INTRODUCTION

Background

The advancement and adoption of technology in the automotive industry, particularly through automation systems, are closely linked to various factors such as efficiency, safety, and emissions reduction. A notable development driven by these factors is the implementation of X-by-wire systems, where mechanical components are replaced with electrical elements like control units, electric motors, actuators, and sensors. One key benefit of this technology is its ability to decrease the overall weight of the vehicle, which enhances fuel efficiency and lowers exhaust emissions. Additionally, the integration of sensors, motors, and electric actuators allows for greater precision, accuracy, and faster response times, thereby improving the vehicle's performance and responsiveness to the driver's inputs (DeBoer et al, 2024).

The X-by-wire concept represents a potential cornerstone for achieving fully integrated vehicle stability control systems, such as collision avoidance mechanisms and even autonomous driving. A prominent example of this technology is Steer-by-Wire (SBW), which eliminates the mechanical link between the steering wheel and the wheels. Consequently, traditional components like steering columns, intermediate shafts, pumps, hoses, fluids, and belts are removed. Instead, an electric motor actuator governs the steering angle and provides feedback to the driver's steering wheel. To achieve this, the driver's steering input is detected and used to control the electric actuator, ensuring the wheels align with the steering wheel's direction and angle (Mortazavizadeh et al, 2020).

As the vehicle moves, disturbances in the tires or sudden changes in road conditions can prevent it from maintaining the desired trajectory. These disruptions may result in a discrepancy between the actual yaw rate and the estimated yaw rate. To address this issue, a control moment with steering compensation is required. In a steer-by-wire system, where there is no mechanical link between the steering column and the steering gear, this compensation can be implemented directly through the front wheel actuator without influencing the steering wheel (Alekseeva, 2018).

In an ideal condition, steering ratio requirements are as follows: (1) at low speeds, a small steering ratio is needed so that a small steering input results in a large front wheel angle, ensuring easy maneuverability; (2) at high speeds, a larger steering ratio is required to prevent excessive steering sensitivity and support handling stability (Huang et al, 2018). A well-designed steering ratio enhances both steering performance and vehicle stability (Zhang et al, 2024). Moreover, a CAN-based networked control system is also introduced for real time control system (Shah et al, 2016). Given the steering system's role in active vehicle safety, overly sensitive steering can compromise the driver's control. Thus, both steering performance and handling stability are prioritized when designing the steering system.

The Steer-By-Wire (SBW) technology is poised to play a pivotal role in advancing automotive innovation, particularly in automated and autonomous vehicles. Commonly referred to as driverless or self-driving cars, these vehicles can navigate existing roadways and adapt to various driving conditions with minimal direct human input. Autonomous vehicles are equipped with radar, cameras, sensors, and systems for communication, computing, and mapping algorithms (Vargas et al, 2021). These technologies enable precise steering, lane-keeping, maintaining safe following distances, automatic braking, parking assistance, road sign recognition, and vehicle-to-vehicle communication. Furthermore, SBW technology enables remote vehicle operation (long-distance remote control) and supports autonomous systems, enhancing safety, convenience, and functionality for future automotive applications (Roy et al, 2023).

A Brief History of steer-by-wire systems

Vehicle technology has progressed significantly, leading to enhanced efficiency, safety, and performance. The steering system, responsible for relaying the driver's commands, has evolved through various stages, transitioning from purely mechanical designs toward fully electronic systems (Song et al, 2008). Mechanical components are increasingly replaced with electronic sensors and actuators to achieve improved performance and responsiveness (Wang et al, 2019).

The evolution of vehicle steering systems began with purely mechanical designs, followed by advancements like the hydraulic power steering (HPS), electro-hydraulic power steering (EHPS), and electric power steering (EPS), ultimately leading to the development of the steer-by-wire (SBW) system (Robert Boch GmbH, 2014). Traditional steering systems include essential components such as the steering wheel, column, gears, rack, and pinion. These parts work together to relay the driver's commands to the vehicle's wheels, ensuring the tires follow the path intended by the driver.

The earliest steering systems were purely mechanical, lacking any form of power assistance, and relied solely on the driver's physical effort to turn the vehicle's wheels and adjust its direction. The introduction of the hydraulic power steering (HPS) system, first implemented by Chrysler Imperial in 1951 (Arogeti et al, 2012), marked a significant advancement in steering technology. This system reduced the driver's effort, enhanced steering responsiveness, and provided greater stability and safety. Additionally, the hydraulic fluid in the HPS system helped to dampen steering wheel vibrations, improving the overall driving experience.

The HPS system was eventually upgraded to an EHPS system to address the high costs associated with design, assembly, and maintenance (Eckstein et al, 2014). Unlike HPS, which relies on a connection to the engine crankshaft, EHPS employs an electric pump to circulate hydraulic oil, reducing fuel consumption (Gaedke et al, 2017). Additionally, EHPS can operate even when the engine is off. In commercial vehicles, replacing HPS with EHPS can lower fuel consumption during long-distance driving by approximately 1% (Gessat, 2017). However, despite these advantages, EHPS still faces several critical drawbacks, particularly its limited flexibility and the design constraints associated with using hydraulic oil.

The next advancement in commercial steering systems was the introduction of the Electric Power Steering (EPS) system in 1996, which utilized an electric motor featuring a compact structure and power-on-demand capabilities (Lequesne, 2015). Unlike EHPS, the EPS system eliminates environmental and noise concerns associated with the use of hydraulic oil (Hu et al, 2009). Various configurations have been explored for the placement of the electric motor. These include mounting it on the steering column, which represents the earliest design; on the steering rack; directly on the steering pinion, which requires slightly more steering effort; on a second pinion, which provides greater force compared to other setups; or along an axis parallel to the rack (Eckstein, 2016).

