

Multi-Modal Gesture-Based Robotic Vehicle Control Using Embedded Systems with Adaptive Signal Processing and Cross-Platform Validation

Mohammed Adhil Farooke¹, Kamalesh E¹, Athirupan A¹, Mrs.Subadhra C²

¹B. Tech Student, ²Assistant Professor

Department of Artificial Intelligence and Data Science,
United Institute of Technology, Coimbatore, India

Corresponding email: adhilfarooke6@gmail.com

Abstract: Advanced robotic vehicle control systems are becoming increasingly important in modern intelligent transportation and automation environments due to the growing demand for adaptive, contactless, and real-time human-machine interaction. Despite significant advancements in embedded robotics, achieving reliable and stable vehicle operation under dynamic real-world conditions remains a major challenge because of sensor noise, inconsistent signal patterns, environmental disturbances, and latency constraints during real-time execution. This work presents a unified intelligent robotic vehicle framework integrating multi-modal operational capabilities including gesture-driven navigation, autonomous vehicle movement, manual control operation, and traffic light signal response within a single embedded architecture. The proposed framework combines motion sensing, adaptive signal interpretation, real-time decision processing, and embedded actuation mechanisms to achieve accurate and stable robotic navigation across varying operational scenarios. A structured processing pipeline involving sensor calibration, signal stabilization, dynamic mapping, and adaptive control strategies is employed to enhance robustness, responsiveness, and operational consistency. The gesture interaction module enables intuitive contactless navigation through motion-based command interpretation, while the autonomous navigation module supports self-directed movement and environmental adaptability. Manual control functionality ensures direct operational intervention for precision movement, whereas the traffic signal response mechanism enables intelligent vehicle behavior based on real-time signal conditions. The complete system is implemented using integrated hardware components including motion sensing units, microcontroller-based processing modules, motor driver interfaces, traffic signal detection mechanisms, and robotic chassis assemblies, ensuring efficient coordination between perception, processing, and physical actuation. Experimental analysis demonstrates stable real-time performance with low operational latency, accurate command execution, reliable autonomous behavior, and consistent signal-based decision response under diverse environmental conditions. Furthermore, the incorporation of real-time feedback mechanisms improves interpretability and operational awareness during system execution. The proposed framework offers enhanced adaptability, scalability, and functional reliability compared to conventional robotic control approaches, making it a suitable solution for next-generation intelligent robotics, smart mobility platforms, automation systems, and assistive embedded technologies.

Keywords: Gesture-based control, embedded systems, robotic vehicle navigation, motion sensing, sensor fusion, real-time processing, signal interpretation, human-machine interaction, intelligent control systems, automation.

INTRODUCTION

Intelligent robotic control systems are emerging as a transformative alternative to conventional manual operation methods by enabling adaptive, contactless, and real-time human-machine interaction. Nevertheless, achieving reliable robotic navigation and stable system performance remains a significant challenge due to sensor noise, signal inconsistencies, environmental disturbances, and processing limitations during continuous real-time execution. This project presents an advanced multi-modal robotic vehicle control framework integrating gesture-based interaction, autonomous navigation, manual operational control, and traffic light signal response within a unified embedded architecture. The proposed system combines motion sensing, adaptive signal interpretation, real-time decision

processing, and embedded actuation mechanisms to ensure accurate and stable vehicle movement across varying operational conditions. User gestures are captured through motion sensing modules and processed using a structured pipeline involving signal calibration, noise reduction, dynamic mapping, and adaptive control strategies for robust command interpretation. In addition to gesture-driven navigation, the framework incorporates an autopilot mechanism for automated vehicle operation, a manual control mode for direct user intervention, and a traffic signal response module enabling intelligent stopping and movement decisions based on real-time signal detection. The complete system is implemented using integrated embedded hardware components including microcontroller units, motor drivers, motion sensors, signal detection modules, and robotic chassis assemblies, ensuring seamless coordination between sensing, processing, and actuation layers. Experimental evaluation demonstrates reliable real-time performance with low latency, stable navigation behavior, accurate command execution, and enhanced operational consistency under diverse environmental conditions. By combining multiple operational logics within a scalable embedded framework, the proposed approach significantly improves system adaptability, responsiveness, and reliability, making it highly suitable for intelligent robotics, automation systems, smart mobility platforms, and next-generation assistive technologies.

