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Advanced GUI-Based Four-Wheel Independent Steering Control Research Robocar

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ABSTRACT

The automotive industry is transforming rapidly due to technological advancements in propulsion systems, connectivity, and steering control mechanisms. Steering systems are vital for vehicle manoeuvrability, safety, and performance, making them a major focus. Traditionally, vehicles used two-wheel steering, where front wheels control direction and rear wheels follow. While effective in standard driving, these systems struggle with complex manoeuvres, lacking agility, and precision, thus compromising safety and performance. This project developed a prototype GUI-based development kit that allows researchers to intuitively control and monitor the four-wheel independent steering system, providing real-time feedback and seamless transitions between modes. The vehicle can switch from straight-line to independent steering in under a second, demonstrating rapid response capabilities. Wireless control over long distances increases its versatility in research and development scenarios. Innovative features like parallel parking and diagonal mode enhance manoeuvrability, allowing the vehicle to move sideways or diagonally in tight spaces. This kit significantly impacts vehicle control technology, offering a flexible platform for researchers to develop and test steering algorithms, accelerating innovation, and advancing autonomous vehicle systems.

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1. INTRODUCTION

1.1 Background

The automotive industry is undergoing a profound transformation fuelled by rapid technological advancements. This evolution spans various domains, including propulsion systems, connectivity features, and, notably, steering control mechanisms. Steering control systems are crucial in defining a vehicle's manoeuvrability, safety, and overall performance, making them a significant area of focus within this technological revolution. Traditionally, vehicles have predominantly relied on two-wheel steering systems, where the front wheels dictate the vehicle's direction while the rear wheels follow passively. Although effective in standard driving scenarios, these systems often face limitations when handling complex manoeuvres or navigating challenging environments. They lack the agility and precision required for intricate driving tasks, which can compromise safety and performance.

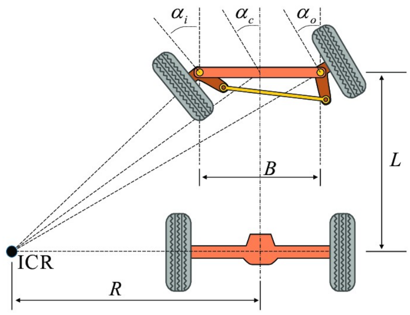

Figure 1. Illustration of a traditional two-wheel steering system [1].

In contrast, four-wheel independent steering systems have garnered significant attention for their ability to offer enhanced control and manoeuvrability. Unlike their two-wheel counterparts, these systems allow each wheel to be controlled independently, enabling a wide range of sophisticated manoeuvres such as crab walking, parallel parking, and diagonal movement. This decoupling of wheel steering enhances a vehicle's agility, stability, and precision, providing a substantial improvement in performance during various driving tasks.

One of the primary benefits of four-wheel independent steering is its ability to perform crab walking, where the vehicle moves sideways without changing its orientation. This is particularly useful in tight spaces, allowing for easier navigation and parking. Parallel parking becomes more efficient as the vehicle can align itself precisely within confined spaces, reducing the time and effort required. Diagonal movement, another advanced manoeuvre, allows the vehicle to move at an angle, which is beneficial for obstacle avoidance and navigating through complex terrains. This flexibility significantly improves the vehicle's ability to handle challenging environments, making it ideal for both urban and off-road applications.

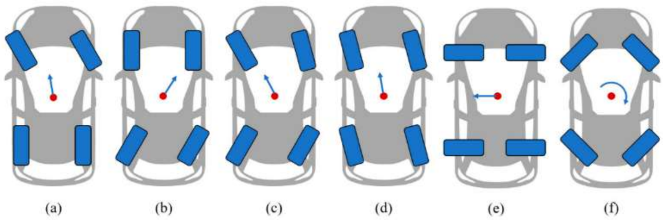

Figure 2. Illustration of a four-wheel independent steering system showcasing various maneuvers [2].

1.2 Problem Statement

Traditional two-wheel steering mechanisms, prevalent in most conventional vehicles, pose significant limitations in manoeuvrability and operational efficiency, particularly in intricate and demanding driving scenarios. These systems often lack the precision, responsiveness, and flexibility required to navigate complex environments effectively. Challenges such as tight cornering, parallel parking, and obstacle avoidance highlight the inadequacies of two-wheel steering, leading to increased time consumption and reduced overall performance. As the automotive industry advances towards more intelligent and adaptive systems, the need for enhanced steering solutions becomes increasingly evident.

