International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 07 | July - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Design, Development, and Testing of an IoT-Based Steer-By-Wire System for an Electric All-Terrain Vehicle

Ravi Gujrati[1], Yogesh Katare[2], Anagha Chougaonkar[3], Hemant Marmat[4]

[1]M. tech student, Department of Internet of Things, Acropolis Institute of Technology and Research, Indore, Madhya Pradesh, India, 'ravigujrati@acropolis.in'
[2]M. tech student, Department of Internet of Things, Acropolis Institute of Technology and Research, Indore, Madhya Pradesh, India, 'katareyogesh70@gmail.com'
[3] Assistant Professor ECE department, Acropolis Institute of Technology and Research, Indore, Madhya Pradesh, India
[4]Associate Professor, Department of Mechanical Engineering, Acropolis Institute of Technology and Research, Indore, Madhya Pradesh, India

ABSTRACT

This research paper outlines the design, development, and testing of an IoT-based Steer-By-Wire (SBW) system for an electric All-Terrain Vehicle (ATV). The system replaces traditional mechanical steering linkages with electronic controls, aiming to enhance control precision, adaptability, and safety in dynamic off-road conditions. The SBW system employs Jetson Nano as the central processing unit and integrates Socket.IO for real-time communication. A dedicated Arduino microcontroller is utilized for steering control, with a rotary encoder for data acquisition and feedback from various sensors. Comprehensive validation tests demonstrate the system's functionality, reliability, and significant potential for improving off-road electric vehicle steering performance.
Keywords: Steer-by-wire, Electric vehicle, IoT-based system, Electric ATV, Vehicle automation, electronic control systems.

I. INTRODUCTION

The increasing demand for off-road mobility, coupled with advancements in automation and electrification, has driven significant progress in automotive technology. One of the most exciting developments is the transition towards Drive-By-Wire (DBW) systems, particularly for off-road All-Terrain Vehicles (ATVs). Traditional mechanical linkages for steering can introduce lag and imprecision in control, making it challenging to achieve optimal performance and safety in dynamic off-road environments. Steer-By-Wire (SBW) systems address these limitations by replacing mechanical linkages with electronic controls, offering significant improvements in precision, control, and adaptability.

This research focuses on the design, implementation, and testing of a comprehensive SBW mechanism for an electric ATV. The system utilizes Jetson Nano as the central processing unit and integrates Socket.IO for real-time communication. A dedicated Arduino microcontroller is employed for the steering subsystem, and a dedicated Mega Arduino is used for data acquisition and feedback from various sensors. This paper details the system architecture, hardware design, communication protocols, and validation test results for the SBW system, along with a discussion of the system's potential impact, including improved safety through automation features and enhanced driver experience. The system enables precise vehicle steering control via electronic commands transmitted through a web interface hosted on a Jetson Nano server, with real-time feedback for adjustments. A manual/automatic switching system has been incorporated, allowing the driver to switch seamlessly between manual and electronic control modes. The hypothesis is that integrating this system will significantly improve the vehicle's overall performance, stability, and control, making it better suited for off-road navigation. Comprehensive validation tests were performed to assess the functionality and reliability of the Steer-By-Wire system. The results demonstrate that the system meets the requirements for automating the control of an electric

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 07 | July - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

ATV, with high accuracy and reliability. After extensive testing, the system proved to be a robust and reliable solution for the steering control of an electric ATV.

II. Related Works

The integration of electronics into vehicles began in the mid-20th century, marking a pivotal shift in the automotive industry. One of the earliest milestones was the introduction of the first transistorized ignition system in vehicles by Lucas Industries in 1955. Shortly thereafter, Advanced Driver Assistance Systems (ADAS) emerged, incorporating electronic devices aimed at enhancing driver and passenger safety and comfort. By the 1960s, significant advancements in automotive electronics began to surface, such as Ford's Mercury Park Lane model featuring Electro-Hydraulic Powered Steering (EHPS) in 1965. By 1990, Honda's NSX became the first vehicle to feature Electric Powered Steering (EPS). Initially, such technologies were mostly confined to high-end vehicles due to their cost, but as research in automotive electronics progressed, these systems began to trickle down to more mainstream vehicles.

