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Multimodal Adaptive AI-Based Interactive Robotic System

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Abstract: ***This paper presents the implementation of a Multimodal Adaptive AI-Based Interactive Robotic System intended to provide practical assistance in real-world environments, with particular emphasis on navigation assistance for visually impaired individuals. The proposed system integrates environmental sensing, voice-based interaction, processing, decision making, and mobility in a unified robotic platform. LiDAR, ultrasonic sensing, a camera, and an inertial measurement unit (IMU) are used to acquire information related to obstacles, objects, orientation, motion, and the surrounding environment. A Raspberry Pi acts as the central processing unit and processes sensor information and user voice commands for navigation, obstacle detection, and decision making. A microphone and speaker support voice interaction, while motor drivers interface the processing unit with the Mecanum wheel-based mobility mechanism for robot movement. A prototype PCB has been designed and assembled, and the control and power-supply circuitry has been implemented. Initial hardware testing has been carried out to verify the functionality of the assembled circuit. The resulting architecture provides a modular basis for future integration of sensing, navigation, safety assistance, indoor guidance, and voice interaction.***

Keywords: Multimodal interaction, assistive robotics, autonomous navigation, LiDAR, ultrasonic sensor, camera, IMU, Raspberry Pi, obstacle detection, voice interaction

I. INTRODUCTION

The advancement of automation and intelligent technologies has increased the demand for service robots capable of assisting people in everyday activities. Assistive robotics has become particularly important in applications such as healthcare, indoor navigation, and support for visually impaired individuals. However, conventional robotic systems may involve high implementation costs, complex operating procedures, and limited interaction capabilities. Developing an affordable, adaptable, and user-friendly robotic system that combines environmental awareness with natural communication is therefore an important engineering challenge.

Multimodal interaction enables a robotic system to interpret information from different sources, including distance sensors, cameras, motion sensors, and voice inputs. Combining these inputs can improve the robot's awareness of its surroundings and support more informed responses to changing environmental conditions. LiDAR and ultrasonic sensors provide distance measurements for obstacle detection, while a camera captures visual information and an Inertial Measurement Unit (IMU) provides orientation and motion data. Integrating these sensing modalities creates a foundation for developing assistive robots that can respond to environmental conditions and user requirements. The proposed work, titled “Multimodal Adaptive AI-Based Interactive Robotic System,” focuses on developing a modular robotic prototype for assistive applications, with particular emphasis on navigation assistance for visually impaired individuals. A Raspberry Pi acts as the central processing unit, receiving sensor information and handling user commands. A microphone and speaker facilitate voice-based interaction, while a relay and motor driver interface the processing unit with a stepper motor to control movement. The prototype PCB and associated control and power-supply circuitry provide the hardware foundation for integrating these components into a unified system.

The primary aim of this project is to establish a practical platform that combines environmental sensing, processing, user interaction, and motor control within a single robotic architecture. The modular design supports the integration and further development of obstacle detection, navigation assistance, indoor guidance, and voice-based feedback. Initial hardware testing has been carried out to verify the functionality of the assembled circuitry. Further integration and systematic testing are required to evaluate the complete system's performance in real-world environments and establish its suitability for assistive applications.’

II. RELATED WORK

Recent research in assistive robotics has focused on improving mobility, environmental awareness, sensor integration, and human–robot interaction for individuals with visual impairments. Existing systems use different combinations of sensing technologies, intelligent processing, and feedback mechanisms to support safer movement and more natural interaction. The following studies are organized into four major research areas relevant to the proposed multimodal adaptive AI-based interactive robotic system.

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A. Assistive Navigation for Visually Impaired Individuals

Bala et al. [1] presented a cognitive assisting aid that uses multisensor fusion for navigation assistance, highlighting the importance of combining sensor information to improve environmental awareness. Okolo et al. [5] examined challenges and opportunities in assistive navigation, while Abidi et al. [6] reviewed navigation technologies ranging from conventional mobility aids to electronic systems using sensors, artificial intelligence, and feedback mechanisms. Casanova et al. [12] further reviewed technological developments in navigation assistance for visually impaired users. Wazirali et al. [15] discussed smart-cane technologies and their role in assistive navigation, while Lee et al. [16] investigated the development of a smart navigation robot for visually impaired individuals. These studies demonstrate the importance of reliable obstacle awareness, navigation support, and user-oriented assistance.

