

Design and Experimental Evaluation of a Wireless Head-Gesture Controlled Smart Wheelchair for Assistive Mobility

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Abstract—This paper presents the design, implementation, and experimental evaluation of a wireless head-gesture controlled smart wheelchair intended to enhance mobility assistance for individuals with severe motor impairments. The proposed system offers an alternative navigation interface for users who are unable to operate conventional joystick-based electric wheelchairs due to limited upper-limb functionality. Head movements are detected using an MPU6050 inertial measurement unit integrated with an Arduino Nano transmitter, while motion commands are transmitted wirelessly via HC-05 Bluetooth modules to a receiver unit responsible for motor control and navigation. To improve command reliability and reduce the influence of involuntary head movements, a moving-average filtering technique combined with threshold-based gesture validation is implemented. The system further incorporates a dual-mode control strategy that enables seamless switching between head-gesture navigation and conventional joystick operation, thereby increasing usability and operational flexibility. For enhanced safety, an ultrasonic obstacle detection module is integrated through a hardware interrupt mechanism capable of immediately overriding motion commands whenever an obstacle is detected within a predefined safety distance. The main contributions of this work include the development of a low-cost wireless control architecture, the integration of dual-mode operation for improved user adaptability, and the implementation of an interrupt-driven safety mechanism for real-time obstacle avoidance. Experimental evaluation demonstrates a gesture-recognition accuracy of 98% and an average system response time of approximately 240 ms, confirming stable and near real-time performance under indoor operating conditions. By employing widely available and affordable embedded hardware components, the proposed wheelchair represents a practical, reliable, and cost-effective assistive mobility solution with significant potential for supporting individuals with severe physical disabilities in everyday environments.

Keywords—*Head-Gesture Control, Smart Wheelchair, Assistive Mobility, Bluetooth Communication, Ultrasonic Obstacle Detection, Dual-Mode Control.*

I. INTRODUCTION

Independent mobility remains a major challenge for individuals affected by severe motor disabilities, including quadriplegia, muscular dystrophy, and advanced neuromuscular disorders. Although powered wheelchairs have significantly improved the autonomy and quality of life of many users, most commercially available systems rely on joystick-based interfaces that require adequate upper-limb functionality. Consequently, individuals with limited or no hand movement often encounter difficulties in operating conventional electric wheelchairs, creating a strong need for alternative assistive control solutions.

In recent years, considerable research efforts have been devoted to the development of intelligent wheelchair systems employing alternative human-machine interaction techniques. Early studies mainly focused on hand-gesture recognition approaches for wheelchair navigation [1]. However, for users suffering from severe upper-limb impairments, head-motion control has emerged as a more practical and accessible solution. Several researchers have demonstrated the feasibility of using head orientation and motion information to generate navigation commands for assistive mobility systems [2], [3], [4]. In parallel, adaptive and multimodal interaction strategies have been proposed to improve system usability and user comfort under different operating conditions [5]. More recently, embedded systems

capable of accurately interpreting head movements have shown promising results in providing reliable wheelchair control for individuals with reduced mobility [6].

Wireless communication technologies have also contributed significantly to the evolution of smart wheelchair architectures. Bluetooth-based communication systems combined with low-cost microcontroller platforms have become particularly attractive because of their affordability, ease of implementation, and reduced wiring complexity. Several studies have successfully integrated Arduino-based control units and wireless communication modules to develop flexible and cost-effective assistive mobility solutions [7], [8], [9], [10].

Despite these advances, several limitations remain. Some existing systems employ wired sensor configurations that may reduce user comfort and restrict movement. Other approaches lack effective filtering techniques for suppressing involuntary head motions, potentially leading to unintended wheelchair commands and reduced operational reliability. Furthermore, many reported systems rely exclusively on a single control modality, which may decrease usability when users experience fatigue, temporary sensor displacement, or changing operational requirements. Safety also remains a critical concern, as not all systems incorporate real-time obstacle detection mechanisms capable of immediately interrupting wheelchair motion when hazardous situations occur.

To overcome these limitations, this work proposes a wireless head-gesture controlled smart wheelchair based on a dual Arduino Nano architecture. Head movements are measured using an MPU6050 inertial measurement unit mounted on the user's head and transmitted wirelessly through HC-05 Bluetooth modules operating at 9600 bps. The received commands are processed by a dedicated control unit responsible for motor actuation and wheelchair navigation. To improve robustness, a moving-average filtering technique combined with threshold-based validation is implemented to

reduce the influence of involuntary head movements. In addition, an ultrasonic obstacle detection module is integrated through a hardware interrupt mechanism capable of instantly overriding navigation commands whenever an obstacle is detected within a predefined safety distance. A secondary joystick-based control mode is also incorporated to provide operational flexibility and ensure continued usability under different operating conditions.