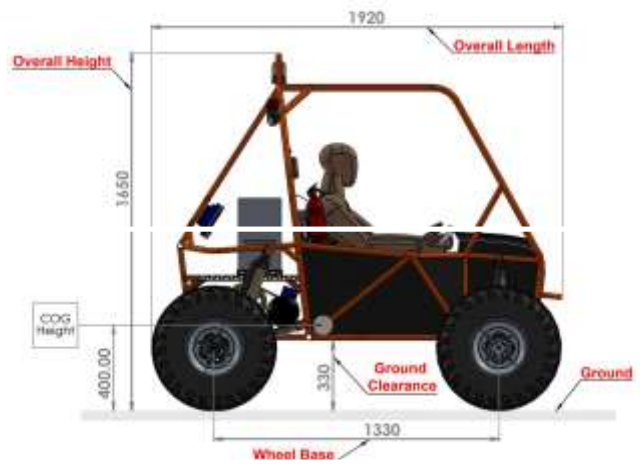
As the automotive industry continued to evolve, the drive-by-wire concept emerged, representing a significant departure from traditional mechanical linkages in favor of electronic control systems. This concept aims to replace mechanical control mechanisms with electronic interfaces, allowing for more precise and flexible vehicle control. Within the broader Drive-By-Wire framework, Steer-By-Wire is one of the three primary subsystems. Several studies have explored the individual components of DBW systems, including steer-by-wire for improved maneuverability. Additionally, research has addressed the importance of real-time control and feedback systems using platforms like Arduino and Jetson Nano for efficient sensor data processing and actuator control (A.N. Singh, 2020). Furthermore, studies have explored the use of communication protocols like Socket.IO to facilitate reliable data exchange between control units and microcontrollers in DBW systems (P. Kumar, 2023). These findings highlight the growing body of research on DBW technology, focusing on both individual components and system-level integration for improved performance and safety in autonomous and electric vehicles.

III. System Architecture

The electric ATV used in this project features a Permanent Magnet Synchronous Motor (PMSM) with a rated power of 5 kW and a maximum speed of 4500 RPM, powered by a 58.8V Lithium-ion battery pack. The chassis is constructed to ensure durability in off-road conditions.

Table4.1. Technical specifications of the ATV vehicle.

Parameter	Value	Parameter	Value
Track Width	*1230mm*	Motor type	PMSM
Wheelbase	1330mm	Rated Power	5kw
Ground Clearance	330mm	Maximum Speed	4500 RPM
Overall, Height	1650 mm	Rated Torque	39 nm
Weight (with driver)	240 kg	Voltage controller	48 - 72v
Weight Distribution(R)	64 %	Battery voltage	58.8
Weight Distribution(F)	36%	Top Speed	55 Km/h
		Max torque	59 nm



(a)Side View

Figure 1. ATV Vehicle Specification

The core architecture of the Steer-By-Wire system, illustrated in Figure 2 of the original document, is designed to electronically control the vehicle's steering system, eliminating the need for traditional mechanical linkages. The system operates through a series of interconnected modules that communicate via a local network, facilitating real-time data exchange between the

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 07 | July - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

steering control system, feedback sensors, and the Jetson Nano for centralized control.

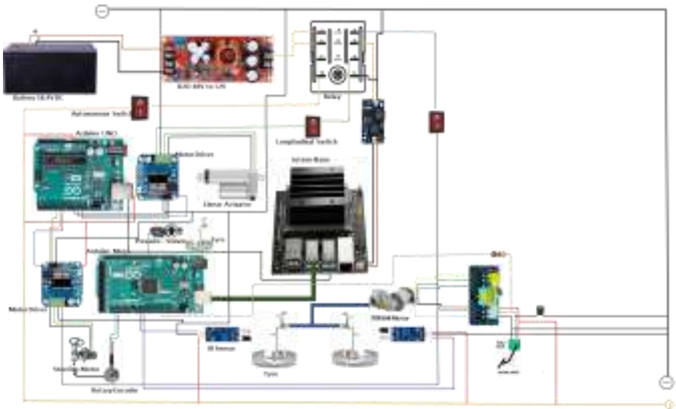


Figure 2: Block diagram of the DBW system architecture

Central Processing Unit

Jetson Nano: This serves as the brain of the system, a powerful central processing unit (CPU) responsible for several critical tasks. It receives commands from the web interface, processes them, and generates control signals for the throttle, brake, and steering systems. Additionally, the Jetson Nano manages communication with all other components within the DBW system.