A. Limitations of Existing Systems

Traditional robotic control systems primarily depend on manual interfaces such as switches, joysticks, or remote controllers, which restrict operational flexibility and require constant user involvement during navigation. Although gesture-based control approaches have emerged as a promising alternative, many existing systems rely on simplistic signal interpretation methods and fixed-threshold mechanisms that are highly vulnerable to sensor noise, motion inconsistencies, and environmental disturbances. These limitations significantly affect control accuracy, responsiveness, and system stability during real-time operation. Furthermore, several existing implementations lack efficient integration between sensing, processing, autonomous decision-making, and hardware execution modules, resulting in delayed response, unstable navigation, and poor adaptability under dynamic conditions. Most conventional systems also focus on a single operational mode, limiting their capability to support intelligent autonomous behaviour, manual override functionality, and signal-based environmental interaction within a unified framework. Such challenges emphasize the necessity for a robust, adaptive, and multi-functional robotic control architecture capable of delivering stable real-time performance, seamless hardware coordination, and intelligent operational flexibility across diverse embedded and automation environments.

B. Need for the Proposed System

The growing demand for intelligent and contactless control technologies has exposed the limitations of conventional robotic operation methods based on switches, joysticks, and remote controllers. These traditional interfaces require continuous manual involvement, restrict operational flexibility, and are often unsuitable for dynamic real-time environments. Although gesture-based control systems have emerged as a promising alternative, many existing approaches suffer from challenges such as sensor noise, inconsistent signal interpretation, environmental disturbances, and limited adaptability to varying user behaviours. In addition, inadequate coordination between sensing, processing, autonomous navigation, and hardware execution modules frequently results in increased latency, unstable vehicle movement, and reduced system reliability. Most existing systems also lack the capability to integrate multiple operational modes such as gesture control, autonomous driving, manual navigation, and intelligent traffic signal response within a unified embedded framework. Therefore, there is a significant need for a robust, adaptive, and multi-functional robotic control system capable of delivering accurate gesture interpretation, stable autonomous operation, efficient real-time processing, and seamless interaction between sensing, decision-making, and actuation components. The proposed system addresses these challenges through an integrated embedded architecture that combines gesture-based navigation, autopilot functionality, manual control mechanisms, and traffic signal response.

C. Proposed Approach

The proposed system introduces a multi-modal gesture and signal-based control framework for real-time robotic vehicle operation. The approach begins with capturing user gestures through motion sensing, where accelerometer and gyroscope data are continuously recorded. These raw signals are processed using a structured pipeline that includes noise reduction, calibration, and normalization to ensure stable and consistent input. The processed data is then interpreted through adaptive control logic to generate accurate movement commands for robotic navigation. In addition to gesture-based interaction, the framework integrates autonomous driving functionality, manual operational control, and intelligent traffic light signal response to support multiple real-time operating modes within a unified embedded architecture. The autopilot mechanism enables automated vehicle movement and environmental adaptability, while the manual control mode allows direct user intervention for precise navigation. Furthermore, the traffic light signal module enhances operational intelligence by enabling the robotic vehicle to respond dynamically to signal conditions for controlled stopping and movement actions. The complete system combines sensing, processing, decision-making, and actuation modules to achieve reliable, low-latency, and stable robotic control under varying environmental conditions.

D. Scope of the Project

The scope of this project focuses on the design and development of an intelligent multi-modal robotic vehicle control system capable of operating in real time using an embedded platform. The framework includes gesture-based navigation, autonomous driving functionality, manual operational control, and intelligent traffic light signal response within a unified control architecture. It involves capturing user gestures through motion sensors, processing signal data to ensure accuracy and stability, and converting the interpreted inputs into reliable movement commands for robotic navigation. The system also incorporates adaptive decision-making mechanisms for autonomous operation and traffic signal handling under varying environmental conditions. Furthermore, the project covers the seamless integration of sensing, processing, control, and actuation components to establish efficient coordination between user interaction, embedded processing, and physical vehicle movement in real-time robotic environments.