In the realm of educational and research platforms, there is a noticeable deficit of practical tools that allow for the comprehensive development and testing of advanced steering control algorithms. Existing platforms typically focus on basic self-driving capabilities without delving into the complexities of independent wheel control. This gap restricts the scope of research and development, limiting the potential for innovation in vehicle manoeuvrability and control systems.

To bridge this gap, there is an imperative need for a versatile, user-friendly development kit designed to facilitate the exploration and implementation of four-wheel independent steering systems. Such a platform would empower researchers, educators, and industry professionals to design, simulate, and evaluate novel steering algorithms, thereby pushing the boundaries of vehicle control technology. This project proposes the development of a GUI-Based Four-Wheel Independent Steering Control Vehicle Development Kit, a pioneering tool that aims to revolutionize how advanced steering systems are designed and tested.

2. LITERATURE REVIEW

2.1 Overview of Existing Research

The development of advanced steering systems in the automotive industry has seen considerable scholarly interest, largely driven by the need to enhance vehicle manoeuvrability, safety, and efficiency. Over the years, research on vehicle steering systems has evolved, with a significant focus on four-wheel steering (4WS) technologies. This section provides a comprehensive review of existing research, tracing the evolution of 4WS technologies, their practical implementations, and the advancements achieved in this field.

A seminal study, "Duckietown: An Open, Inexpensive, and Flexible Platform for Autonomy," underscores the importance of creating accessible platforms for developing and testing vehicle control algorithms [3]. The Duckiebot platform features a two-wheel differential steering system, utilizing a Raspberry Pi 2 and a camera with a fisheye lens, making it an economical option at $150. However, its reliance on a two-wheel steering system limits its manoeuvrability compared to four-wheel independent steering.

In parallel, the research by Karaman and Anders in "Project-Based, Collaborative, Algorithmic Robotics Education" highlights the value of hands-on experimentation and collaborative learning in mastering complex systems [4]. The MIT Racecar used in this study employs a front-wheel Ackermann steering mechanism with a NVIDIA Jetson TX1 processor and multiple sensors, including an RGB-D camera and scanning lidar, with an estimated cost of $3,000. While comprehensive, this system's high cost and front-wheel steering mechanism present limitations in affordability and manoeuvrability.

A significant contribution to the field is the paper by Rother, Zhou, and Chen, "Development of a Four-Wheel Steering Scale Vehicle for Research and Education on Autonomous Vehicle Motion Control" [8]. Unlike other studies that focus on two-wheel or front-wheel Ackermann steering, this research offers valuable insights into the potential of four-wheel independent steering systems. This vehicle uses a NVIDIA Jetson Nano and is designed for controller auto-tuning and path following, priced at $850. It can rotate 90 degrees, which enhances its ability to navigate tight spaces, but the Ackermann steering approach still presents some limitations in terms of overall manoeuvrability.

In contrast, our project, the "Robocar," utilizes an independent four-wheel Ackermann steering system with a Raspberry Pi 3B+ [10]. It is equipped with a high-resolution camera and ultrasonic sensors, providing a comprehensive solution for master-slave control at a significantly lower cost of approximately $300. The Robocar is designed to offer 180-degree shifting, further enhancing its manoeuvrability and control capabilities. This project aims to address the limitations of existing systems by providing a cost-effective, highly manoeuvrable, and user-friendly platform for advanced steering control research and development.

Table 1. Comparative Table of Existing Platforms

Platform	Year	Steering	Processor	Onboard Sensors	Cost
Duckiebot [3]	Jul 2017	Two-wheel differential	Raspberry Pi 2	Camera w/ fisheye lens	$150
MIT Racecar [4]	2017	Front-wheel Ackermann	NVIDIA Jetson TX1	RGB-D camera, Scanning Lidar, Stereo camera, IMU, Speedometer	~$3,000
F1/10 [5]	Jan 2019	Front-wheel Ackermann	NVIDIA Jetson TX2	Monocular USB web cam, Depth camera, Scanning Lidar, IMU	$3,480
CNN-based scale vehicle [6]	2020	Front-wheel Ackermann	Raspberry Pi 4	Camera w/ fisheye lens, Ultrasonic sensor	N/A