Steering Control System:

Arduino Uno (Steering): This is an electric motor that is responsible for physically turning the steering column of the ATV. Ultimately, this controls the direction of the wheels. The system utilizes a Hyundai Electric Power Steering Motor. The Arduino Uno controls this motor by sending it PWM signals. By changing the speed and direction of the motor, the system achieves precise steering control.

Steering Motor: This is an electric motor that is responsible for physically turning the steering column of the ATV. Ultimately, this controls the direction of the wheels. The system utilizes a Hyundai Electric Power Steering Motor. The Arduino Uno controls this motor by sending it PWM signals. By changing the speed and direction of the motor, the system achieves precise steering control.

Fig 3: Real time position of our steering motor.

Rotary Encoder: This sensor is crucial for providing feedback to the system. It measures the angular position of the steering wheel. This information is sent to the Arduino Mega, which is used for data acquisition. This feedback is essential for monitoring the steering angle and can be used in control algorithms to ensure accurate and responsive steering.

Fig 4: Real time position of our Rotary Encoder.

Communication System:

Wi-Fi Module: This module enables wireless communication between the Jetson Nano and the web interface. Users can send control commands to the DBW system from a remote device connected to the web interface through a Wi-Fi network.

Socket.IO: This real-time communication library facilitates bidirectional communication between the web interface and the Jetson Nano. It allows for the seamless exchange of control commands and sensor data between these two components in real-time.

USB Communication: The Arduino Uno dedicated to steering control is connected to the Jetson Nano via a USB cable. This enables serial communication, allowing the Jetson Nano to transmit control signals and receive sensor data from the individual Arduino microcontroller.

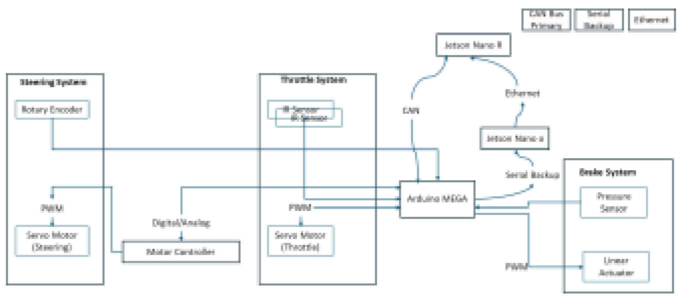


Fig 6: Ccommunication Protocol of Drive-By-Wire System

Control Functions and Sensor Connection: The Steer-By-Wire (SBW) system meticulously manages steering control through a sophisticated interplay between high-level processing and precise low-level actuation. At the pinnacle of this control hierarchy resides the Jetson Nano, serving as the system's central processing unit and its ultimate "brain." This powerful component is responsible for orchestrating the initial phase of steering: receiving commands. These commands are typically transmitted from a user interface, allowing for remote or direct input of the desired steering action. The Jetson Nano's role extends beyond mere reception; it intelligently processes these high-level directives, converting them into actionable steering commands that can be interpreted and executed by the system's more specialized components. This ensures that every user’s input, whether subtle or significant, is accurately translated into a foundational instruction for the subsequent stages of steering.