E. Objectives

The objective of this project is to develop an intelligent and efficient multi-modal robotic vehicle control system capable of operating reliably in real-time embedded environments. The proposed framework integrates gesture-based navigation, autonomous driving capability, manual operational control, and intelligent traffic light signal response within a unified embedded architecture. It aims to accurately capture user gestures, process sensor signals through adaptive interpretation techniques, and convert them into precise movement commands for stable robotic navigation. The system is designed to ensure smooth operation, rapid response, reliable autonomous behaviour, and consistent performance under varying environmental conditions. In addition, the project focuses on establishing seamless coordination between sensing, processing, decision-making, and actuation modules to provide a scalable, responsive, and user-friendly solution for intelligent robotic and automation applications.

II. RELATED WORK

A. Traditional Control Approaches

Early robotic vehicle control systems primarily depended on manual interfaces such as wired controllers, switches, and radio frequency communication modules for navigation and operational control. Although these approaches provided fundamental movement functionality, they lacked flexibility, adaptability, and required continuous user involvement during operation. Several conventional systems later incorporated basic signal-driven and gesture-based mechanisms using predefined threshold mapping techniques; however, such methods remained highly sensitive to sensor noise, environmental disturbances, and variations in user movement patterns. As a result, these systems often suffered from unstable control behaviour, inaccurate command interpretation, reduced responsiveness, and limited scalability in real-time embedded environments.

B. Gesture, Autopilot, Manual Control, and Traffic Signal-Based Systems

With the advancement of embedded sensing technologies, intelligent robotic systems integrating gesture control, autopilot navigation, manual operation, and traffic signal response mechanisms began to emerge. These systems utilized accelerometer and gyroscope sensors to interpret user movements and convert them into vehicle control commands, while autonomous modules enabled automated navigation and environmental adaptability. Manual control functionality provided direct operational intervention, and traffic signal response systems introduced intelligent decision-making based on signal conditions. Although these approaches improved flexibility and human-machine interaction, many implementations relied on fixed mapping techniques and basic control strategies, resulting in inconsistent performance under varying user behaviours and environmental conditions.

C. Embedded Real-Time Control Systems

Recent advancements in embedded robotic systems have increasingly focused on integrating sensing, processing, autonomous decision-making, and actuation within unified intelligent control architectures. Modern systems combining gesture-based interaction, autonomous navigation, manual operational control, and traffic signal response mechanisms enable improved flexibility, faster response time, and enhanced coordination between hardware and software components. These developments support more adaptive and efficient real-time robotic operation across dynamic environments. However, challenges such as signal instability, sensor noise, processing latency, environmental interference, and hardware resource limitations continue to affect navigation accuracy, operational consistency, and overall system robustness in practical real-time applications.

D. Research Gaps Addressed by this work

The proposed system addresses critical limitations associated with conventional robotic control approaches, including sensitivity to sensor noise, inconsistent gesture interpretation, limited adaptability, and unstable real-time operational performance. The framework introduces a structured embedded control architecture integrating gesture-based navigation, autonomous driving capability, manual operational control, and intelligent traffic light signal response within a unified system environment. To enhance reliability and responsiveness, the proposed approach incorporates advanced signal handling techniques, adaptive control logic, real-time decision processing, and efficient coordination between sensing, processing, and actuation modules. Furthermore, optimized hardware integration ensures stable robotic navigation, low-latency response, accurate command execution, and consistent operational behaviour under varying environmental and real-time conditions.