The main contributions of this work can be summarized as follows:

- Development of a low-cost wireless smart wheelchair controlled through head gestures using an MPU6050 inertial sensing unit.
- Integration of a dual-mode control architecture allowing seamless switching between head-gesture navigation and conventional joystick control.
- Implementation of an interrupt-driven ultrasonic obstacle detection mechanism to enhance user safety during wheelchair operation.
- Adoption of a modular wireless design that reduces wiring complexity and facilitates future system expansion.
- Experimental validation demonstrating a gesture-recognition accuracy of 98% and an average response time of approximately 240 ms, confirming reliable near real-time performance.

The remainder of this paper is organized as follows. Section II describes the proposed system architecture and hardware implementation. Section III presents the control strategy and software development. Section IV discusses the experimental setup and performance evaluation. Finally, Section V concludes the paper and outlines future research directions.

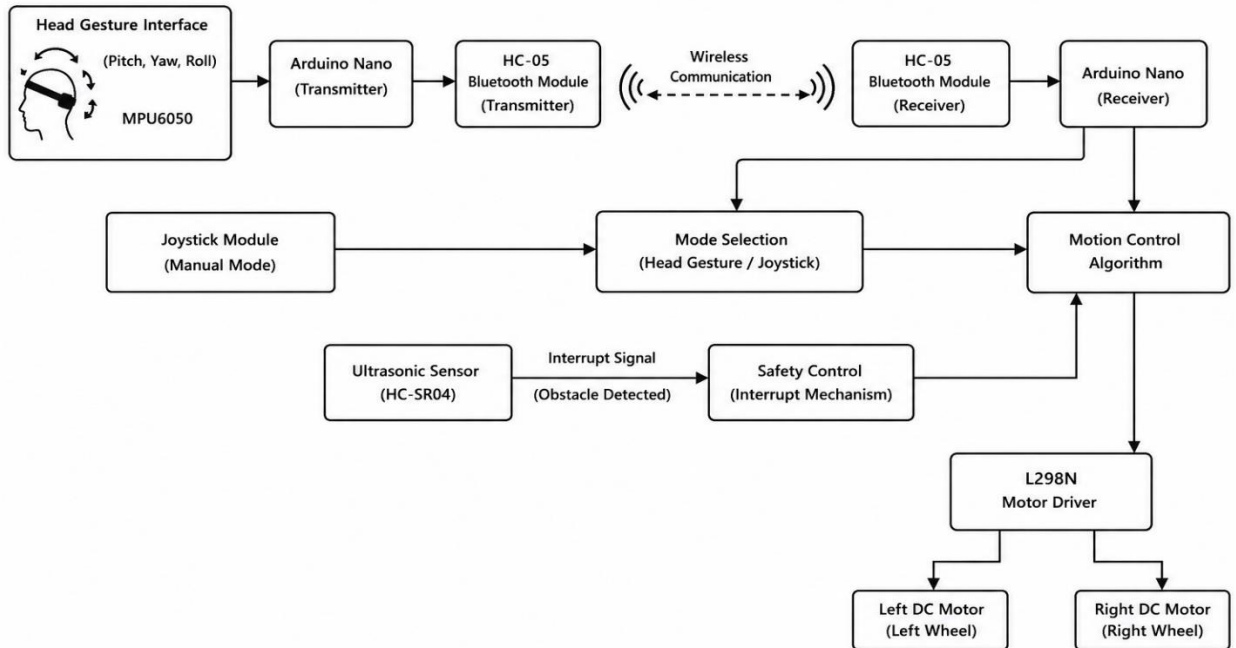


Fig. 1. Overall System Architecture of the Proposed Smart Wheelchair

II. SYSTEM ARCHITECTURE AND IMPLEMENTATION

A. Overall System Architecture

The proposed smart wheelchair system is organized into two main subsystems: the Head Orientation Detection Unit (transmitter side) and the Wheelchair Control Unit (receiver side). Such a modular architecture separates sensing and actuation functionalities, thereby improving system reliability, scalability, and distributed processing efficiency, as reported in previous assistive mobility studies [2], [8]. The complete system architecture is presented in Figure (1).