DC motors are commonly utilized in EPS systems due to their ease of control. However, the increasing power requirements of larger vehicles, advancements in power electronics, and the adoption of advanced control methods such as field-oriented control and direct torque control for AC motors have shifted the focus toward permanent magnet synchronous motors (PMSM). This shift is also influenced by the higher capital (CAPEX) and operational (OPEX) costs associated with DC motors, making PMSM a more attractive option for modern applications (Eckstein et al, 2014).

EPS is considered the optimal choice for passenger vehicles due to its advantages, including reduced weight and size, simpler design, lower maintenance costs, and enhanced steering functionality. It can improve fuel efficiency by up to 5% thanks to its power-on-demand feature and offers added comfort through functions like lane-keeping assistance, smart parking assist, and vehicle stability management. However, it still faces some design challenges, particularly related to the use of column-based steering systems (Gadke et al, 2017). To address these issues, fault-tolerant EPS systems are a major focus of industrial research and patents. Solutions such as multi-winding electric motors, fault-tolerant control techniques, and virtual sensor approaches based on advanced estimation methods have been proposed by Ghaderi for improving EPS performance (Gessat, 2007; Lequesne, 2015).

These advancements paved the way for the development of the next-generation SBW steering system. SBW is a column-free steering system that utilizes an electrical link between the steering wheel and the vehicle's wheels. Since there is no direct mechanical connection between the steering wheel and the tires, most road vibrations are not transmitted directly to the steering wheel, enhancing driver comfort. The system requires two separate control loops: one for the steering wheel and one for the motor driving the road wheels. The motor driving the road wheels is responsible for accurately transmitting the driver's commands to the tires, while the motor controlling the steering wheel must provide the driver with feedback reflecting the road surface (Wilwert et al, 2005).

Eliminating the mechanical link offers key advantages, such as reduced weight and space, along with greater design flexibility. However, challenges remain in the broader adoption of such systems, including the complexity of the required control mechanisms and reduced overall reliability due to the extensive use of sensors. Despite these challenges, several conceptual designs and a number of commercially available vehicles featuring this system have emerged.

State of the Arts

Technological advancements in the automotive industry, particularly with the implementation of automation systems, have led to the development of steer-by-wire technology. This innovation replaces mechanical components in the steering system with electronic devices, such as control units, actuators, and sensors, to regulate steering rotation via the wheel. One of the key advantages of this system is the reduction in the vehicle's overall weight, which in turn improves fuel efficiency. Furthermore, the steer-by-wire system serves as a foundation for driverless vehicle technology, where electronic controls replace the driver's functions.

Steer-by-wire (SBW) technology offers several advantages over traditional steering systems, including enhanced handling performance, simplified design, and greater flexibility. As vehicle speeds increase, the demand for safer driving has also risen. Modern chassis control systems aim to protect drivers from potentially hazardous dynamic reactions that may result from unintended driver inputs. Since the driver’s reaction time can be at least half a second, dangerous yaw movements may already occur, potentially leading to overreactions. SBW systems can respond more rapidly to control yaw movements, preventing excessive tire side slip angles and only requiring a small additional steering angle (less than ±2°) to correct the situation.

The SBW system consists of a steering column, steering wheel motor (feedback motor), and front-wheel motor (Che et al, 2005). Other steering systems: steering wheel, rack and pinion, tie rod, and front wheel based on reduced order modeling. The dynamic equations of motion of the SBW system are determined, based on a vehicle model with two DOFs.

Alekseeva (2018) identified the safety-critical requirements and failure modes for steer-by-wire applications. These failure modes can stem from various underlying issues, with the most common being the failure of encoders that measure the handwheel angle (θh) or steering wheel angle (θs). This paper suggests using a Search-based Online Observer without a Commissionable Sensor (SONIC) to obtain the required steering angles for comparison with encoder measurements. Without reliable sensor estimates, an error condition can arise if a discrepancy from the encoder is detected. While sensorless estimation may not achieve the accuracy of high-resolution encoders (with high counts per revolution or high bit counts), the estimates tend to be more stable since they rely on electronic sensors instead of electromechanical ones. Both optical and magnetic encoders are susceptible to failure due to mechanical misalignment and vibration. Additionally, the technologies mentioned have their own limitations, such as increased complexity when applied to smaller vehicles.

The proposed invention aims to address the aforementioned issues by simplifying the steering mechanism design. Instead of using a steering gearbox, a direct drive actuator motor shaft is employed to move the wheel knuckle through a link. Additionally, two linear sensors are integrated into the steering wheel mechanism to detect the direction and amount of angular rotation of the steering wheel, and into the wheel mechanism to measure the angular position of the wheel. The purpose of these linear sensors is to control the electric motor actuator, enabling the wheels to move in response to steering rotation. The feedback signal generated by the sensors helps compensate for any discrepancies, allowing the angular position of the wheels to be adjusted according to the input signal from the sensors.

Based on the background outlined above, the problem formulation for the research on steer-by-wire technology is as follows: (1) it is essential to detect both the direction and magnitude of the torque applied by the driver to the steering wheel to ensure the correct motor response for moving the gearbox and wheels; (2) disturbances in the vehicle's wheels, often caused by road conditions, can lead to discrepancies between the actual and estimated yaw rates, thus requiring steering compensation; (3) there is a need to adjust the motor power ratio based on variations in vehicle speed in order to fine-tune the steering sensitivity, enhancing both steering stability and performance. However, the primary goal of this research is to develop a prototype of a steer-by-wire (SBW) system that can be applied to a small electric vehicle, with a particular focus on autonomous (driverless) vehicles. The significance of this research lies in advancing a crucial sub-system for autonomous vehicles, contributing to the continued development of autonomous driving technology.