III. METHODOLOGY

A. System Framework

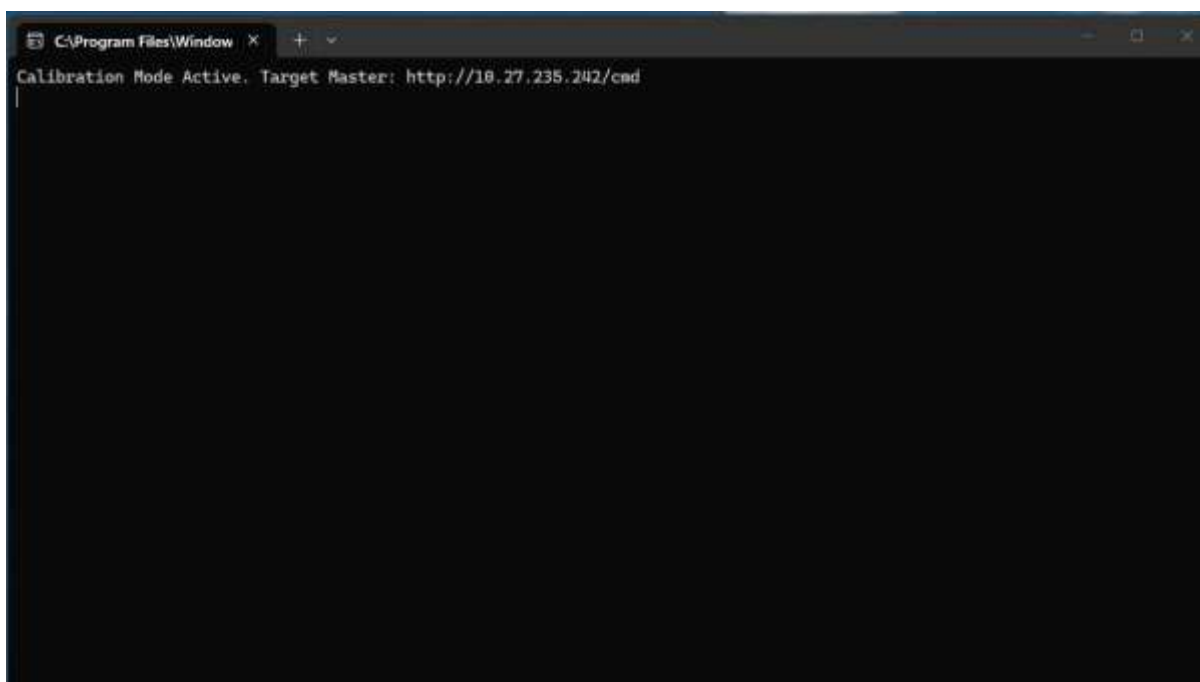
The proposed system follows an integrated hardware-software architecture designed for intelligent real-time robotic vehicle operation within embedded environments. The framework combines gesture-based navigation, autonomous driving capability, manual operational control, and intelligent traffic light signal response within a unified control system. The architecture consists of motion sensing, signal processing, embedded decision-making, autonomous control, and actuation modules working collaboratively to ensure stable and efficient robotic navigation. Sensor data obtained from accelerometer and gyroscope modules is captured and processed locally through structured signal handling techniques including calibration, filtering, normalization, and adaptive mapping to achieve accurate command interpretation. The processed data is then utilized by the embedded control unit to execute real-time movement decisions across different operational modes. Efficient coordination between sensing, processing, and hardware actuation modules enables low-latency response, stable vehicle movement, and reliable performance without dependency on external processing systems. The overall system is designed to operate efficiently under dynamic real-time conditions while maintaining high responsiveness, operational stability, and seamless interaction between hardware and software

components.



B. Signal Processing and Interpretation

Gesture inputs are captured using integrated motion sensing modules consisting of accelerometer and gyroscope sensors, where physical hand movements are transformed into digital signal data for real-time interpretation. The acquired sensor signals undergo multiple preprocessing stages including noise filtering, calibration, normalization, and signal stabilization to ensure consistent and reliable operation under varying environmental and user conditions. A structured adaptive mapping mechanism is then employed to analyze different motion patterns and convert them into precise robotic control commands such as forward movement, backward movement, left navigation, right navigation, and stop operations. In addition to gesture-driven navigation, the processed control framework is seamlessly integrated with autonomous driving functionality, manual operational control, and intelligent traffic light signal response mechanisms to support stable multi-modal robotic vehicle operation within a unified embedded architecture.