Following the command generation by the Jetson Nano, the system transitions to the crucial phase of low-level actuation, primarily managed by a dedicated Arduino Uno microcontroller. Upon receiving the refined steering commands from the Jetson Nano, the Arduino Uno undertakes the critical task of processing these instructions and generating precise Pulse Width Modulation (PWM) signals. These PWM signals are the fundamental mechanism for controlling the Hyundai Electric Power Steering Motor, which is directly responsible for rotating the steering column. By dynamically varying the width of these pulses, the Arduino Uno meticulously regulates both the speed and direction of the motor's rotation. This intricate control allows the system to achieve highly precise steering movements, ultimately enabling the ATV's road wheels to turn accurately, with a demonstrated capability of reaching an angle of 30 degrees for both left and right turns.

Crucial to the system's accuracy and responsive performance is the integration of real-time feedback, primarily facilitated by a Rotary Encoder. This vital sensor is strategically positioned to continuously measure the exact angular position of the steering column in real-time. The precise data generated by the Rotary Encoder is then transmitted back to the Jetson Nano, completing a critical feedback loop within the system. This continuous stream of information allows the Jetson Nano to constantly monitor the actual steering angle, comparing it against the desired angle. Based on this real-time comparison, the system can dynamically adjust subsequent steering inputs, ensuring that the actual steering behavior aligns perfectly with the intended commands. This adaptive capability, driven by the feedback loop, is essential for maintaining optimal steering precision, ensuring smooth operation, and enhancing the overall efficiency and handling of the ATV across diverse and dynamic driving conditions.

IV. SOFTWARE SYSTEM

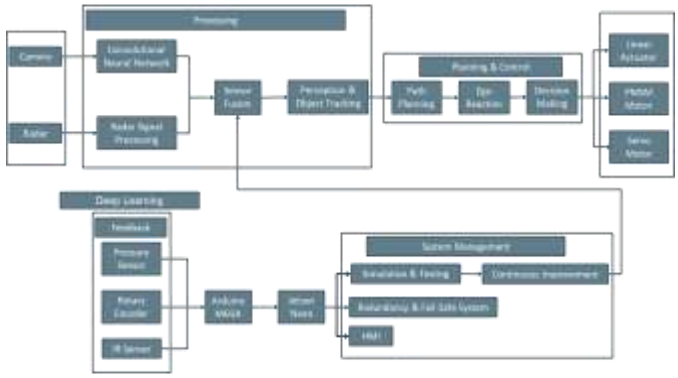


Fig 7: Complete Vehicle Software Architecture

The software architecture underpinning the Drive-By-Wire system, particularly its Steer-By-Wire module, is meticulously designed to ensure precise control, efficient communication, and continuous real-time feedback. This sophisticated system is logically segmented into three primary components, each playing a distinct yet interconnected role: the Perception and Control System, the Central Processing Unit, and the User Interface. The Perception and Control System serves as the vehicle's direct interface with its actuators, specifically implemented on an Arduino microcontroller dedicated solely to steering control. This microcontroller is instrumental in converting digital commands into physical actions. It achieves this by generating Pulse Width Modulation (PWM) signals, which are essential for precisely controlling the steering actuator. Furthermore, this subsystem incorporates advanced Proportional-Integral-Derivative (PID) algorithms, enabling fine-tuned adjustments to the steering based on real-time sensor feedback. The integration of a rotary encoder within the steering subsystem is crucial, as it provides continuous data on the steering angle, ensuring that precise angular adjustments are made in response to user commands. The use of interrupt-based programming on the Arduino further enhances system performance by facilitating prompt and efficient responses to sudden real-time changes in operating conditions or command inputs.

Functioning as the system's core intelligence, the Central Processing Unit is embodied by the Jetson Nano. This powerful processing unit acts as the central hub, meticulously managing high-level commands, aggregating data from various sensors, and overseeing communication with all other interconnected components. The Jetson

Nano operates a Python Flask application, which serves as the backend for the system's web interface. This application seamlessly interfaces with the website via Socket.IO, a real-time communication library that establishes a robust, bidirectional link between the user and the vehicle's electronic systems. In this capacity, the Jetson Nano efficiently processes all inputs received from the web interface, translating them into actionable control commands that are then transmitted to the Arduino for steering adjustments. Simultaneously, it actively collects real-time feedback data, such as the current steering angle, from the microcontroller. This continuous monitoring and data collection are vital for system optimization, allowing for dynamic adjustments and ensuring that the vehicle's performance remains consistent and reliable.