The Head Orientation Detection Unit is responsible for acquiring and processing the user's head movements. Head-motion-based interaction has been widely recognized as an effective alternative control strategy for individuals with severe upper-limb disabilities [2], [3], [4]. In the proposed implementation, an MPU6050 inertial measurement unit (IMU), integrating a three-axis accelerometer and a three-axis gyroscope, is used to measure head orientation and angular motion. The sensor communicates with an Arduino Nano microcontroller through the I²C interface, enabling real-time acquisition and processing of orientation data.

The generated navigation commands are transmitted wirelessly using an HC-05 Bluetooth module configured at a baud rate of 9600 bps. Bluetooth communication provides a low-cost, low-power, and low-latency solution that has been successfully adopted in numerous embedded assistive systems [7], [10], [11].

On the receiver side, a second HC-05 Bluetooth module receives the transmitted commands and forwards them to another Arduino Nano responsible for wheelchair navigation and motor control. The control unit generates the required actuation signals through an L298N dual H-bridge motor driver, which controls two 12-V DC geared motors attached to the wheelchair drive wheels. Similar Arduino-based architectures have demonstrated satisfactory real-time performance and affordability in smart wheelchair applications [6], [10].

To enhance operational safety and flexibility, the receiver subsystem integrates an HC-SR04 ultrasonic sensor for obstacle detection, a piezoelectric buzzer for acoustic warning, a manual joystick module, and a mode-selection pushbutton. The joystick allows direct manual operation whenever required, while the mode-selection button enables seamless switching between head-gesture navigation and manual control. The integration of multiple control modalities improves usability, adaptability, and user comfort under different operating conditions [5].

The complete electronic system is powered by a rechargeable 12-V battery pack. A voltage regulation stage provides a stable 5-V supply for the Arduino Nano boards, Bluetooth modules, MPU6050 sensor, ultrasonic sensor, and auxiliary electronic circuits. The adopted hardware configuration was selected to ensure low implementation cost, ease of maintenance, and compatibility with commercially available embedded-system components.

TABLE I.

HARDWARE COMPONENTS AND TECHNICAL SPECIFICATIONS

Component	Model	Function
Microcontroller (Transmitter)	Arduino Nano	Head movement acquisition and processing
Microcontroller (Receiver)	Arduino Nano	Motion control and command execution
Inertial Measurement Unit	MPU6050	Head orientation detection (Pitch, Yaw, Roll)
Wireless Communication Module	HC-05 Bluetooth	Wireless data transmission
Wireless Communication Module	HC-05 Bluetooth	Wireless data reception
Motor Driver	L298N Dual H-Bridge	DC motor actuation
Obstacle Detection Sensor	HC-SR04	Obstacle detection and safety interruption
Manual Control Interface	Joystick Module	Manual wheelchair control
Alarm System	Piezo Buzzer	Acoustic warning
Power Supply	12-V Rechargeable Battery	System power source

B. Control Strategy and Safety Mechanism

The operational sequence of the proposed control strategy is illustrated in Figure (2). During head-control operation, the MPU6050 continuously measures the orientation of the user's head. The acquired sensor data are transmitted to the Arduino Nano, where signal conditioning and gesture classification are performed.

To improve measurement stability and suppress involuntary head movements, a moving-average filtering technique is applied before gesture classification. Signal filtering has been reported to significantly improve command smoothness and reliability in gesture-controlled assistive systems [6].

The filtered orientation value at sample k is calculated as:

$$\theta_f(k) = \frac{1}{N} \sum_{i=0}^{N-1} \theta(k-i) \quad (1)$$

Where $\theta_f(k)$ is the filtered orientation value, $\theta(k-i)$ represents the raw sensor measurements, and N denotes the moving-average window size. In the implemented system, a window size of $N = 5$ samples was selected to provide an effective compromise between noise attenuation and response speed.

Following the filtering stage, the resulting orientation parameters are compared against predefined threshold values to determine the intended motion command. Forward motion is activated when the pitch angle exceeds $+15^\circ$, backward motion when it falls below -15° , right turning when the yaw angle exceeds $+20^\circ$, and left turning when it falls below -20° . A neutral zone of $\pm 10^\circ$ is maintained around the resting position to prevent unintended command activation (Table II).