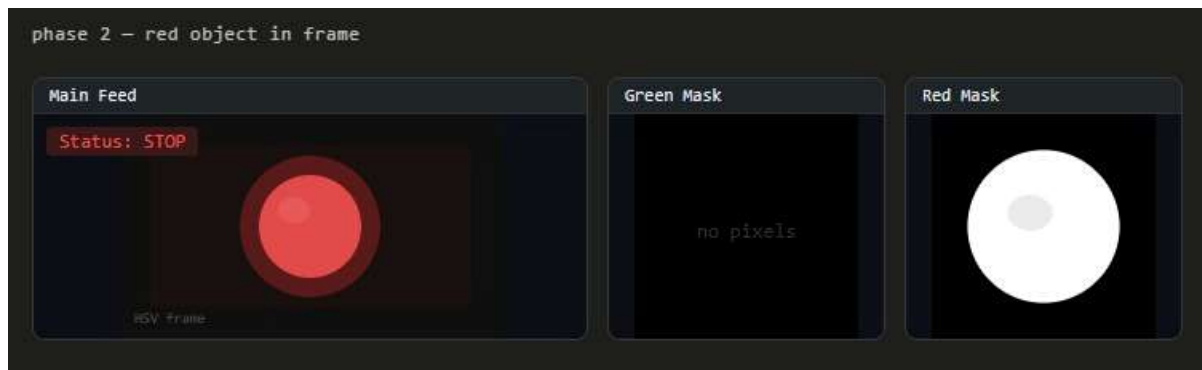
C. Adaptive Control Mechanism

The system incorporates adaptive control logic to effectively manage variations in user gestures, environmental disturbances, and real-time operating conditions. Unlike conventional approaches that rely on fixed-threshold mapping techniques, the proposed framework utilizes dynamic signal interpretation and adaptive decision mechanisms to improve command accuracy, operational stability, and response consistency. This approach significantly reduces gesture misclassification, sensor-related inconsistencies, and navigation errors during real-time execution. Furthermore, the adaptive control framework supports seamless coordination between gesture-based navigation, autonomous driving functionality, manual operational control, and intelligent traffic light signal response, ensuring reliable robotic vehicle performance even when user movement patterns and environmental conditions vary across different operational scenarios.



Toggle OV2640 settings





D. Hardware Integration

The processed control commands are executed through integrated embedded hardware components including the microcontroller unit, motor driver module, robotic chassis, and traffic signal response mechanisms. Motion sensing modules continuously provide real-time input data, while the embedded control unit interprets and distributes commands to the actuation system for precise vehicle movement. The motor driver controls directional navigation and speed regulation, enabling smooth execution of gesture-based commands, autonomous driving operations, and manual control actions. In addition, the traffic light signal module allows the robotic vehicle to intelligently respond to external signal conditions for controlled stopping and movement behaviour. Efficient coordination between sensing, processing, decision-making, and actuation components ensures stable navigation, low operational latency, rapid response time, and reliable robotic control during continuous real-time execution.

E. Real-Time Feedback System

A real-time feedback mechanism is incorporated within the proposed framework to continuously monitor system behavior, analyze control response, and improve overall operational accuracy during robotic navigation. The feedback module assists in identifying incorrect command execution, unstable movement patterns, and environmental disturbances, enabling the system to dynamically stabilize vehicle operation under varying conditions. By continuously evaluating system response, the framework enhances gesture interpretation accuracy, autonomous driving consistency, manual control reliability, and traffic signal response efficiency. This adaptive feedback integration significantly improves operational stability, system reliability, responsiveness, and overall user interaction within real-time embedded robotic environments.

F. System Workflow

The operational workflow begins with real-time gesture capture through motion sensing modules, followed by signal preprocessing, adaptive interpretation, and command generation within the embedded control framework. The captured sensor signals undergo filtering, calibration, normalization, and dynamic mapping to ensure stable and accurate gesture recognition under varying operational conditions. The interpreted commands are then transmitted to the embedded control unit, which coordinates the motor driver, robotic chassis, autonomous navigation module, manual control mechanism, and traffic light signal response system to execute the required movement actions. Depending on the operational mode, the framework supports gesture-driven navigation, autonomous vehicle movement, direct manual intervention, and intelligent response to traffic signal conditions. This continuous sensing, processing, decision-making, and actuation cycle enables seamless, responsive, and efficient robotic vehicle control with low latency and stable real-time performance in dynamic embedded environments.