The User Interface completes this integrated software ecosystem, offering an intuitive and interactive platform for human-system interaction. As a web-based interface, it provides users with the convenience of remote control over the vehicle's steering system, allowing for operation from a distance. Beyond mere control, a key feature of this interface is its ability to display live feedback data, including the precise steering angle, enabling operators to monitor the vehicle's real-time status. The interface is enhanced with interactive controls and sophisticated real-time data visualization tools, significantly boosting user engagement and comprehension. Moreover, it dynamically presents historical performance metrics, such as trends in steering angles, through streaming charts. These visualizations offer invaluable insights into the system's behavior over time, aiding in performance analysis and diagnostics. Collectively, this modular software design ensures a robust, responsive, and remarkably user-friendly Steer-By-Wire system, specifically tailored to meet the rigorous demands of electric All-Terrain Vehicles operating in dynamic and challenging off-road environments.

Control Algorithm: The precise control of the Steer-By-Wire (SBW) system relies on a robust closed-loop feedback mechanism, designed to achieve the desired accuracy in steering. At the initiation of any steering command, the user inputs a target angle through the intuitive web interface, which serves as the primary command input. This target angle is then securely transmitted from the Jetson Nano, acting as the system's central processing unit, to the dedicated Arduino microcontroller responsible for steering operations. In response, the Arduino generates and outputs a Pulse Width Modulation (PWM) signal directly to the Electric Power Steering (EPS) motor, initiating the physical steering action.

As the EPS motor engages and turns the steering column, a critical feedback mechanism comes into play. A highly sensitive rotary encoder continuously measures the actual steering angle of the column in real-time. This actual angle data is then relayed back to the Jetson Nano, where it becomes integral to the closed-loop control. The Jetson Nano performs a continuous comparison between the user-defined desired angle and the measured actual angle, calculating the error signal using the following fundamental equation:

$$\text{Error} = \theta_{desired} - \theta_{actual}$$

Based on this calculated error, a sophisticated proportional control logic, which can optionally be expanded to a full Proportional-Integral-Derivative (PID) algorithm dynamically adjusts the PWM output. The immediate adjustment is governed by the formula:

$$PWM_{new} = PWM_{old} + K_p \times \text{Error}$$

Here, Kp represents the proportional gain, a critical tuning parameter that determines the responsiveness of the system to the error. This iterative adjustment allows the system to continuously converge towards the correct steering position, effectively compensating for external loads, minor drifts, or any discrepancies between the desired and actual angles. To further refine the control and ensure seamless operation, a low-pass filter is implemented. This filter is crucial for smoothing the PWM signal, effectively preventing any unwanted jittering or oscillations that could compromise the precision and comfort of the steering response. This comprehensive control algorithm ensures a smooth steering response and maintains accurate tracking within stringent ±2° error margins, as demonstrated in validation tests.

V. RESULTS AND DISCUSSION

The Steer-By-Wire (SBW) system underwent a rigorous and comprehensive testing phase designed to meticulously assess its accuracy in translating manual steering inputs into corresponding validation angles of the vehicle's wheels. These crucial evaluations were conducted across various controlled environments located within the University Campus, encompassing both laboratory settings and outdoor terrains. The overarching results, as meticulously detailed in Table 6 of the original research document, unequivocally demonstrated that the system performed exceptionally well. A standout finding was the minimal deviation observed between the manual input commands and the actual validation angles, consistently showcasing the system's remarkably high precision.

The Steer-By-Wire (SBW) system underwent rigorous testing in both a controlled laboratory environment and diverse outdoor settings to thoroughly evaluate its performance and reliability. During these evaluations, the web interface served as the primary tool for testers to input specific target steering angles, enabling precise control over the vehicle's direction. The vehicle's behavior was meticulously observed both while it was stationary and during low-speed movements, allowing for comprehensive assessment of the steering system's response under different conditions.

Key aspects of the experimental methodology included: The rotary encoder values, which provide real-time feedback on the actual steering angle, were logged at a high frequency of 10 Hz, ensuring a detailed capture of steering dynamics.