METHODS

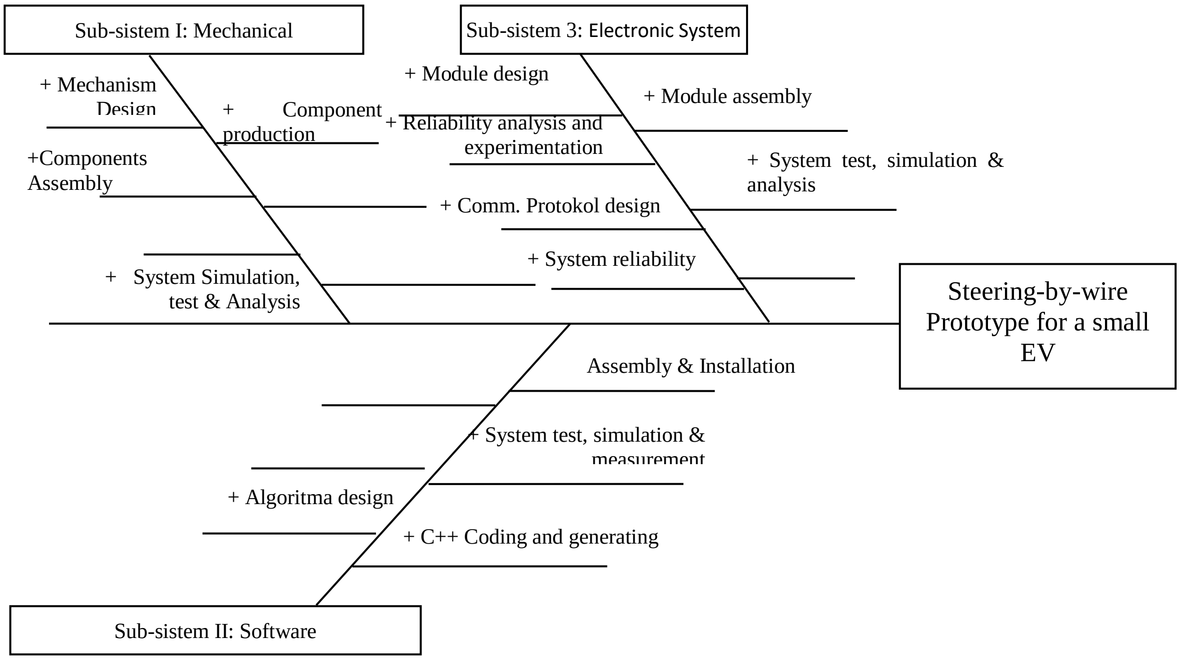
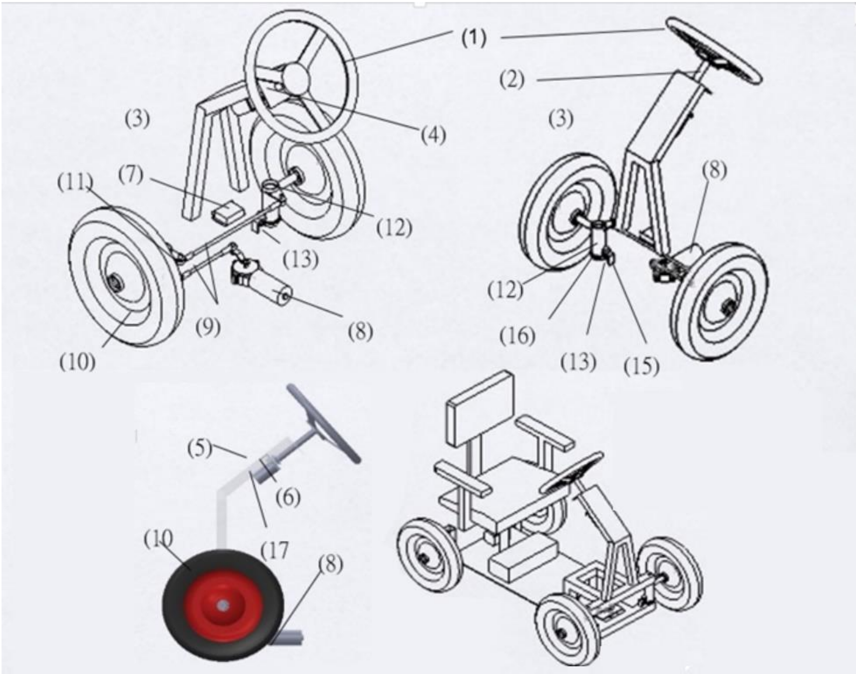


Figure 1. Research method to achieve the outcome of Steering-by-wire for a small EV prototyping

To achieve the goal of this study, several stages were implemented, beginning with the conceptual SBW design and modelling, followed by hardware and software development, and parts integration. Moreover, testing and validation were carried out to evaluate the prototype of the SBW components and sub-system functionalities. Subsequently, the data acquired from the performance tests were analyzed to determine the correlation between input signals (steering wheel angle) and output (wheel position), enabling the evaluation of error rates in sensor readings and actuator performance. Accordingly, the hardware and software components were refined to optimize system performance. Figure 1 above illustrates the detailed work plan during the project, culminating in a prototype of the SBW system for a small EV with excellent performance.