B. Multimodal Human–Robot Interaction

Su et al. [2] reviewed recent advances in multimodal human–robot interaction, including communication through voice, images, text, and other input or feedback modalities. Qin et al. [3] investigated a multimodal interaction system for domestic service robots designed for people with reduced expressive abilities. Wang et al. [4] examined multimodal interaction in human-centric smart manufacturing, and Duncan et al. [8] surveyed multimodal perception methods for human–robot interaction in social environments. Zhang et al. [17] introduced NaviGPT, a navigation assistance prototype combining LiDAR-based obstacle detection, vibration feedback, image recognition, and language-model responses. These studies highlight how combining different interaction modalities can make robotic systems more accessible and improve the exchange of information between users and machines.

C. Sensor Fusion and Mobile Robot Navigation

Ou et al. [7] explored mobile robot navigation using sensor fusion and deep reinforcement learning. The study listed as [10] focuses on integrating multiple two-dimensional LiDAR and visual–inertial sensors within a SLAM framework. The survey identified as [11] addresses current requirements and advancements in assistive systems for visually impaired people. Ušinskis et al. [13] examined sensor-fusion-based navigation for autonomous mobile robots, while Al-Tawil et al. [14] addressed mobile robot navigation using enhanced two-dimensional mapping and multisensor fusion. Together, these research directions emphasize the role of combining complementary sensor inputs to improve environmental perception and navigation. For the proposed system, LiDAR, ultrasonic sensing, a camera, and an IMU provide a hardware foundation for gathering different types of environmental and motion-related information. However, the effectiveness of their integration must be established through implementation and testing.

D. Specialized Assistive Systems and Robotic Guidance

The work listed in [9] concerns a robotic shopping guidance system for visually impaired users, representing an application of assistive robotics in indoor or public environments. Reference [18] focuses on a wireless embedded wearable haptic navigation device, illustrating an alternative approach in which guidance is delivered through tactile feedback. Reference [19] describes a voice-enabled assistive robotic navigator based on machine learning and path-adaptive line following. Li et al. [20] presented BUDD-e, an autonomous robotic guide for visually impaired users, and reported prototype testing with visually impaired volunteers in a real-world setting. These approaches illustrate the range of possible assistive solutions, from wearable devices to mobile robotic guides, and highlight the importance of selecting appropriate feedback and guidance mechanisms for the intended environment.

E. Research Gap and Relevance to the Proposed System

The reviewed studies address several important aspects of assistive technology, including multisensor navigation [1], [6], [12], multimodal interaction [2], [8], [17], sensor-fusion-based mobile robotics [7], [13], [14], and specialized assistive guidance [18]–[20]. However, these systems differ in their hardware configurations, interaction approaches, navigation methods, and levels of implementation.

The proposed Multimodal Adaptive AI-Based Interactive Robotic System focuses on establishing a modular hardware platform using a Raspberry Pi as the central processing unit, with LiDAR, ultrasonic sensing, a camera, and an IMU for environmental and motion-related data acquisition. A microphone and speaker provide the hardware basis for voice interaction, while a relay, motor driver, and stepper motor form the movement-control section. The prototype's control and power-supply circuitry has been assembled, and initial hardware testing has been carried out.

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The present work therefore establishes a hardware foundation for integrating sensing, processing, interaction, and movement control into one assistive robotic platform. Further software integration and systematic testing are required to evaluate obstacle detection, navigation, voice interaction, and indoor guidance. This distinction is important because the proposed system is a developing prototype rather than a fully validated autonomous navigation solution.

Table I. Comparison Of Selected Related Works

Ref	Key feature	Limitation
[1]	Multisensor fusion for navigation assistance	System performance depends on sensor integration and validation
[2]	Multimodal human–robot interaction	Integrating different interaction modalities increases system complexity
[3]	Multimodal interaction for people with reduced expressive abilities	Applicability to visually impaired navigation is not established
[4]	Multimodal interaction in human-centric systems	Focuses on smart manufacturing rather than assistive navigation
[5]	Reviews challenges in assistive navigation for visually impaired people	Review-based work; does not itself provide a unified robotic prototype
[6]	Comprehensive review of navigation systems for visually impaired users	Does not implement a single integrated robotic solution
[7]	Sensor fusion and deep reinforcement learning for mobile robot navigation	Requires computational resources and experimental validation
[8]	Multimodal perception for social human–robot interaction	General interaction focus rather than dedicated mobility assistance