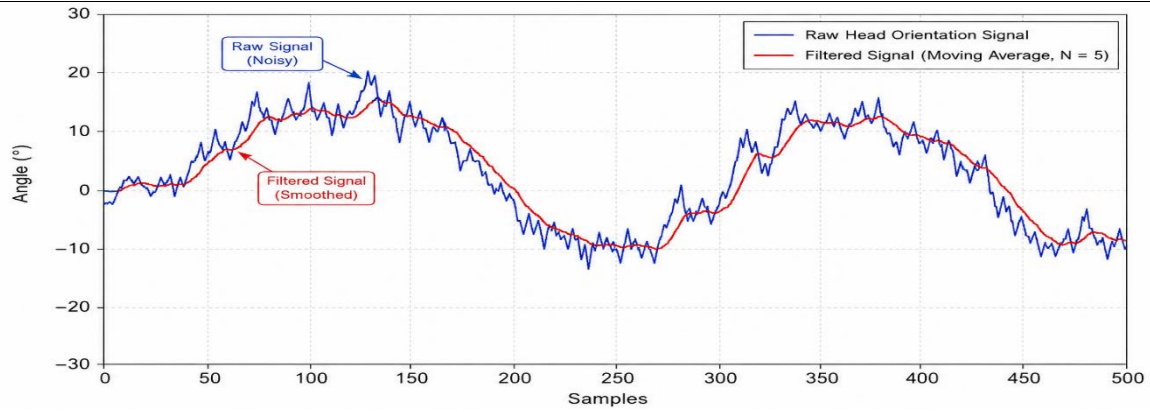


Fig. 2. Comparison between raw and filtered head-orientation signals using the moving-average filter.

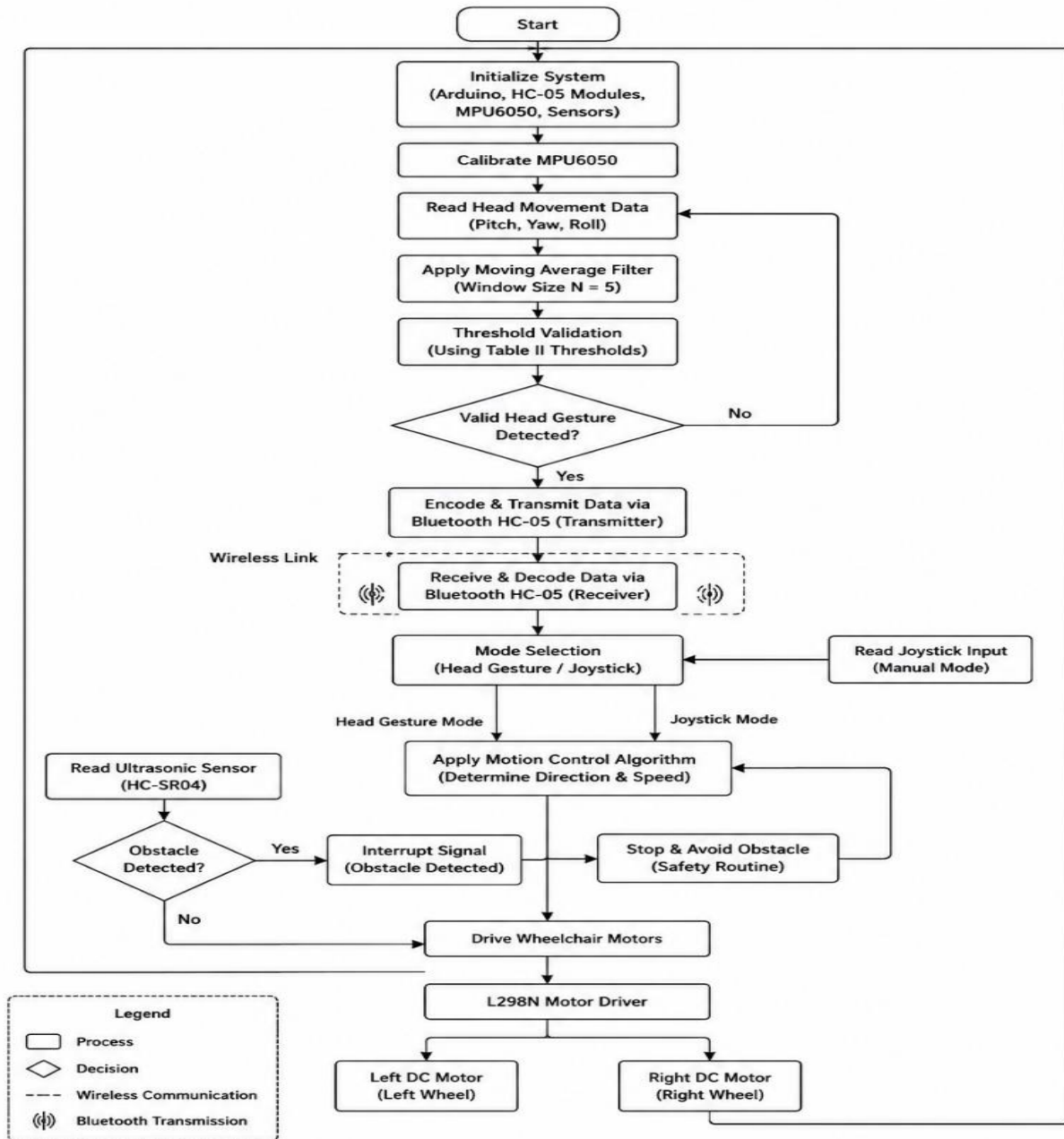


Fig. 3. Operational Flowchart of the Wireless Head-Gesture Wheelchair Control System.