SBW Design and Modeling



Description:
1. Steering wheel
2. Steering wheel shaft
3. Steering column frame
4. Steering wheel angle sensor location
5. Upper steering cover
6. Steering wheel sensor mechanism
7. SBW controller
8. Motor actuator
9. Linkages
10. Vehicle wheel
11. The tierod end
12. Wheel hub
13. Wheel angle sensor
14. Wheel angle sensor support
15. Wheel angle sensor lock nut
16. Lower bearing
17. Feedback electric motor

Figure 2. Steering-by-wire mechanism design using CAD

The steering actuator, which consists of the steering motor and gearbox, is controlled by a servo amplifier within the ECU. This configuration generates a steering reaction torque that mirrors the driver's effort on the steering wheel. Additionally, the ECU provides force feedback to the motor connected to the steering gear, offering sensory input to the driver. This feedback informs the driver about the vehicle's dynamics and road conditions. The steering effort results from the interaction between the front tires and the road surface, which typically creates a slip angle or side slip during vehicle motion. In vehicle dynamics, the slip angle refers to the difference between the wheel's intended direction and its actual path. This angle generates a cornering force at the tire's contact patch, which is perpendicular to both the patch and the wheel's center. One effect of these cornering forces is the self-centering of the steering wheel, which occurs when the driver releases the wheel after a turn. Both the self-aligning effect and torque feedback are essential in replicating the feel of a traditional steering system.

The CAD design of a small four-wheeled EV used in this project is shown in Figure 2. A traction in-wheel motor is applied to the right rear wheel, which is integrated with an SBW system installed on the front wheels. Thus, the front wheels control the direction of the vehicle, while the right rear wheel provides traction for vehicle propulsion, and the left rear wheel functions as a passive wheel.

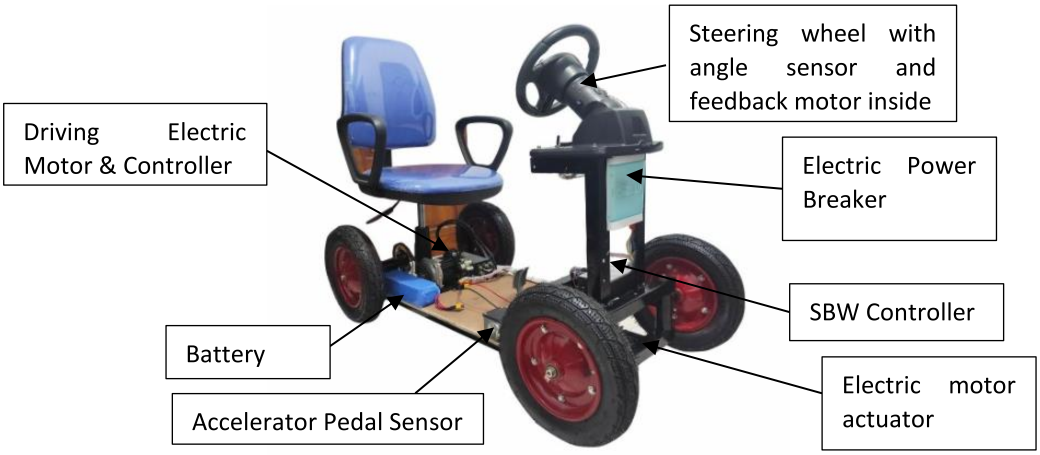


Figure 3. The prototype of a small electric vehicle with steering-by-wire system

However, Figure 3 shows the final product of the small EV with SBW. It can be seen that a 1.5 kW in-wheel BLDC motor, which is mounted and connected to the right-rear wheel using a sprocket and chain, serves as the traction motor that enables the vehicle to move forward or backward. The motor spins the wheel and transmits power to the ground. The system is designed for battery-powered electric vehicles, and the technology eliminates the need for a clutch, transmission shaft, and/or universal joint. The detailed specifications of the small EV are shown in Table 1 below.

Table 1. The small EV system parameters specification

Powertrain Systems	350W BLDC traction motor Single rear-wheel drive 12” wheels with tube type
Chassis and Steering Systems	A 14mm ladder frame steel with backbone No suspension system attached Steel shaft to support front wheels Single rear wheel with steering model with gearbox unit, operated by electric power steering unit 1 x 24V BLDC motor for steering position control
Electronic System	1 x 24V drive with EtherCAT communication protocol for steering 1 x 48V drive for traction controls 1 x 45Ah 48V Li-ion battery for traction system 2 x 12V battery for steering system 1 main controller with display
Physical Specifications	Vehicle length: 1630 mm Vehicle width: 750 mm

	Wheelbase: 1200 mm Wheel Tread: 700 mm Vehicle Gross weight: 30.35 kg Front-wheel weight: 2 x 1.45 kg Rear wheel weight (including traction motor): 8.2 kg Front end frame (including gearbox and steering motor): 10.7 kg Brake caliper weight: 2 x 0.565 kg