Motor commands were issued in discrete steps, with target angles such as 10°, 20°, 30°, and 35° used to systematically evaluate the system's accuracy and response across its operational range. The system's robustness was assessed under both static and dynamic load conditions, simulating various real-world scenarios to ensure consistent performance.

The Equipment utilized for these tests included: A laptop, serving as the interface for command input to the system. A Wi-Fi router, facilitating wireless communication between the control interface and the Jetson Nano. The core Steer-By-Wire setup, comprising the Jetson Nano, an Arduino Uno, and the Electric Power Steering (EPS) Motor. An oscilloscope, employed for precise validation of the PWM signals generated by the Arduino, ensuring their accuracy and stability.

The Testing Conditions were carefully selected to represent typical operating environments for an ATV: Initial tests were conducted on a flat concrete floor to establish baseline performance metrics under ideal, predictable conditions. Subsequent evaluations took place on an uneven terrain track, which included minor inclines and scattered rocks, to challenge the system's ability to maintain control and precision in more realistic and demanding off-road scenarios. The data collected from these extensive tests was compiled into comprehensive reports, with Table 6 (from the original paper) and corresponding graphs being generated to visually represent the system's performance and validate its adherence to design specifications.

To illustrate this high precision, specific data points from the testing provide compelling evidence of the system's accuracy. For instance, when a manual steering input of 10 degrees was applied, the system consistently achieved a validation angle of 9 degrees, resulting in a remarkably small difference of just 1 degree. Similarly, for a more significant manual input of 30 degrees, the system delivered a validation angle of 28 degrees, exhibiting a minor 2-degree difference. Further testing reaffirmed this pattern: a 20-degree manual input corresponded to an 18-degree validation angle, again with a 2-degree discrepancy, and a 35-degree manual input resulted in a 33-degree validation angle, maintaining the 2-degree difference. These consistent outcomes, with angle differences ranging only from 1 to 2 degrees, underscore the system's ability to precisely execute steering commands with very high fidelity.

Beyond mere accuracy, these detailed results collectively indicate that the Steer-By-Wire system maintains a remarkably consistent and reliable linear relationship between the manual steering input provided by the operator and the corresponding validation angle achieved by the wheels. This linearity is a critical characteristic, ensuring that the system's response is predictable and uniform across its entire operational range, from subtle adjustments to more pronounced turns. Such consistent and linear behavior is paramount for providing smooth and controlled steering, which is not only essential for optimal vehicle performance in diverse conditions but, more importantly, plays a crucial role in ensuring the overall safety of the vehicle's operation in real-world scenarios.

Furthermore, a comprehensive Reliability and Failure Analysis was systematically conducted as an integral part of the broader Drive-By-Wire (DBW) system testing. This in-depth analysis involved collecting extensive data from a series of rigorous tests designed to probe the system's endurance and stability. A highly significant finding from this analysis was the complete absence of any significant failures observed across the Steer-By-Wire system's components throughout the entire testing period. This absence of critical failures serves as a strong indicator of the system's inherent high reliability and its robust design, suggesting that the components are well-engineered to withstand operational stresses.

Table 6: Experimental results of Table Steering-by-wire Validation Angle

S.NO	Manual Angle	Validation Angle	Difference of Angle
1	10	9	1
2	20	18	2
3	30	28	2
4	35	33	2

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 07 | July - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Fig 10. The graphs represent the performance analysis of the steer by wire system during the step

This reliability analysis strongly suggests that the Steer-By-Wire system demonstrated consistent and dependable performance, even when subjected to varying operational conditions. Notably, this consistent performance was observed even without the full integration of higher-level autonomous modules, such as advanced perception and complex decision-making systems. This reinforces the system's foundational ability to operate effectively and reliably in diverse real-world scenarios, thereby contributing directly to enhanced stability and safety during driving. The complete absence of observed failure points during extensive testing further solidifies the system's intrinsic durability and its readiness for future integrations with more complex autonomous functionalities, positioning it as a robust building block for advanced electric vehicle control systems.