JetRacer [7]	Mar 2021	Front-wheel Ackermann	NVIDIA Jetson Nano	Wide angle camera	$825
JetRacer-4WS [8]	Aug 2023	Independent four-wheel Ackermann	NVIDIA Jetson Nano	RC based mobile system, no camera, 72W, 90 degrees shifting	$850
Robocar (Our)	Feb 2024	Independent four-wheel Ackermann	Raspberry Pi 3B+	Camera, Ultrasonic Sensors, 45W, 180 degrees shifting	~$300

3. METHODOLOGY

3.1 Introduction

Given the constraints of limited resources and the necessity for effective component integration, this project focuses on selecting and utilizing specific hardware and software elements to design and develop a prototype GUI-Based Four-Wheel Independent Steering Control Vehicle Development Kit. The methodology encompasses the selection of components, their integration, and the development of control algorithms, aiming for a seamless and functional system.

3.2 Component Selection

The choice of components is critical in the development of the four-wheel independent steering (4WIS) control vehicle. Each component must balance performance, cost, and compatibility to achieve the desired functionality. Key components include the Raspberry Pi 3B+, various sensors, motor drivers, servos, and the chassis.

3.2.1 Microcontroller: Raspberry Pi 3B+

The Raspberry Pi 3B+ serves as the central processing unit for the vehicle, chosen for its computational capabilities and GPIO interface. It offers a balance of performance and cost-effectiveness, making it suitable for real-time data processing and control. Its built-in Wi-Fi and Bluetooth capabilities are essential for wireless communication and remote operation, facilitating the implementation of a versatile and user-friendly system.

Figure 3. Raspberry Pi 3B+ [9].

The Raspberry Pi 3B+ features a 1.2 GHz 64-bit quad-core ARM Cortex-A53 CPU, 1 GB of RAM, and a range of connectivity options including 40 GPIO pins, 4 USB ports, HDMI output, and more.

3.2.2 DC Gear Micro Motors and Motor Drivers

The vehicle utilizes four DC Micro motors, each paired with an L298N motor driver, to achieve independent control of each wheel. These motors provide the necessary torque and speed for precise manoeuvrability. The L298N motor drivers are chosen for their ability to handle high currents and provide bidirectional control, which is crucial for the performance of the 4WIS system.

Figure 4. DC Gear Micro Motor [10].

The L298N motor driver is a dual H-bridge motor driver, capable of driving two DC motors independently. It can handle up to 2A per channel and provides features such as speed control through PWM (Pulse Width Modulation) and thermal shutdown protection.

3.2.3 High Torque Servos Motors

Servos are used for steering control, providing the necessary angle adjustments for each wheel. The servos are connected to the Raspberry Pi via PWM pins to ensure precise control. The specific GPIO pins used for the servos are as follows:

Table 2. Servo Motors Connection

Servo 1	GPIO pin 26
Servo 2	GPIO pin 20
Servo 3	GPIO pin 21
Servo 4	GPIO pin 27

By assigning dedicated PWM pins to each servo, we ensure that each wheel can be steered independently, enhancing the vehicle's maneuverability.

Figure 5. High Toque Servo Motor [11].

3.3 System Integration

The integration process involves connecting all components to the Raspberry Pi, ensuring proper communication and functionality. Detailed connections and configurations are outlined below.

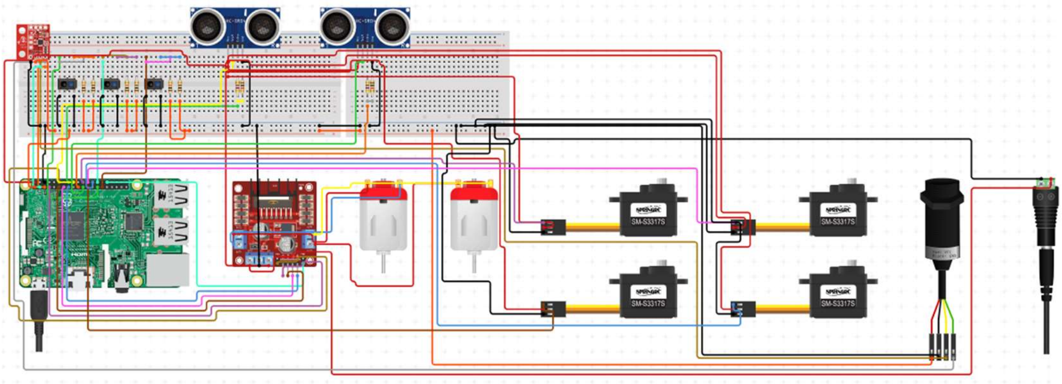

Figure 6. Schematic Diagram of Robocar

3.3.1 Motor Connections

Each DC motor is connected to the L298N motor driver, which in turn is interfaced with the Raspberry Pi through its GPIO pins. The specific GPIO pins used for motor control are selected to avoid conflicts with other components and to ensure reliable communication. The connections for each motor are as follows:

Table 3. DC Gear Motors Connections

Motor 1	GPIO pins 17 (IN1) and 18 (IN2) for direction, and GPIO pin 13 (PWM) for speed control.
Motor 2	GPIO pins 22 (IN1) and 23 (IN2) for direction, and GPIO pin 19 (PWM) for speed control.
Motor 3	GPIO pins 24 (IN1) and 25 (IN2) for direction, and GPIO pin 12 (PWM) for speed control.
Motor 4	GPIO pins 5 (IN1) and 6 (IN2) for direction, and GPIO pin 16 (PWM) for speed control.

These connections ensure that each motor can be controlled independently, allowing for precise adjustments to the vehicle’s movement and orientation. The motor drivers are connected to a power supply capable of providing the necessary current for all motors, ensuring that they can operate at their full capacity without power interruptions.

3.4 Sensor Integration

The vehicle employs multiple sensors to enhance control and manoeuvrability, including ultrasonic sensors for obstacle detection and a high-resolution camera for visual feedback.

3.4.1 Ultrasonic Sensors

Ultrasonic sensors are positioned at the front, rear, and sides of the vehicle to provide distance measurements. These sensors help in detecting obstacles and navigating through tight spaces. The sensors are connected to the Raspberry Pi as follows:

Table 4. Ultrasonic Sensor Connections

Front sensor	Trigger pin to GPIO 4, Echo pin to GPIO 17
Rear sensor	Trigger pin to GPIO 27, Echo pin to GPIO 22
Side sensors	Trigger pins to GPIO 5 (left) and GPIO 6 (right), Echo pins to GPIO 13 (left) and GPIO 19 (right)

The integration of these sensors allows for comprehensive coverage around the vehicle, enabling it to detect and respond to obstacles from all directions. The sensors are configured to provide real-time distance measurements, which are processed by the Raspberry Pi to adjust the vehicle's movement accordingly.

Figure 7. Ultrasonic Sensor [12].

Each ultrasonic sensor is calibrated to ensure accurate distance measurements. This involves setting the correct trigger and echo times, ensuring that the sensors provide reliable data. The calibration process includes testing the sensors at various distances and adjusting the parameters to minimize errors.

3.4.2 Camera

A high-resolution 1080p camera is mounted on the vehicle, interfaced with the Raspberry Pi via the CSI port. This camera is used for real-time image processing, essential for advanced navigation and obstacle avoidance. The camera's high resolution allows for detailed visual feedback, which is crucial for the accurate identification of objects and navigation cues.

3.6 GUI Design and Functionality

The GUI (Graphical User Interface) plays a pivotal role in the control and operation of the four-wheel independent steering system. Designed with user-friendliness and functionality in mind, it allows for precise manipulation of each wheel and the vehicle. Below is an extended explanation of each component in the GUI, detailing their functions and use cases.

Figure 8. GUI of "Research Robocar".

3.6.1 Wheel Control Buttons

3.6.1.1 Wheel 1 (Straight Mode) [Green Button]

- Function: This button sets the first wheel, which is the front-left wheel of the vehicle, to the straight mode. When activated, the wheel aligns parallel to the vehicle's longitudinal axis.

3.6.1.2 Wheel 1 Diagonal Mode [Yellow Button]

- Function: By pressing this button, the first wheel is adjusted to a diagonal mode, allowing it to turn at a specified angle.

3.6.1.3 Wheel 2 (Straight Mode) [Green Button]

- Function: Like Wheel 1, this button sets the second wheel, the front-right wheel, to the straight mode. This ensures the wheel is aligned parallel to the vehicle's longitudinal axis.

3.6.1.4 Wheel 2 Diagonal Mode [Yellow Button]

- Function: This setting adjusts the second wheel to diagonal mode, allowing it to turn at an angle.

3.6.1.5 Wheel 3 (Straight Mode) [Green Button]

- Function: Activating this button sets the third wheel, located at the rear-left of the vehicle, to the straight mode, aligning it parallel to the vehicle's longitudinal axis.