Steer-By-Wire Dynamics

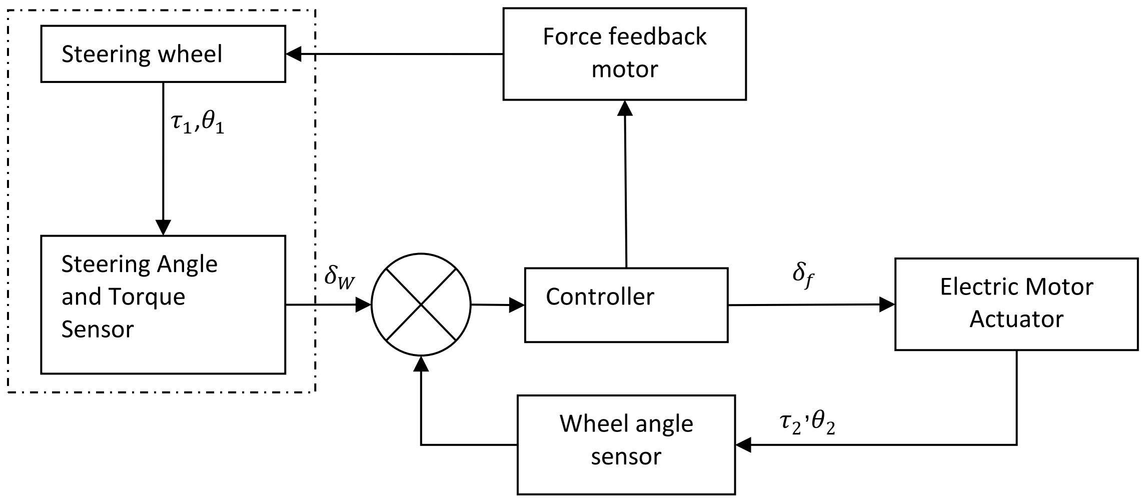


Figure 4. Steer-by-wire system schematics

Figure 4 above shows the proposed SBW system schematics of the small EV in this project. A linear sensor is applied to measure the direction and magnitude of the steering torque provided by the driver via the steering wheel. Next, on the steering shaft, a torsional shaft of length l is placed. Thus, if the driver turns the steering wheel in the direction θ_1 with a torque of τ_1, then at the end of the axle the torque will produce rotation in the direction θ_2 with a torque of τ_2. Thus, if the variables θ_1 and τ_1 have been given, then the other two variables can be obtained as follows.

The dynamics of the torsion shaft are described by the following partial differential equation:

$$\frac{\partial^2\theta(t,x)}{\partial x^2} - \mu^2\frac{\partial^2\theta(t,x)}{\partial x^2} = 0 \quad (1)$$

By $\mu^2 = \frac{I}{kl^2}$, where I is the shaft inertia, l is the length of the shaft, and k is the stiffness factor of the shaft.

Hence the total torsional of the shaft is:

$$\tau(t,x) = kl\frac{\partial\theta(t,x)}{\partial t^2} \quad (2)$$

By using the Laplace transform, formula (1) becomes:

$$\theta(s,x) = k_1 e^{-\mu sx} + k_2 e^{\mu sx} \quad (3)$$

Where k_1 and k_2 are parameters determined by the boundary conditions. Meanwhile, the boundary conditions are assumed to be as follows:

$$\begin{cases} \theta(s,x)|_{x=0} = \theta_1(s) \\ \theta(s,x)|_{x=l} = \theta_2(s) \end{cases} \quad (4)$$

The complete solution of the partial differential equation (1) in the Laplace domain is obtained:

$$\theta(s,x) = \frac{e^{\mu sx}\theta_2 - e^{2\mu ls}\theta_2}{1 - e^{2\mu ls}} e^{-\mu sx} + \frac{\theta_1 - e^{2\mu ls}\theta_2}{1 - e^{2\mu ls}} e^{\mu sx} \quad (5)$$

Next, the angular position of each torsional shaft cross-section is obtained by equation (5). By following equations (2) and (5), the overall torque at the first end of the shaft is obtained:

$$\tau_1(s) = k\mu ls \left(\frac{1 + e^{2\mu ls}}{1 - e^{2\mu ls}}\theta_1 - \frac{2e^{\mu ls}}{1 - e^{2\mu ls}}\theta_2\right) \quad (6)$$

And the torque at the other end of the torsional shaft is:

$$\tau_2(s) = k\mu ls \left(\frac{2e^{2\mu ls}}{1 - e^{2\mu ls}}\theta_1 - \frac{1 + e^{\mu ls}}{1 - e^{2\mu ls}}\theta_2)\right) \quad (7)$$

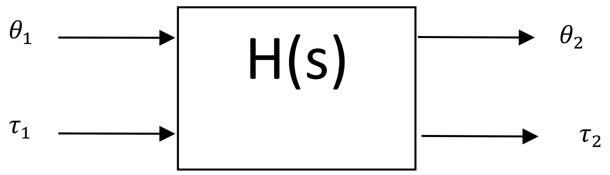


Figure 5. Block diagram of fractional order model of torsional shaft

At this point, we can approximate the magnitude of the angular position and torque vectors using the transfer function H(s), as measured by the linear sensor. The block diagram of fractional order model of torsional shaft of the SBW is illustrated in Figure 5.

To assess the steering frequency response influenced by road conditions, the estimated self-aligning torque is calculated. This is done using a linear vehicle model, where the side-slip angle and yaw rate are represented as follows.

$$\dot{x} = x = Ax + B\delta_f \quad (8)$$

$$\tau_a = Cx + D\delta_f$$

where

$$x = [\beta\ r]^T \tag{9}$$

$$A = \begin{bmatrix} \frac{-C_{\alpha,f} - C_{\alpha,r}}{mV_x} & -1 + \frac{C_{\alpha,r^b} - C_{\alpha,f}a}{mV_x{}^2} \\ \frac{C_{\alpha,r}b - C_{\alpha,f}a}{I_z} & \frac{-C_{\alpha,f}a^2 - C_{\alpha,r}b^2}{I_zV_x} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{C_{\alpha,f}}{mV_x} \\ \frac{C_{\alpha,f}a}{I_z} \end{bmatrix}$$

$$C = \begin{bmatrix} -C_{\alpha,f}(t_p + t_m) & -C_{\alpha,f}(t_p + t_m)\frac{a}{V_x} \end{bmatrix}$$