VI. CONCLUSION

The Steer-By-Wire system for the ATV has been rigorously tested and validated to ensure its performance under controlled conditions. The system demonstrated high accuracy, with an angular response up to 2 degrees difference from the manual input, ensuring smooth and controlled steering inputs. Although not fully detailed in the overall paper, the steer-by-wire system has shown promising results that align with the performance metrics observed in the throttle and brake systems, indicating its reliability and accuracy. These findings confirm the robustness and precision of the Steer-By-Wire system, establishing a reliable foundation for future integration with higher-level autonomous functions.

This study successfully demonstrates the feasibility and effectiveness of a Steer-By-Wire system specifically designed for electric All-Terrain Vehicles (ATVs). By meticulously integrating a rotary encoder feedback loop with an IoT-enabled control architecture utilizing the Jetson Nano and Arduino microcontrollers, the research team was able to achieve highly accurate steering control characterized by exceptional real-time responsiveness. The validation tests confirmed the system's ability to precisely translate commands into physical steering actions, with minimal deviation and high reliability, showcasing its readiness for practical application.

The developed Steer-By-Wire system offers significant potential benefits, particularly for the advancement of autonomous vehicles. Its inherent design lends itself well to terrain-adaptive applications, where precise and responsive steering is paramount for navigating diverse and challenging off-road environments. Furthermore, this work establishes a robust foundation for the development of a modular, fail-safe, and inherently scalable steering control architecture. This architecture can be expanded and adapted for various vehicle platforms and applications, ensuring both reliability and future adaptability.

Future Work: Building upon the successful implementation and validation of the current Steer-By-Wire system, several avenues for future research and development have been identified to further enhance its capabilities and prepare it for more complex autonomous functions:

Integration with IMU for Terrain Compensation: Future efforts will focus on integrating an Inertial Measurement Unit (IMU) to provide real-time data on the vehicle's orientation and motion. This integration will enable the steering system to perform terrain compensation, allowing for more stable and adaptive steering control over uneven or challenging terrain.

Development of Redundancy Mechanisms for Critical Failures: To enhance the system's safety and reliability, especially for critical applications, future work will involve the development and implementation of robust redundancy mechanisms. These mechanisms will ensure that the steering system can maintain functionality even in the event of component failures.

Autonomous Steering Using Camera Vision Input: A significant area for future work involves enabling autonomous steering capabilities by incorporating camera vision input. This would allow the vehicle to perceive its environment, identify paths, and navigate autonomously, transforming the current control system into a fully autonomous steering solution.

Enhanced Safety via Software-Limited Steering Range: To further improve operational safety, future development will include implementing software-limited steering ranges. This feature will prevent the steering system from exceeding safe physical limits, protecting both the vehicle and its occupants from potential damage or instability caused by extreme steering inputs. This pioneering work significantly contributes to the ongoing research in vehicle automation by providing a practical, thoroughly tested, and highly capable steer-by-wire prototype specifically developed for challenging off-road platforms. It lays essential groundwork for the next generation of intelligent and autonomous ATVs.

VII. REFERENCES

1] D. A. Pomerleau, "Alvinn: An autonomous land vehicle in a neural network," Advances in neural information processing systems, vol. 1, 1988.

[2] A. Broggi, Automatic vehicle guidance: the experience of the ARGO autonomous vehicle. World Scientific, 1999.

[3] M. Buehler, K. Iagnemma, and S. Singh, The 2005 DARPA grand challenge: the great robot race. Springer, 2007, vol. 36.

[4] M. Buehler, K. Iagnemma, and S. Singh, The DARPA urban challenge: autonomous vehicles in city traffic. springer, 2009, vol. 56.

[5] S. Thrun, M. Montemerlo, H. Dahlkamp, D. Stavens, A. Aron, J. Diebel, P. Fong, J. Gale, M. Halpenny, G. Hoffmann et al., "Stanley: The robot that won the darpa grand challenge," Journal of field Robotics, vol. 23, no. 9, pp. 661–692, 2006.