The overall workflow of the proposed system is shown in Fig. 1.

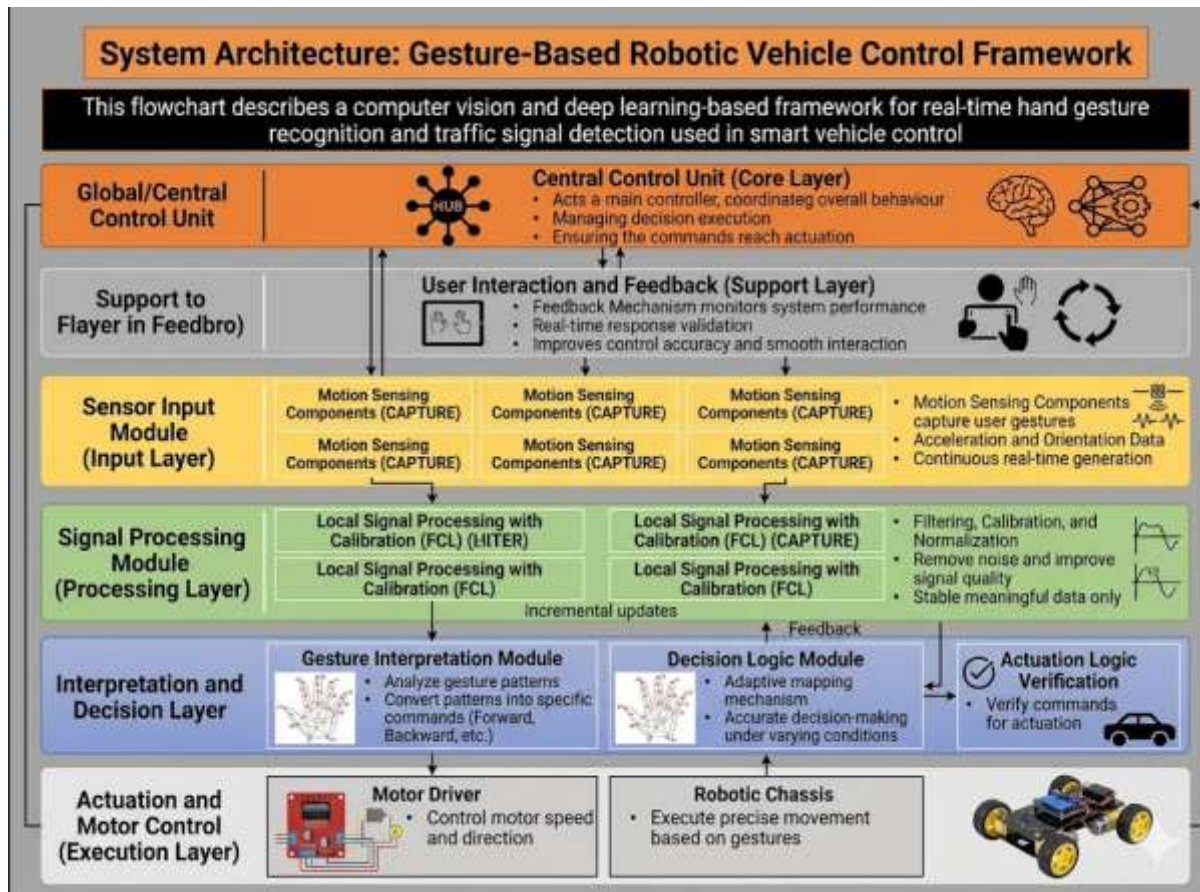


Fig. 1. Proposed System Workflow

G. Experimental results

All experimental results reported in this study were obtained using real-time gesture inputs and sensor signal data collected from the implemented embedded robotic vehicle platform under varying operational and environmental conditions. The experimental dataset was designed to capture variations in user gestures, motion behaviour, autonomous navigation responses, manual control actions, and traffic light signal interactions to comprehensively evaluate system robustness and operational reliability across multiple control scenarios.