$$D = C_{\alpha,f}(t_p + t_m)$$

If it is assumed that the sideslip angle is small (less than 4°), then the front wheel sideslip angle α_f is obtained using the following formulation:

$$\alpha_f = \beta + \frac{ar}{V_x} - \delta_f \tag{10}$$

Assuming the vehicle’s longitudinal speed remains constant, the transfer function relating the front wheel angle relative to the road to the self-aligning torque τ(s) can be derived using the following formulation:

$$\tau(s) = C(sI - A)^{-1}B + D \tag{11}$$

Steer-by-wire Controller Design

The driver-vehicle interface remains the most widely utilized human-machine interaction system today, yet there is limited empirical understanding of the driver’s dynamic behavior and the interaction between the driver and the vehicle’s dynamic characteristics. To address this, a simplified driver model is employed to examine improvements in transient vehicle behavior through sliding mode control applied to the reference model. This driver model uses a predictor-corrector control approach that incorporates steering delay times, providing an algorithm for mathematically and theoretically modeling the closed-loop driver-vehicle directional control system.

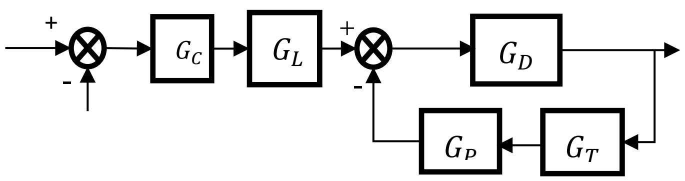


Figure 6. A simple driver model schematic of the SBW controller

Where the transfer function of the driver model above can be expressed as follows:

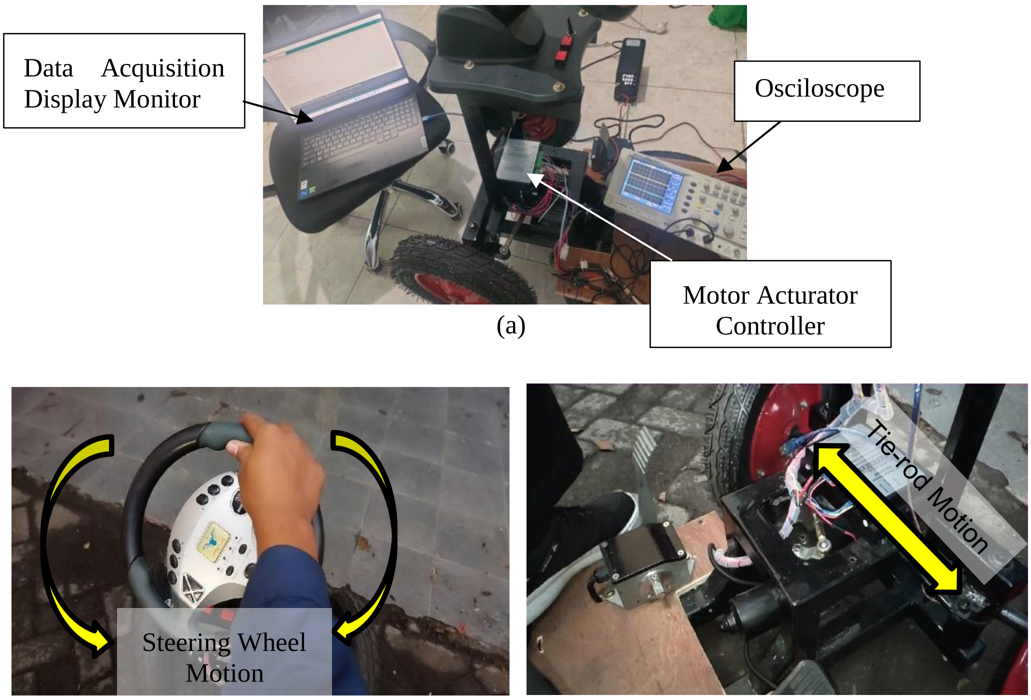
$$G = G_c \,.\, G_L \cdot \frac{G_D}{1 + G_P \,.\, G_T \,.\, G_D} \tag{12}$$

Here, G_c represents the error gain signal, G_L denotes the driver's visual delay, and G_D, G_P, and G_T correspond to the dynamic characteristics of the SBW driver, the joint, and tire traction, respectively. According to the equation, the driver's feedback compensation for the path tracking error at the preview point generates the steering wheel angle through a combination of first-order phase delay and pure time delay. The SBW system with a drive model is theoretically represented in Figure 6, showing the reference model for the control system's compact sliding mode control output, the feedback control law incorporating the sliding mode control scheme, and the driver model based on a predictor-corrector control approach. Similar to a human driver, the closed-loop system produces a steering angle input.

Steer By Wire Verification

To evaluate and validate the SBW performance of the proposed model, a series of experiments were conducted. A vehicle with the parameters presented in Table 1 was tested using straight and cornering motion tests on the road, following the test method proposed by Ismail et al (2022). The vehicle was assumed to move along a straight path and perform a 90° cornering motion, requiring the use of the steering wheel. Together, these tests provide a comprehensive assessment of how effectively the steer-by-wire technology enables precise and reliable control under various driving conditions.

However, a static performance test is conducted before the on-road test. The setup for the static performance test of the SBW model is shown in Figure 7(a). A data acquisition (DAQ) system monitors the steering angle and wheel angle parameters generated by the steering wheel and wheel sensors. Additionally, an oscilloscope provides readings of the output voltages from the steering wheel and wheel sensors. The static performance test involves analyzing the response of the actuator motor as it steers the front wheel of the small EV when the steering wheel is rotated. Accordingly, input and output data parameters are collected for further evaluation. This static performance test aims to ensure the functionality of the steering wheel and sensors (shown in Figure 7(b)), as well as the electric motor actuator and front wheel (shown in Figure 7(c)).