Ref	Key feature	Limitation
[9]	Robotic shopping guidance for visually impaired users	Applicability beyond the intended shopping environment needs evaluation
[10]	LiDAR and visual–inertial sensor integration for SLAM	Complex sensor integration and calibration requirements
[11]	Reviews assistive-system requirements and advancements	Review findings require practical implementation and validation
[12]	Systematic review of navigation technologies for visually impaired users	Identifies existing approaches but does not implement a new robotic system
[13]	Sensor-fusion-based mobile robot navigation	Navigation performance requires validation across different environments
[14]	Enhanced mapping and multisensor fusion for mobile robots	Mapping performance may depend on sensor quality and environmental conditions
[15]	Smart-cane technology and assistive navigation	A cane-based approach may offer less mobility and interaction flexibility than a mobile robot
[16]	Smart navigation robot for visually impaired users	Practical effectiveness depends on navigation reliability and real-world testing
[17]	Multimodal AI-driven navigation assistance	Requires evaluation of response accuracy, usability, and reliability
[18]	Wearable haptic navigation assistance	Tactile feedback alone may provide limited environmental information
[19]	Voice-enabled robotic navigation and adaptive line following	Line-following approaches may be constrained by the available path and environment

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[20]	Autonomous robotic guide for visually impaired users	Deployment requires reliable navigation, safety evaluation, and real-world validation
Proposed	Raspberry Pi-based platform integrating LiDAR, ultrasonic sensor, camera, microphone, speaker, and stepper-motor control	Further software integration and systematic testing are required to validate obstacle detection, navigation, and voice interaction.

III. PROBLEM IDENTIFICATION AND OBJECTIVES

A. Problem Identification

Visually impaired individuals face challenges in navigating unfamiliar environments, identifying nearby obstacles, and accessing timely guidance while moving independently. Conventional mobility aids may not provide comprehensive environmental information or integrated interaction capabilities.

Existing assistive technologies employ different sensing and feedback mechanisms; however, integrating multiple sensors, processing units, user-interaction components, and movement-control hardware into a single system presents practical challenges. Reliable coordination between these components is necessary to develop an effective assistive robotic platform.

The proposed system addresses the need for a modular hardware platform that combines environmental sensing, central processing, voice-interaction hardware, and motor control. The prototype is intended to establish a foundation for future implementation of obstacle detection, navigation assistance, and indoor guidance. Further software integration and systematic testing are required to evaluate its practical performance.

B. Objectives

1) To develop a modular assistive robotic prototype intended to support visually impaired individuals.
2) To integrate LiDAR, ultrasonic sensing, a camera module, and an IMU for environmental and motion-related data acquisition.
3) To use a Raspberry Pi as the central processing unit for sensor interfacing and navigation-related processing.
4) To provide microphone and speaker interfaces for voice interaction and audio feedback.
5) To implement a Mecanum wheel-based movement mechanism using motor drivers.

IV. PROPOSED SYSTEM ARCHITECTURE

Fig. 1 Shows the block diagram of the proposed system, illustrating the interconnection between the sensor unit, Raspberry Pi, user interface, motor driver, stepper motor, and power supply.

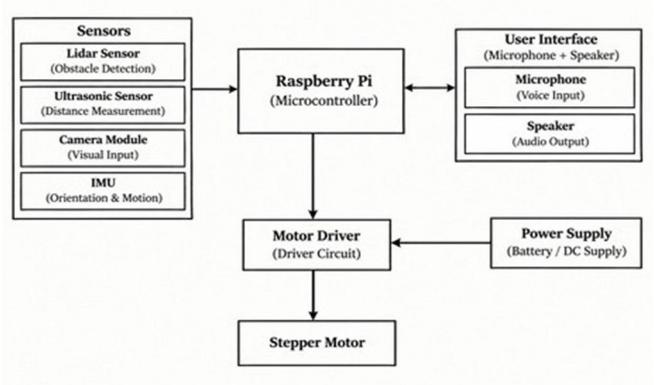


Fig. 4.1 Block diagram of the proposed multimodal adaptive AI-based interactive robotic system.

The proposed Multimodal Adaptive AI-Based Interactive Robotic System consists of four major units: the sensor unit, central processing unit, user interface, and movement-control unit. These units are interconnected to establish a modular platform for assistive robotics.