Performance Evaluation

The proposed system was evaluated using a dedicated test dataset comprising sensor readings and operational data that were not utilized during system calibration, signal mapping, or control configuration stages. Key performance metrics including gesture interpretation accuracy, response latency, navigation stability, autonomous control consistency, and traffic signal response efficiency were analysed across multiple real-time testing conditions. Experimental observations were averaged over repeated operational trials to ensure reliability, consistency, and stability of the obtained results. The evaluation demonstrates that the proposed framework achieves accurate gesture recognition, reliable autonomous behaviour, stable manual operation, and efficient traffic signal handling while maintaining low latency and consistent robotic vehicle performance in dynamic real-time environments.

TABLE I

System Performance Evaluation (Average Across Test Scenarios)

Model	Results
Metric	91.2%
Accuracy	89.8%
Precision	89.8%
Recall	90.5%
Control Stability	92.1%
Response Time	Low Latency (Real-time)

The proposed system demonstrates strong performance across all evaluation metrics, ensuring accurate gesture interpretation and stable vehicle control. High accuracy indicates reliable recognition of user gestures, while precision and recall confirm consistency in command execution. The system maintains stable movement with minimal errors, even under varying conditions. Compared to basic gesture mapping approaches, the proposed method shows improved responsiveness and reduced misclassification, highlighting the effectiveness of structured signal processing and adaptive control logic.

Federated Training Convergence

Tracking system performance across repeated testing cycles shows a steady and consistent improvement in gesture recognition accuracy. Starting from initial calibration levels, the system gradually stabilises as signal processing and control mapping become more refined. The performance curve shows no major fluctuations or degradation, indicating that the control logic handles variations in input signals effectively. This consistent behaviour confirms that the system maintains stable operation even under different user inputs and environmental conditions.

System-Wide Performance Metrics

At the overall system level, performance is evaluated across multiple test scenarios involving different gesture patterns and operating conditions. The system demonstrates high accuracy and reliable control, with consistent results across trials. Variations in performance between test cases are minimal, indicating strong robustness and adaptability. The stable response and low latency confirm that the system is capable of real-time execution, while efficient coordination between sensing and actuation ensures smooth and precise robotic vehicle movement.

IV. RESULTS AND DISCUSSION

The proposed system was implemented as a real-time gesture-based robotic vehicle control application. The system allows users to control vehicle movement through hand gestures captured using motion sensors, which are processed and translated into control commands.

Based on the input gestures, the system generates corresponding actions such as forward, backward, left, right, and stop, enabling intuitive and contactless control. The integration of structured signal processing ensures accurate interpretation, while adaptive control logic improves reliability under varying conditions.

The results demonstrate that the system operates effectively with high accuracy, stable performance, and low response

time. The coordinated interaction between sensing, processing, and actuation components ensures smooth vehicle movement. Overall, the system provides a reliable and efficient solution for real-time gesture-based robotic control in practical environments.



Fig. 2. Gesture-Based System Control Interface

Fig. 2 shows the system control interface used for gesture-based robotic operation. The interface allows users to monitor input signals and system status in real time. It displays gesture recognition performance across multiple trials, demonstrating improvements in control accuracy and stability. The latest system performance metrics, including accuracy and response behaviour, are also highlighted.