TABLE II. GESTURE CLASSIFICATION THRESHOLDS USED FOR COMMAND GENERATION.

Motion Command	Orientation Parameter	Threshold
Forward	Pitch	$>+15^\circ$
Backward	Pitch	$<-15^\circ$
Turn Right	Yaw	$>+20^\circ$
Turn Left	Yaw	$<-20^\circ$
Stop	Neutral Zone	$\pm 10^\circ$

To further improve command reliability, the detected gesture must remain valid for at least 200 ms before transmission is authorized. This validation stage reduces false activations caused by transient movements or measurement noise.

On the receiver side, incoming commands are continuously monitored. The HC-SR04 ultrasonic sensor operates through a hardware interrupt mechanism that immediately overrides all navigation commands whenever an obstacle is detected within a predefined safety distance of 30 cm. Upon obstacle detection, motor actuation is instantly halted and an acoustic warning signal is generated through the buzzer.

The combination of signal filtering, threshold-based classification, temporal validation, and interrupt-driven obstacle avoidance provides a robust multi-layer safety

strategy that ensures reliable real-time operation and enhances user safety.

C. Conceptual System Overview

A conceptual representation of the implemented smart wheelchair system is shown in Figure (4). The diagram illustrates the interaction between the head-orientation sensing subsystem, wireless communication stage, receiver control unit, motor driving circuitry, safety monitoring subsystem, and manual control interface.

The architecture employs two Arduino Nano microcontrollers connected through dual HC-05 Bluetooth modules, enabling wireless command transmission while minimizing wiring complexity. The integration of both head-gesture and joystick control modes provides operational redundancy and increased adaptability compared with conventional single-mode assistive systems [5], [8].

The ultrasonic interrupt-based safety layer continuously supervises the surrounding environment and can immediately override navigation commands whenever a potential collision risk is detected. Consequently, the proposed architecture achieves a balanced combination of reliability, safety, flexibility, and cost-effectiveness suitable for practical assistive mobility applications.