A. Sensor Unit

The sensor unit consists of a LiDAR sensor, ultrasonic sensor, camera module, and Inertial Measurement Unit (IMU). The LiDAR sensor supports environmental distance sensing, while the ultrasonic sensor measures the distance to nearby objects. The camera module provides visual input, and the IMU supplies orientation and motion-related information. Together, these sensors provide different types of data for future implementation of environmental perception and navigation assistance.

B. Central Processing Unit

The Raspberry Pi acts as the central processing unit of the proposed system. It serves as the interface between the sensor unit, user interface, and motor-control section. The processing unit provides the hardware foundation for sensor-data handling and future integration of algorithms for obstacle detection and navigation assistance.

C. User Interface Unit

The user interface consists of a microphone and speaker. The microphone is intended to receive voice input from the user, while the speaker provides a means of delivering audio feedback. This arrangement supports the planned development of voice-based interaction between the user and the robotic system.

D. Movement-Control Unit

The movement-control unit consists of motor drivers interfaced with the Mecanum wheel-based mobility mechanism, enabling the robot to move in different directions. This provides the hardware foundation for future navigation-related functionality.

E. Power Supply Unit

The power-supply unit provides electrical power to the Raspberry Pi and motor-control circuitry. The power arrangement is designed to support the operation of the processing and movement-control sections.

V. METHODOLOGY

The methodology of the proposed system is represented using a flowchart, as shown in Fig. 2. The process begins with the initialization of all sensors, followed by the acquisition of sensor data. The system then establishes the location, pose, and destination using the proposed SLAM-based approach.

Next, the system processes the path between the source and destination and checks for obstacles along the planned route. If an obstacle is detected, the camera is activated to obtain visual information, and the system follows the retracing and path-processing loop. If no obstacle is detected, the system continues along the planned path towards the destination.

The destination status is then checked. If the destination has not been reached, the system returns to the path-processing stage and continues the navigation process. Once the destination is reached, the task is marked as completed and the system stops.

This flowchart describes the intended navigation sequence of the proposed system.

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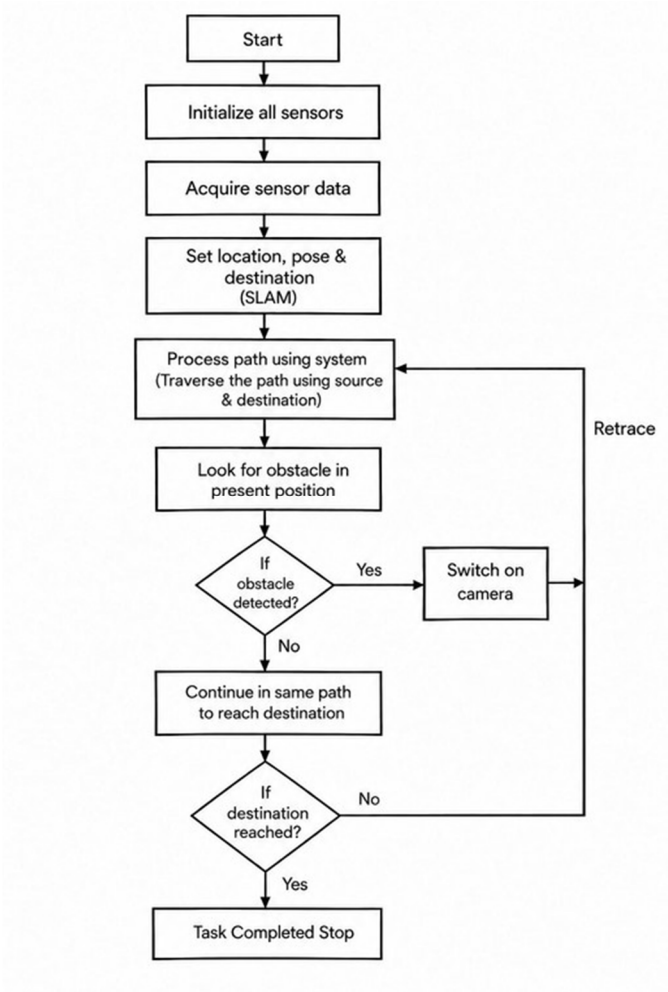


Fig. 5.1 Flowchart of the proposed system methodology.