(b) (c)

Figure 7. The static performance test of the SBW system and mechanism: (a) The test setup, (b) The steering wheel and sensor function, and (c) The electric motor actuator and wheels function

Subsequently, the straight-line and cornering motion of a small electric vehicle equipped with a steer-by-wire system are performed to evaluate its maneuverability, stability, and safety on the road. As shown in Figure 8 (a), during the straight-line test, the vehicle is driven at a speed of about 40 km/h while the steering wheel is held steady in a straight direction. The primary purpose of the straight-line test is to evaluate the vehicle's ability to maintain a stable trajectory without significant oscillations or deviations. This test provides insights into the precision of the steer-by-wire system, which eliminates the physical connection between the steering wheel and the wheels, relying solely on electronic control for directional stability. Consistency and responsiveness in straight-line motion also reflect the accuracy of sensor feedback and control algorithms.

In cornering test as shown in Figure 8 (b), the vehicle's performance in handling turns during a 90-degree cornering motion is evaluated to observe the effectiveness of the steer-by-wire system in achieving smooth, controlled cornering. The test examines how the input step of the steering wheel angle sensor corresponds to the response of the wheel angle sensor parameters. This determines how the system adapts to cornering scenarios while maintaining driver input accuracy and minimizing output deviation.

(a) (b)

Figure 8. On-road driving test: (a) Straight path, and (b) Cornering

RESULT AND DISCUSSION

The results of the static performance test for the steering wheel angle sensor θ_1 and the wheel angle sensor θ_2 are shown in Figure 9. The signals from both sensors are synchronized, although there is a slight response delay of 0.2 seconds at Δt. Both signals exhibit a linear relationship between changes in angle and time.

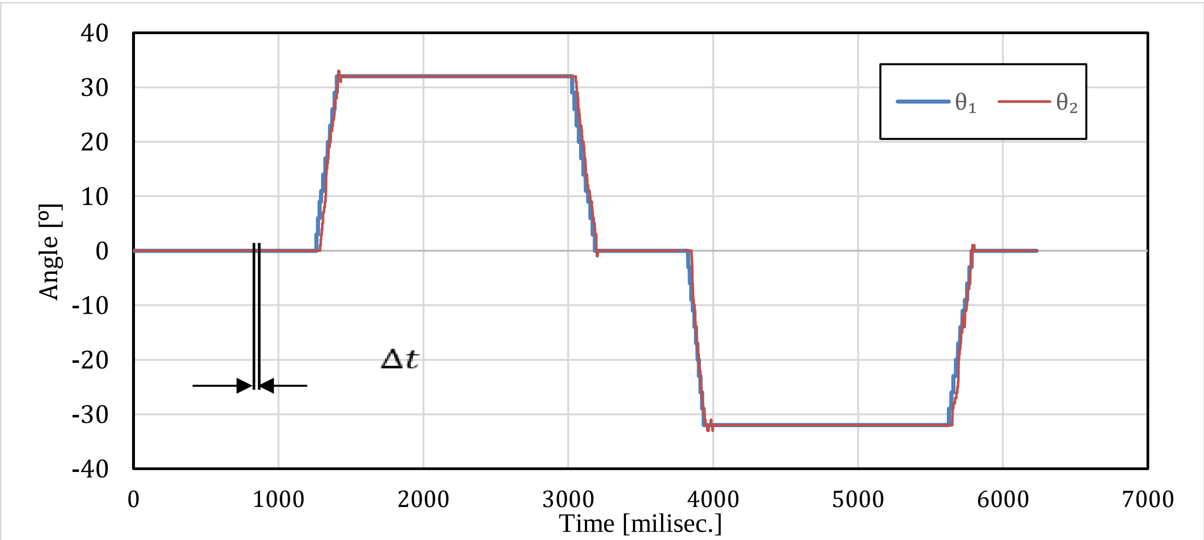


Figure 9. Static performance test result of SBW

According to the equation (5), the wheel angle θ_2 is generated through the driver's feedback compensation for the steering error at the preview point, incorporating both first-order phase delay and pure time delay. The vehicle's SBW system is modeled with a drive model, a reference model for the compact sliding mode control output, a feedback control law using sliding mode control, and a driver model based on a predictor-corrector control approach. Similar to human steering, the output loop generates a steering angle input θ_1, which is read by a linear sensor and transmitted to the controller. Simultaneously, the controller monitors the pitch error, which is the difference between the input θ_1 and the feedback θ_2. The controller then commands the motor to adjust the wheel angle, reducing the pitch error until it matches the reference input. When the pitch error equals zero, the motor will stop.

Figure 10 shows the step input and response results from the wheel steering sensor and wheel angle sensor during straight motion test. The steering pitch error, which is maintained within an angle of less than 3°, demonstrates the responsive performance of the steer-by-wire (SBW) system in maintaining precise vehicle control. This minimal pitch error indicates that the system is effectively compensating for any discrepancies between the desired and actual steering inputs, ensuring stable and accurate maneuvering. The ability to keep the pitch error consistently below this threshold highlights the system's responsiveness, allowing for smooth transitions and reliable performance under varying driving conditions. Such precision is crucial for achieving optimal stability and driver confidence, as it minimizes deviations in the vehicle's path and enhances overall safety.