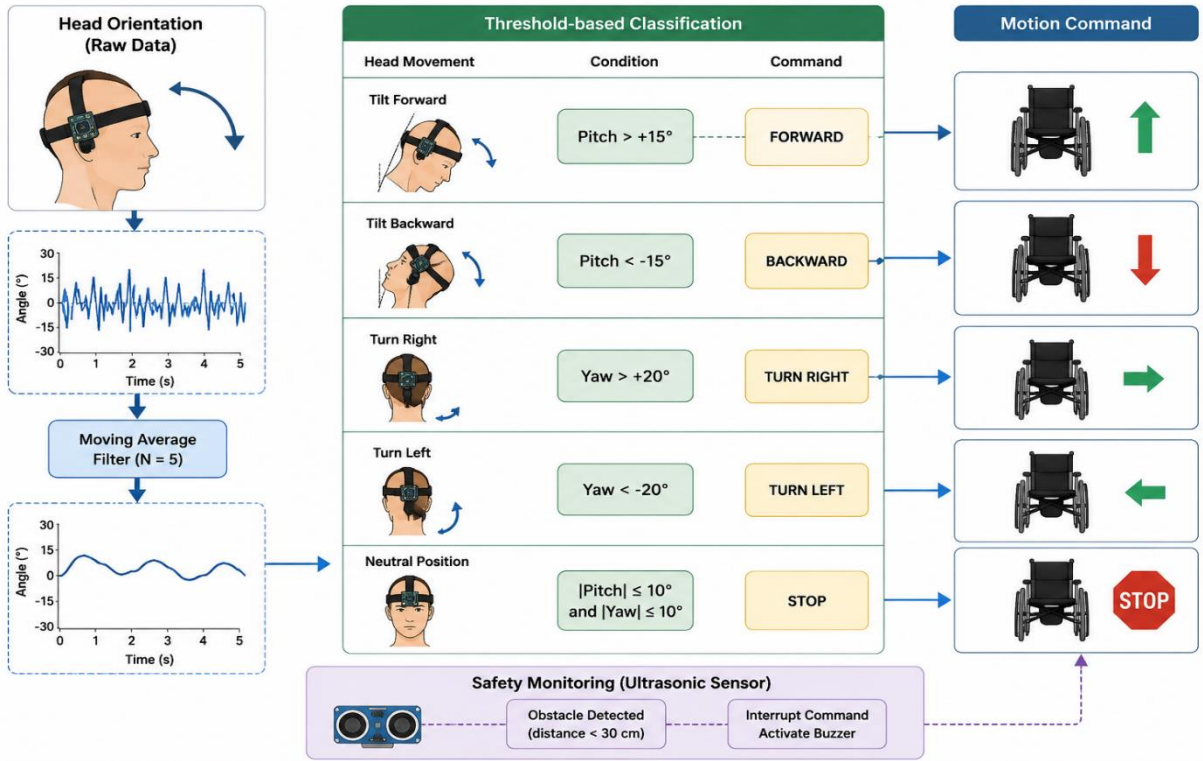


Fig. 4. Motion Command Generation Using Head-Orientation Thresholds.

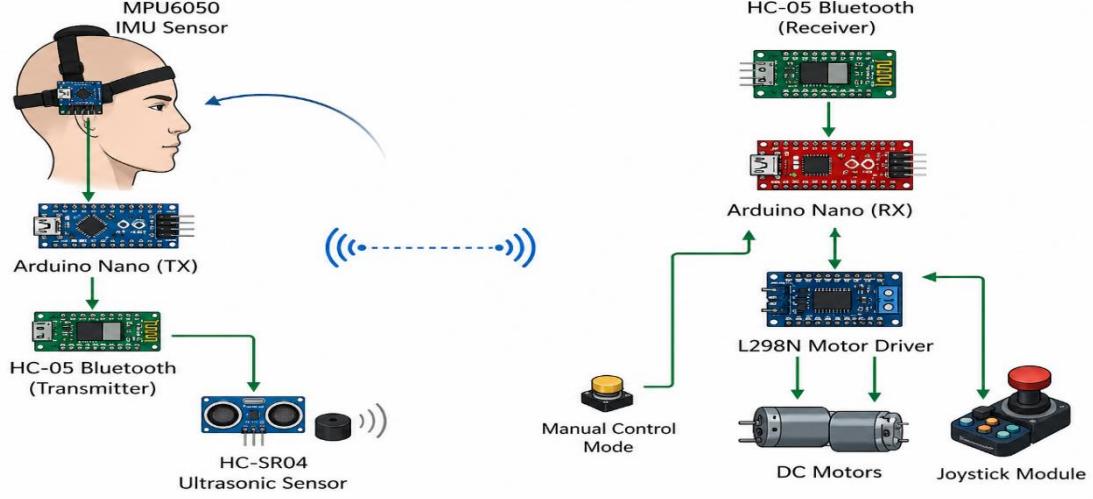


Fig. 5. Conceptual schematic of the dual-mode wireless head-gesture controlled wheelchair system.

III. EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION

To evaluate the practical performance of the proposed wireless head-gesture controlled wheelchair, a series of controlled indoor experiments were conducted. The experimental assessment focused on gesture-recognition accuracy, command response time, wireless communication reliability, and obstacle-detection performance.

The objective of the present experimental evaluation was to demonstrate the feasibility and functional reliability of the proposed prototype under controlled laboratory conditions. Although the number of trials was intentionally limited during the prototype-validation phase, the obtained results provide an initial indication of system effectiveness and support future large-scale evaluations involving multiple users and extended testing scenarios.

The experiments were carried out in an indoor environment free from significant electromagnetic interference. A single participant performed a predefined set of wheelchair commands consisting of forward, backward, left-turn, right-turn, and stop operations. Each command was repeated ten times under identical testing conditions, resulting in a total of fifty experimental trials.

The response time was measured from the instant the filtered head-orientation value exceeded the predefined classification threshold until motor actuation was initiated by the wheelchair control unit.

TABLE III. GESTURE RECOGNITION ACCURACY AND RESPONSE-TIME EVALUATION

Command	Number of Trials	Successful Executions	Accuracy (%)	Avg. Response Time (ms)
Forward	10	10	100	238
Backward	10	10	100	242
Turn Right	10	9	90	245
Turn Left	10	10	100	239
Stop	10	10	100	238
Total	50	49	98	240±15

As presented in Table III, the proposed system achieved an overall gesture-recognition accuracy of 98%, demonstrating reliable command classification and stable system behavior. Among the evaluated commands, only one misclassification occurred during the right-turn tests, resulting in a command-specific accuracy of 90%. This isolated error was attributed to a rapid transitional head movement that briefly approached the decision threshold.