VI. EXPECTED BENEFITS AND LIMITATIONS

A. *Expected Benefits*

The proposed system is designed to provide a modular assistive robotic platform for visually impaired individuals. The integration of LiDAR, an ultrasonic sensor, a camera module, and an IMU provides multiple sources of environmental and motion-related information. The Raspberry Pi offers a central platform for processing sensor inputs and supporting future navigation-related functions.

The microphone and speaker provide the hardware foundation for voice-based interaction and audio feedback. Additionally, the motor driver and stepper motor establish a basis for implementing movement-control functions. The modular architecture allows individual components to be developed, tested, and integrated progressively, supporting future improvements in obstacle detection, navigation assistance, and indoor guidance.

B. *Limitations and Future Work*

The proposed system integrates multiple sensing and hardware components, making efficient coordination between the sensors, processing unit, and movement-control section an important consideration. The effectiveness of the system depends on the accuracy of sensor data and the reliability of communication between the interconnected modules. The integration of different sensing modalities also requires appropriate processing and calibration to ensure consistent operation.

In the future, the system can be improved by combining data from LiDAR, the camera, ultrasonic sensor, and IMU to help the robot understand its surroundings better. AI-based object detection can be added to identify obstacles and nearby objects. SLAM techniques can also be used to create indoor maps and help the robot understand its location while moving.

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The system can further be enhanced with smart path planning to find safer routes when obstacles are present. Voice interaction can be improved to understand user commands and provide clear audio guidance. AI processing can also be optimized to run efficiently on the Raspberry Pi. Further testing in different indoor environments can help improve the system's accuracy, safety, and usefulness for visually impaired people.

VII. RESULTS

The developed Multimodal Adaptive AI-Based Interactive Robotic System was successfully assembled as a functional hardware prototype. The system integrates a vision sensor, LiDAR sensor, embedded processing unit and mecanum wheel-based mobility mechanism. The vision sensor provides visual input, while the LiDAR sensor supports environmental sensing and spatial awareness. The embedded processing hardware acts as the central unit for processing inputs and coordinating the robotic operations. The mecanum wheels provide multidirectional movement, allowing the robot to move in different directions. The prototype demonstrates the integration of sensing, processing and mobility components into a single robotic platform. The developed architecture provides a hardware foundation for multimodal interaction, adaptive response generation and intelligent robotic operation.



Figure 7.1 – Front View of the Robotic System with Integrated Vision Sensor

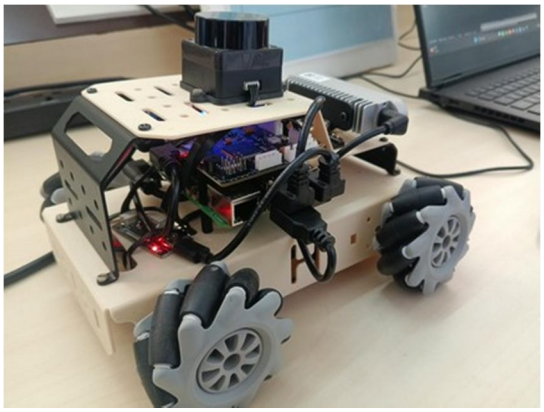


Figure 5.2 – Complete Hardware Prototype of the Multimodal Adaptive AI-Based Interactive Robotic System

VIII. CONCLUSION

The proposed Multimodal Adaptive AI-Based Interactive Robotic System aims to provide navigation assistance for visually impaired individuals by combining multiple sensors, a Raspberry Pi, voice-interaction components, and motor-control hardware. The integration of LiDAR, an ultrasonic sensor, a camera, and an IMU provides a foundation for collecting environmental and motion-related information. The prototype hardware and control circuitry have been assembled, and initial hardware testing has been completed.

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The modular design provides a foundation for further development of obstacle detection, indoor navigation, and voice-based interaction. Future improvements can include AI-based object detection, smarter path planning, and better audio guidance to make the system more useful and adaptable. With further integration and testing, the proposed system has the potential to support safer and more independent mobility for visually impaired individuals.