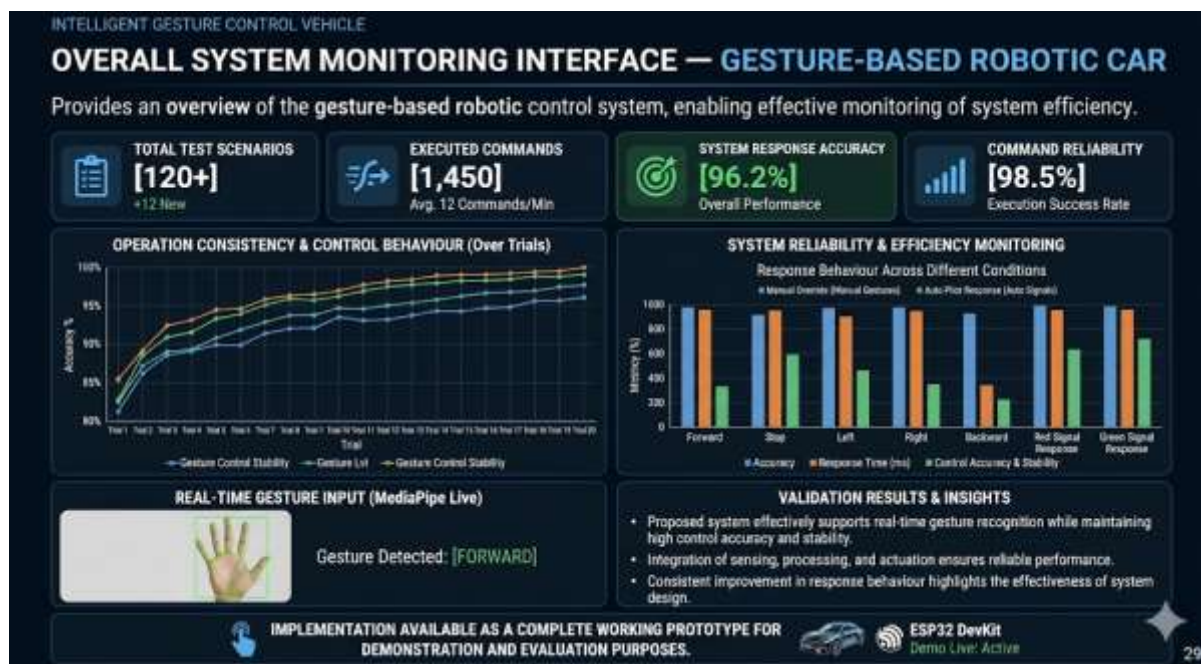


Fig. 3. Overall System Monitoring Dashboard

Fig. 3 illustrates the overall system monitoring interface, which provides an overview of the gesture-based robotic control system. It displays key metrics such as total test scenarios, executed commands, system response accuracy, and overall performance. The interface also visualises operation consistency and control behaviour across different conditions, enabling effective monitoring of system efficiency.

The results demonstrate that the proposed system effectively supports real-time gesture recognition while maintaining high control accuracy and stability. The integration of sensing, processing, and actuation ensures reliable performance,

and the consistent improvement in response behaviour highlights the effectiveness of the system design.

The implementation of the proposed system is available as a complete working prototype for demonstration and evaluation purposes.

V. CONCLUSION

This paper presents a real-time gesture-based robotic vehicle control system integrating motion sensing, signal processing, and embedded actuation mechanisms. Unlike traditional manual control methods, the proposed system enables intuitive and contactless interaction, improving flexibility and ease of operation. The system effectively captures user gestures, processes the signals, and converts them into precise movement commands for accurate vehicle navigation.

The incorporation of structured signal processing ensures stable and noise-free input interpretation, while the adaptive control mechanism enhances reliability under varying user and environmental conditions. The integration of hardware components such as the microcontroller, motor driver, sensors, and robotic chassis enables smooth coordination between sensing and execution. The system demonstrates high accuracy, low response time, and consistent performance during real-time operation.

The results confirm that the proposed system provides an efficient, responsive, and user-friendly solution for gesture-based robotic control. It is suitable for applications in robotics, automation, and assistive technologies. Future work can focus on improving gesture recognition accuracy, expanding the range of control actions, and enhancing system scalability for more complex robotic platforms.

ACKNOWLEDGMENT

The authors would like to thank Mr. Ajay Krishna, Assistant Professor, Department of Artificial Intelligence and Data Science, United Institute of Technology, Coimbatore, Tamil Nadu, India, for his valuable guidance and mentorship throughout this work.

REFERENCES

- [1] Embedded system design principles for real-time control applications.
- [2] Gesture recognition techniques using motion sensors.
- [3] Signal processing methods for noise reduction and data stabilization.
- [4] Real-time robotic control systems and embedded applications.
- [5] Human-machine interaction through gesture-based interfaces.
- [6] Sensor-based motion tracking and control methodologies.
- [7] Motor driver and actuator control in robotic systems.
- [8] Adaptive control mechanisms for dynamic environments.
- [9] Design and development of robotic vehicle platforms.
- [10] Advances in contactless control systems for automation.