The average command response time was approximately 240 ms, indicating near real-time operation suitable for assistive mobility applications. The measured response times remained relatively consistent across all evaluated commands, with an estimated standard deviation of approximately ± 15 ms, confirming stable communication and processing performance. Fig.

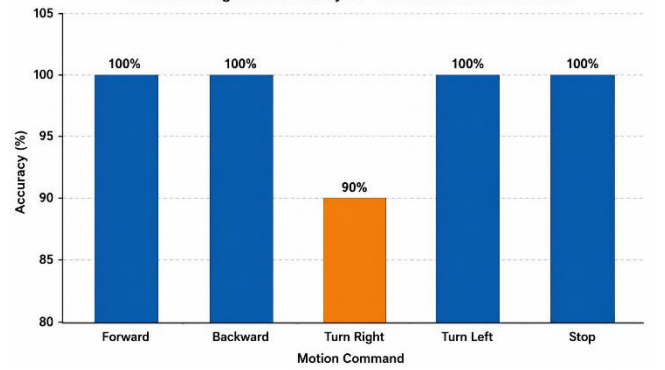


Fig. 6. Gesture Recognition Accuracy for Different Motion Commands

The obtained results demonstrate that the proposed architecture provides an effective balance between responsiveness, reliability, and implementation simplicity. Furthermore, the achieved performance is comparable to previously reported head-controlled wheelchair systems while maintaining a low-cost and modular hardware configuration [2], [8], [4].

A. Obstacle Detection and Safety Performance

The obstacle-detection subsystem was evaluated by positioning stationary obstacles at different distances in front

of and behind the wheelchair. The HC-SR04 ultrasonic sensor was configured to operate through a hardware interrupt mechanism capable of immediately overriding navigation commands when an obstacle was detected within the predefined safety zone.

TABLE IV. OBSTACLE DETECTION PERFORMANCE

Distance (cm)	Obstacle Detected	Motor Response	Buzzer Activated
20	Yes	Stopped	Yes
40	Yes	Stopped	Yes
80	Yes	Stopped	Yes
150	Yes	Stopped	Yes
200	No	Normal Motion	No

The experimental results indicate that the ultrasonic sensor reliably detected obstacles located between 20 cm and 150 cm. Upon obstacle detection, motor actuation was immediately interrupted and an acoustic warning signal was generated through the buzzer. No delayed response or unintended motion was observed during testing.

Objects positioned at 200 cm remained outside the predefined safety detection range and therefore did not trigger an interruption event. These observations confirm the effectiveness of the interrupt-driven safety mechanism and demonstrate its suitability for assistive mobility applications requiring reliable collision avoidance [6], [10].

B. Communication Reliability

Wireless communication performance was evaluated using dual HC-05 Bluetooth modules configured at a baud rate of 9600 bps. The transmitter and receiver units were separated

by distances ranging from 1 m to 8 m under normal indoor operating conditions.

Throughout the experimental evaluation, no packet loss, communication interruption, or noticeable transmission delay was observed. The average communication latency remained negligible compared with the overall command-processing time.

The adopted Bluetooth-based architecture therefore provides a reliable and cost-effective wireless communication solution while avoiding the additional complexity associated with network-dependent Internet-of-Things implementations [10].

TABLE V. BLUETOOTH COMMUNICATION RELIABILITY AT DIFFERENT INDOOR DISTANCES.

Distance(m)	Communication Status	Packet Loss (%)	Average Delay (ms)
1	Stable	0	8
2	Stable	0	9
4	Stable	0	10
6	Stable	0	11
8	Stable	0	12

C. Comparison with Existing Smart Wheelchair Systems

To better position the proposed work within the current state of the art, a comparison with representative smart-wheelchair systems reported in the literature is presented in Table VI.

TABLE VI. COMPARISON BETWEEN THE PROPOSED SYSTEM AND EXISTING SMART WHEELCHAIR SOLUTIONS.

Reference	Control Method	Accuracy (%)	Response Time (ms)	Obstacle Detection	Dual-Mode Control	Wireless Communication
<i>Hassani et al. [2]</i>	Head Gesture	N/A	N/A	No	No	No
<i>Shayban and Khan [7]</i>	Head Gesture	95	280	No	No	Yes
<i>Wangchuk and Choden [8]</i>	Head Gesture	96	260	No	No	Yes
<i>Gomez et al. [5]</i>	Head Gesture	97	250	Yes	No	Yes
<i>Proposed System</i>	Head Gesture+ Joystick	98	240	Yes	Yes	Yes

The comparison demonstrates that the proposed system achieves competitive gesture-recognition accuracy and response time while incorporating several practical advantages, including dual-mode operation, interrupt-driven obstacle avoidance, modular wireless architecture, and low implementation cost. These characteristics contribute to improving usability, safety, and deployment feasibility for assistive mobility applications.