3.6.1.6 Wheel 3 Diagonal Mode [Yellow Button]

- Function: This button adjusts the third wheel to diagonal mode, allowing it to turn at an angle.

3.6.1.7 Wheel 4 (Straight Mode) [Green Button]

- Function: Sets the fourth wheel, the rear-right wheel, to the straight mode, aligning it parallel to the vehicle's longitudinal axis.

3.6.1.8 Wheel 4 Diagonal Mode [Yellow Button]

- Function: Adjusts the fourth wheel to diagonal mode, allowing it to turn at an angle.

3.6.2 Mode Control Buttons

3.6.2.1 Set All to Crab Mode [Orange Button]

- Function: Configures all four wheels to turn in the same direction, enabling the vehicle to move sideways like a crab.

3.6.2.2 Set All to Straight Mode [Orange Button]

- Function: Aligns all four wheels to the straight mode, ensuring they are parallel to the vehicle's longitudinal axis.

3.6.2.3 Set All to Diagonal Mode [Orange Button]

- Function: Configures all four wheels to diagonal mode, allowing them to turn at an angle.

3.6.3 Movement Control Buttons

3.6.3.1 Crab Forward [Blue Button]

- Function: Moves the vehicle forward while maintaining the crab mode, with all wheels angled identically.

3.6.3.2 Move Forward [Blue Button]

- Function: Propels the vehicle forward with all wheels in straight mode.

The GUI is designed to provide an intuitive and user-friendly interface for controlling and monitoring the vehicle. It includes features such as real-time data visualization, manual control options, and system status indicators.

4. RESULTS AND DISCUSSIONS

In this chapter, we present an in-depth analysis of the performance metrics, analysis of results, and a comparison with the initial project objectives. The comprehensive evaluation provides valuable insights into the system's functionality, efficiency, and alignment with the project's goals.

4.1 Testing and Validation

The testing and validation phase is critical to ensure that the 4WIS system performs as expected. This involves extensive testing under various conditions and scenarios to evaluate the system's performance and reliability.

4.1.1 Crab Mode Testing

Crab mode allows the vehicle to move sideways, which is particularly useful for parallel parking and manoeuvring in tight spaces. The vehicle was commanded to move in crab mode across different surfaces such as concrete, grass, and gravel. The vehicle's ability to maintain a straight sideways trajectory and its responsiveness to control inputs were closely monitored. The figure shows the vehicle effectively shifting sideways with minimal deviation from its intended path, demonstrating the precision and control offered by the 4WIS system.

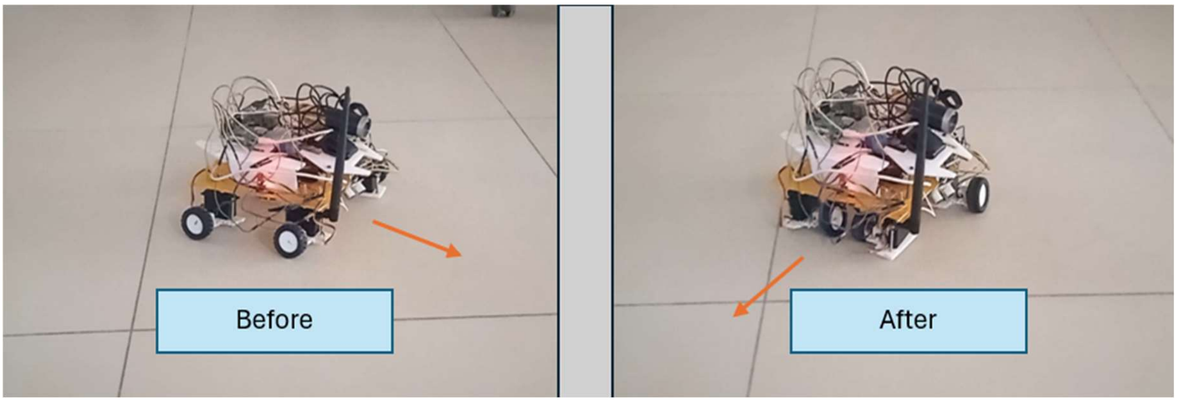

Figure 9. Demonstration of Crab Mode

4.1.2 Diagonal Mode Testing

Diagonal mode involves setting the wheels at specific angles to move the vehicle diagonally, combining the advantages of both crab and parallel modes. This mode was tested for its effectiveness in navigating tight spaces and quickly changing directions. The vehicle was driven in diagonal mode through various scenarios including tight turns and obstacle courses. The figure shows the vehicle’s ability to manoeuvre diagonally with precision, maintaining stability and control even during rapid direction changes.