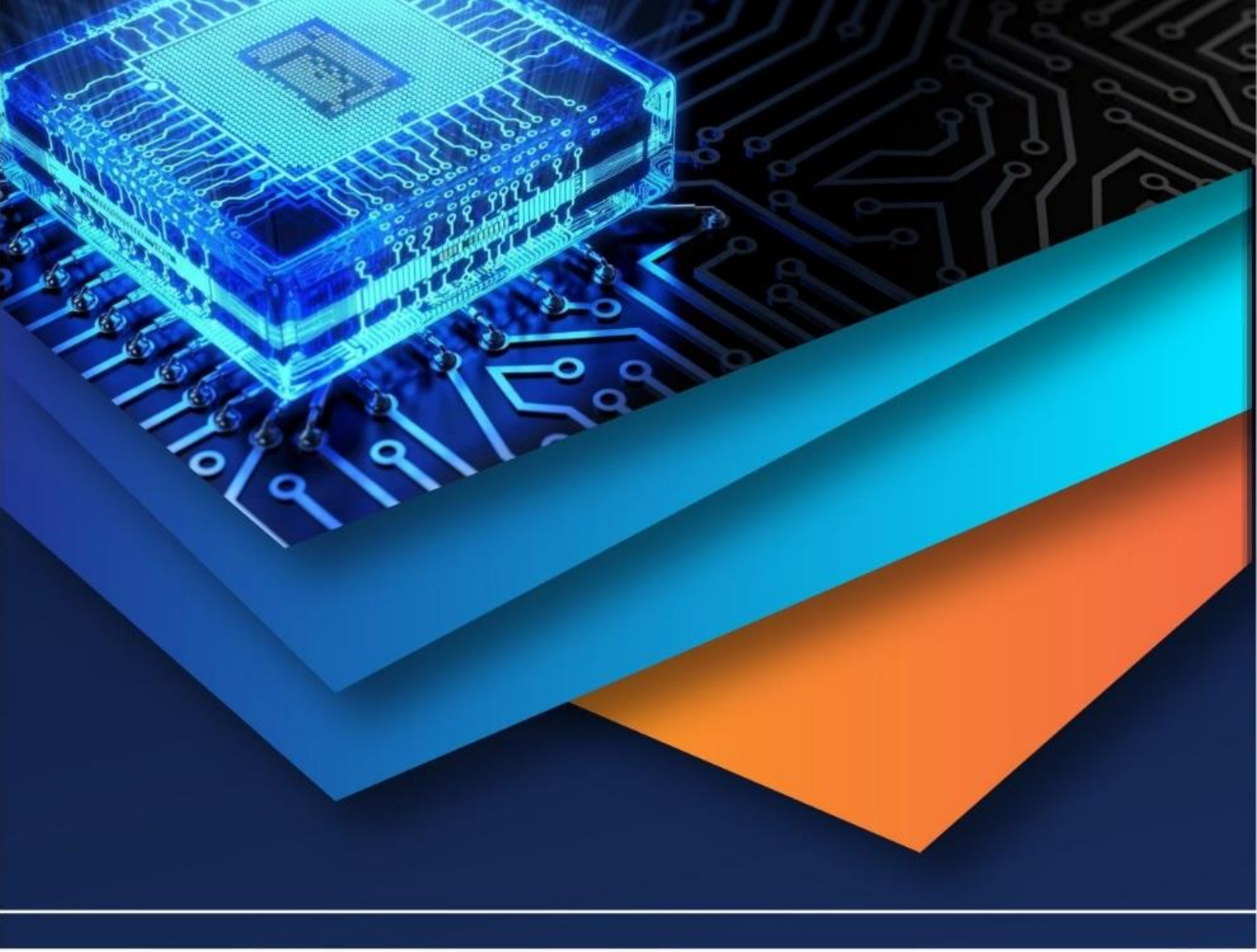
IX. FUTURE SCOPE

The Multimodal Adaptive AI-Based Interactive Robotic System has significant scope for future enhancement through the integration of advanced artificial intelligence, machine learning and sensor technologies. The system can be improved to support simultaneous processing of voice, text and visual inputs, enabling more natural human-robot interaction. Advanced object detection, natural language processing and real-time adaptive learning can be incorporated to enhance its understanding and decision-making capabilities. Further development of autonomous navigation using SLAM, real-time mapping and obstacle avoidance can improve its ability to operate independently in complex environments. Cloud connectivity and IoT integration can also be introduced to support remote monitoring, data storage and smart environment interaction. The existing mecanum wheel mechanism can be optimized for improved mobility and stability. With these advancements, the system can be extended to practical applications such as healthcare assistance, smart homes, educational institutions and industrial automation, making it a more intelligent, efficient and autonomous robotic platform.

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