[6] M. Montemerlo, J. Becker, S. Bhat, H. Dahlkamp, D. Dolgov, S. Et- tinger, D. Haehnel, T. Hilden, G. Hoffmann, B. Huhnke, D. Johnston, S. Klumpp, D. Langer, A. Levandowski, J. Levinson, J. Marcil, D. Orenstein, J. Paefgen, I. Penny, A. Petrovskaya, M. Pflueger, G. Stanek, D. Stavens, A. Vogt, and S. Thrun, "Junior: The stanford entry in the urban challenge," in Springer Tracts in Advanced Robotics, vol. 56, 2009, pp. 91–123.

[7] C. Urmson, J. Anhalt, D. Bagnell, C. Baker, R. Bittner, M. Clark, J. Dolan, D. Duggins, T. Galatali, C. Geyer et al., "Autonomous driving in urban environments: Boss and the urban challenge," Journal of field Robotics, vol. 25, no. 8, pp. 425–466, 2008.

[8] S. Kato, E. Takeuchi, Y. Ishiguro, Y. Ninomiya, K. Takeda, and T. Hamada, "An open approach to autonomous vehicles," IEEE Micro, vol. 35, no. 6, pp. 60–68, 2015.

[9] Baidu, "Apollo," https://github.com/ApolloAuto/apollo.

[10] E. Prassler, D. Schwammkrug, B. Rohrmoser, and G. Schmidl, "A robotic road sweeper," in Proceedings 2000 ICRA. Millennium Con- ference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No. 00CH37065), vol. 3. IEEE, 2000, pp. 2364–2369.

[11] J. Jeon, B. Jung, J. C. Koo, H. R. Choi, H. Moon, A. Pintado, and P. Oh, "Autonomous robotic street sweeping: Initial attempt for curbside sweeping," in 2017 IEEE International Conference on Consumer Electronics (ICCE). IEEE, 2017, pp. 72–73.

[12] S. Zhiwei, H. Weiwei, W. Ning, W. Xiaojun, W. C. Y. Anthony, V. B. Saputra, B. C. H. Quan, C. J. Simon, Z. Qun, Y. Susu et al., "Map free lane following based on low-cost laser scanner for near future autonomous service vehicle," in 2015 IEEE Intelligent Vehicles Symposium (IV). IEEE, 2015, pp. 706–711.

[13] J. Yu and Z. Yu, "Mono-vision based lateral localization system of low-cost autonomous vehicles using deep learning curb detection," in Actuators, vol. 10, no. 3. MDPI, 2021, p. 57.

[14] H. Andersen, Y. H. Eng, W. K. Leong, C. Zhang, H. X. Kong, S. Pendleton, M. H. Ang, and D. Rus, "Autonomous personal mobility scooter for multi-class mobility-on-demand service," in 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC). IEEE, 2016, pp. 1753–1760.

[15] S. Belakaria, M. Ammous, L. Smith, S. Sorour, and A. Abdel-Rahim, "Multi-class management with sub-class service for autonomous elec-

tric mobility on-demand systems," IEEE Transactions on Vehicular Technology, vol. 68, no. 7, pp. 7155–7159, 2019.

[16] S. Pendleton, T. Uthaicharoenpong, Z. J. Chong, G. M. J. Fu, B. Qin, W. Liu, X. Shen, Z. Weng, C. Kamin, M. A. Ang et al., "Autonomous golf cars for public trial of mobility-on-demand service," in 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2015, pp. 1164–1171.

[17] M. Quigley, K. Conley, B. P. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, "Ros: an open-source robot operating system," in ICRA Workshop on Open Source Software, 2009.

[18] S. Sun, "Lidar obstacle detector," 12 2021. [Online]. Available: https://github.com/SS47816/lidar obstacle detector

[19] I. Kurniawan, "Yolov4 tensorrt ros object detector," 8 2021. [Online]. Available: https://github.com/indra4837/yolov4 trt ros

[20] P. Biber, "The Normal Distributions Transform: A New Approach to Laser Scan Matching," in IEEE International Conference on Intelligent Robots and Systems, vol. 3, 2003, pp. 2743–2748.