D. Limitations of the Present Study

Although the proposed system demonstrated promising performance, certain limitations should be acknowledged. The experimental evaluation was conducted using a single participant and a limited number of command trials. Consequently, the reported performance metrics may not fully capture the variability associated with a broader population of users.

In addition, the experiments were performed exclusively under controlled indoor conditions. Therefore, environmental factors such as uneven terrain, outdoor obstacles, variable lighting conditions, and electromagnetic interference were not investigated.

Future work will include experiments involving multiple participants with different physical characteristics and mobility conditions, extended long-term reliability assessments, outdoor navigation testing, power-consumption analysis, and more comprehensive statistical evaluations to further validate system performance under real-world operating conditions.

IV. CONCLUSION

This paper presented the design, implementation, and experimental evaluation of a dual-mode wireless smart

wheelchair controlled through head-gesture recognition. The proposed system combines an MPU6050 inertial measurement unit, dual Arduino Nano microcontrollers, HC-05 Bluetooth communication modules, and an interrupt-based ultrasonic safety subsystem to provide an accessible and reliable mobility-assistance solution for individuals with severe motor impairments.

The main contribution of this work lies in the integration of three complementary features within a single low-cost embedded platform: wireless head-gesture control, dual-mode operation through both head gestures and manual joystick control, and real-time interrupt-driven obstacle avoidance. Unlike many conventional single-modality implementations, the proposed architecture improves operational flexibility while maintaining system simplicity and affordability.

Experimental evaluation demonstrated an overall gesture-recognition accuracy of 98% with an average response time of approximately 240 ms, confirming stable and near real-time system performance. The implemented moving-average filtering and threshold-validation strategy effectively reduced unintended command activation, while the ultrasonic interrupt mechanism ensured immediate motor interruption whenever an obstacle was detected within the predefined safety zone. The obtained results indicate that the proposed architecture can provide reliable and responsive wheelchair navigation under controlled indoor conditions.

Furthermore, comparison with previously reported smart-wheelchair systems demonstrated that the proposed solution achieves competitive performance while employing widely available and cost-effective hardware components. The modular wireless architecture also facilitates future system expansion and maintenance.

Although the current study provides a successful proof-of-concept implementation, further investigations involving multiple participants, outdoor environments, long-term reliability assessment, and advanced adaptive control algorithms are recommended. Future developments may also incorporate machine-learning-based gesture classification and multimodal sensing technologies to further enhance system robustness, user comfort, and environmental awareness.

Overall, the results demonstrate that the proposed system represents a practical, affordable, and effective assistive mobility solution with strong potential for future deployment in rehabilitation and healthcare environments.

V. FUTURE WORK

Although the proposed system demonstrated reliable performance under controlled indoor conditions, several directions remain for further enhancement and real-world validation.

First, the current evaluation was conducted using a single healthy participant. Future investigations should include users with varying degrees of motor impairment to better assess usability, adaptability, and long-term comfort in clinical or rehabilitation environments. User-centered validation has been emphasized as a critical factor in assistive wheelchair research [5], [4].

Second, the implemented control strategy relies on fixed threshold-based gesture classification. While computationally

efficient, this approach may be sensitive to variations in user behavior or environmental dynamics. Incorporating adaptive calibration techniques or lightweight machine-learning algorithms could enhance classification robustness and reduce false triggering, as suggested in advanced modality-independent assistive interfaces [5] and recent head-motion control studies [6].

From a safety perspective, the current design utilizes ultrasonic sensing for obstacle detection. Although effective within moderate ranges, integrating complementary sensing technologies—such as infrared, depth, or vision-based systems—could further improve environmental awareness and obstacle detection reliability in complex scenarios [6], [10].

Finally, extended durability testing and mechanical optimization of the wheelchair structure should be conducted to evaluate long-term stability, energy efficiency, and user comfort. These improvements are essential for transitioning from a laboratory prototype to a deployable assistive mobility platform.

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Ethics Statement: The participant involved in the experimental evaluation voluntarily agreed to participate in the study. The experiments were conducted exclusively for prototype validation purposes. No personal, medical, or sensitive data were collected, stored, or processed during the experimental evaluation.

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