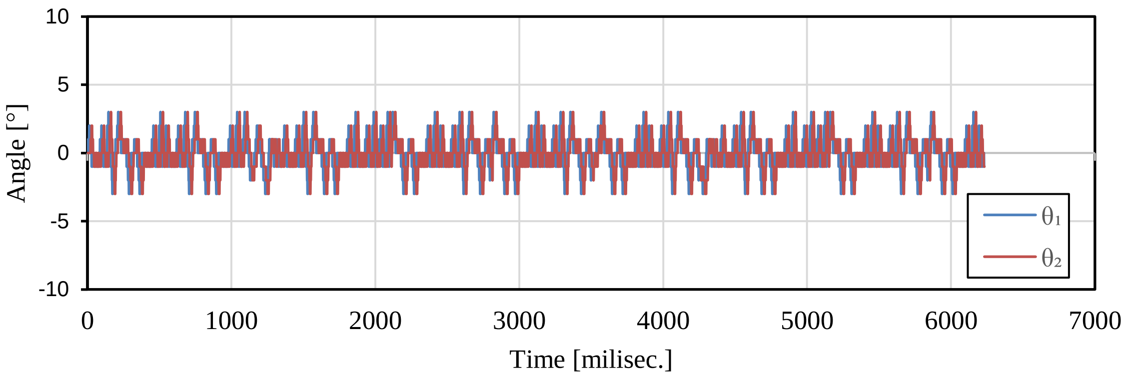


Figure 10. Step input and response results from the wheel steering sensor and wheel angle sensor during straight motion test

The mechanical backlash in the steering system configuration, which contributes to a delay in the electric vehicle's orientation response δ, is also analyzed. The backlash is determined by examining the decoupling and re-engagement phases of the steering mechanism at Δt_1 and Δt_2. This is achieved by comparing the input step time of δ with the electric vehicle's orientation response time, as illustrated in Figure 11. Based on the cornering motion test, the estimated backlash is approximately 0.06 rad, which represents the average value measured during the decoupling and re-engagement phases Δt_1 and Δt_2 of the cornering motion. This backlash introduces a slight delay in the steering mechanism's response to the small EV's orientation δ. This delay is particularly noticeable during the decoupling and re-engagement phases of the cornering curvature, causing a minor misalignment between the steering angle and the wheel angle.

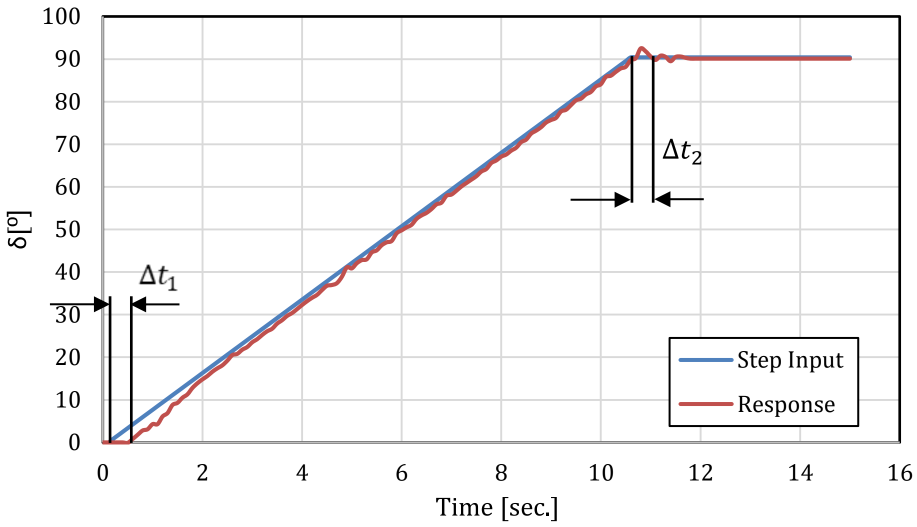


Figure 11. Step input of the steering wheel sensor and response results from of wheel angle sensor during the cornering motion test

CONCLUSION

A steering-by-wire system with linear sensors, designed for a small electric vehicles, has been developed. This system consists of a steering wheel, an angle and torque sensor mounted on the steering wheel mechanism, an electric motor actuator connected to the left and right wheel knuckles via linkages, a wheel angle feedback sensor connected to the wheel knuckle, and the linkages. The SBW system operates to control wheel angles electrically, eliminating the need for a conventional steering gearbox. An electric actuator motor is installed on the steering mechanism and directly connected to the left and right wheel knuckles via linkages. A linear sensor on the steering wheel provides the steering wheel angle signal θ_1, while a linear sensor on the wheel knuckle provides the wheel angle feedback signal θ_2. The controller calculates the actual pitch error rate and compensates for the wheel's angular position based on input from both signals using an algorithm written in C++. Test results from the experiment, comparing the steering wheel angle θ_1 from the steering wheel angle sensor to the wheel angle θ_2 from the wheel angle sensor, show that both signals are synchronized, with a delay time response measured at 0.3 seconds at Δt. Both signals exhibit linear relationships between angle changes and time. Subsequently, the steering pitch error is maintained within an angle of less than 3° during straight motion test indicates that the system is effectively compensating for any discrepancies between the desired and actual steering inputs, ensuring stable and accurate maneuvering. Furthermore, the mechanical backlash in the steering system configuration, measured at 0.06 rad, contributes to a delay in the electric vehicle's orientation response δ and results in a slight discrepancy between the steering angle and the wheel angle.

Thus, the mechanism and application of linear sensors in Steer-By-Wire (SBW) technology for small vehicles can reduce system complexity while enhancing the precision, accuracy, and response speed of wheel angular movements to the driver's steering input. Furthermore, steer-by-wire technology serves as a foundation for advancing future vehicle innovations, including remote vehicle control and autonomous driving systems.

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