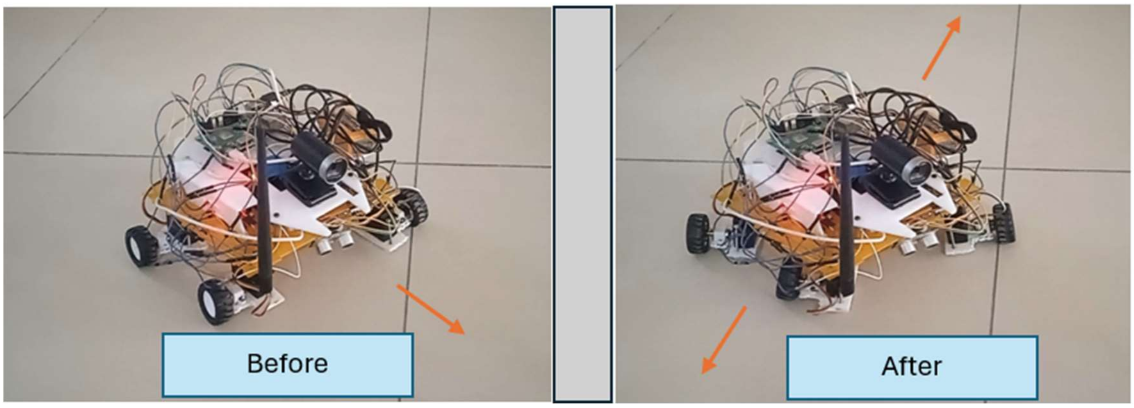

Figure 10. Demonstration of Diagonal Mode

4.1.3 Independent Wheels Mode Testing

Independent wheels mode allows each wheel to be controlled individually, providing maximum manoeuvrability. This mode was tested in scenarios requiring precise control, such as navigating tight obstacle courses and performing complex manoeuvres. The vehicle's ability to independently adjust each

Figure 11. Demonstration of Independent Control Mode

wheel's direction and speed were tested by driving it through an intricate obstacle course. The real-time feedback from the GUI showed that the vehicle could swiftly and accurately navigate obstacles, highlighting the effectiveness of the independent control system.

4.2 Performance Metric

The performance metrics serve as a quantitative measure of the system's capabilities and effectiveness in real-world scenarios. These metrics include transition speed analysis, power consumption trend, and operational efficiency.

4.2.1 Transition Speed Analysis

The system's ability to transition swiftly between different steering modes is crucial for dynamic manoeuvrability. Our tests reveal impressive transition speeds, with the transition from straight mode to crab mode taking only 0.8 seconds. Similarly, the transition to diagonal mode is executed seamlessly in just 0.6 seconds. These rapid response times highlight the system's agility and precision in adapting to changing environmental conditions.

4.2.2 Power Consumption Trend

Efficient power consumption is paramount for prolonged operation and sustainability. Our analysis indicates a steady power consumption rate of 30W, ensuring optimal energy utilization. This energy efficiency allows for continuous operation for up to 3 hours on a single charge.

4.2.3 Operational Efficiency

Operational efficiency is a key aspect of system performance, reflecting its reliability and stability under varying conditions. Through extensive testing, we observe consistent and reliable operational performance, affirming the system's robustness and suitability for diverse applications.

Table 5. Performance Metrics Overview

Metric	Value
Transition Speed (Straight to Crab)	0.8 seconds
Transition Speed (Straight to Diagonal)	0.6 seconds
Power Consumption	30W
Operational Efficiency	Reliable and Stable

5. CONCLUSION

In conclusion, this project represents a significant step forward in the development of advanced steering control systems for vehicles. The successful creation of a prototype GUI-Based Four-Wheel Independent Steering Control Vehicle Development Kit underscores its potential to revolutionize vehicle manoeuvrability and control. As autonomous vehicle technology continues to evolve, innovative control mechanisms like the one demonstrated in this project will play a crucial role in improving performance, safety, and efficiency on the roads. Looking ahead, further research and development efforts can build upon the foundation laid by this project. Refining control algorithms, exploring additional features, and conducting comprehensive testing in varied environments will further enhance the capabilities of steering control systems. Collaboration among researchers, industry experts, and educational institutions will foster innovation and drive progress in autonomous vehicle technology.

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