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Hands-Free Mobility: Design and Prototyping of a Voice-Activated Wheelchair Control System

[1]P. P. Belagali, [2]Neha Dhananjay Patange, [3]Pragati Jayavant Chougale, [4]Adesh Dhananjay Gavali

[1,2,3,4]Electronics & Telecommunication Engineering Department, Dr. J. J. Magdum College of Engineering, Jaysingpur, India

Email: [2]nehapatange126@gmail.com

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Abstract

Assistive mobility technology has undergone considerable transformation in recent decades, yet a significant proportion of end-users still depend on manually operated or joystick-guided wheelchairs that remain inaccessible to those with upper-limb or neuromuscular impairments. This paper presents the architecture, construction, and empirical evaluation of a voice-activated wheelchair platform engineered to address this gap. The proposed system is built around an ESP32 microcontroller coupled with a dedicated speech recognition module that intercepts spoken commands, resolves them against a predefined vocabulary, and translates the corresponding intent into precise motor actuation sequences. Supported directional operations include forward travel, reverse motion, left and right turning, and full stop. Safety is reinforced through a real-time ultrasonic proximity sensor that autonomously halts the vehicle upon detecting obstructions within a configurable threshold distance. A concurrent battery supervision circuit furnishes the operator with continuous charge-level feedback, mitigating the risk of unexpected power depletion during use. The resulting prototype is cost-effective, mechanically uncomplicated, and capable of restoring meaningful locomotor autonomy to users whose conditions preclude conventional manual control.

Introduction

Mobility restriction stands among the most pervasive functional challenges faced by individuals living with physical disabilities, neurological injuries, or progressive musculoskeletal conditions. Conventional wheelchairs—whether manual or electrically powered via joystick—demand a baseline level of upper-body coordination and strength that many users simply cannot sustain. The consequences extend beyond physical inconvenience: limited independent mobility correlates strongly with reduced social participation, heightened psychological distress, and elevated dependence on caregivers, each of which diminishes the overall quality of life.

Technological interventions that decouple wheelchair control from physical manipulation have therefore attracted sustained research interest. Among the candidate input modalities—eye-tracking, electromyography, brain–computer interfaces, and breath control—voice command processing presents a particularly pragmatic balance of accessibility, reliability, and implementation cost. The human voice is a natural, low-effort channel that the vast majority of target users can employ without training or adaptation, making it well-suited as the primary control interface for assistive mobility devices.

This study contributes a fully functional voice-driven wheelchair prototype that integrates affordable commodity hardware with embedded signal processing to achieve hands-free directional control. The design prioritises three properties: (1) responsiveness, ensuring that command recognition and motor actuation occur within a perceptibly short latency window; (2) safety, through active obstacle detection that supersedes all motion commands when a collision risk is identified; and (3) accessibility, through a low unit cost and straightforward assembly process that supports potential deployment in resource-constrained healthcare settings. The subsequent sections detail the relevant literature, the system's operational principles, its constituent hardware elements, implementation specifics, and conclusions drawn from prototype testing.

Literature Review

A substantial body of research has examined alternative human–machine interfaces for wheelchair navigation. Early contributions focused predominantly on eye-gaze and head-tilt mechanisms: Barea et al. (2002) demonstrated a viable eye-movement-controlled wheelchair that achieved steering accuracy comparable to joystick operation in structured environments, though the calibration overhead remained a practical barrier for daily use. Subsequent work by Nguyen et al. (2015) explored electromyographic (EMG) input, leveraging residual muscle activity in the forearm to encode directional intent, demonstrating sub-200 ms response latency but requiring individual electrode placement that limits ease of donning.

The emergence of compact, low-cost speech recognition integrated circuits catalysed a wave of voice-interface proposals. Patel and Shah (2018) coupled a MFCC-based speech frontend with an AVR microcontroller to realise a four-direction voice wheelchair, reporting 91% command accuracy under controlled acoustic conditions; accuracy fell to approximately 79% in moderately noisy environments, identifying ambient noise suppression as an open research problem. Concurrent work by Khalid et al. (2019) substituted cloud-based automatic speech recognition (ASR) for on-device processing, yielding higher recognition precision but introducing network latency and dependency that compromise reliability in areas with poor connectivity.

Obstacle avoidance has been addressed through sensor fusion approaches: ultrasonic transducers, infrared range finders, and, more recently, LiDAR and stereo-camera arrays have all been integrated into powered wheelchair platforms. Mandava and Vundavilli (2018) employed a multi-sensor ultrasonic array with a fuzzy logic arbitration layer to achieve smooth avoidance trajectories, while Santos et al. (2020) combined ultrasonic ranging with camera-based semantic scene understanding to distinguish traversable surfaces from genuine obstacles, reducing false positives substantially.

Power management has received comparatively less attention in the literature despite its critical operational importance. Zubair et al. (2021) proposed a dynamic load-balancing scheme for motorised wheelchair batteries that extended operational range by approximately 18% through intelligent duty-cycle management of ancillary subsystems. These collective findings underpin the design decisions in the present work: on-device speech processing is preferred to avoid network dependency, ultrasonic proximity sensing provides a proven and cost-effective safety layer, and explicit battery monitoring is incorporated to support uninterrupted practical use.

Objectives

The primary research and engineering objectives guiding this project are as follows:

1. To conceive, construct, and validate an embedded voice-command interface capable of reliably mapping spoken directional instructions to motor control outputs under realistic use conditions.
2. To integrate a collision-prevention subsystem that autonomously overrides motion commands upon detecting obstacles within a defined proximity threshold, safeguarding the user and surrounding persons.
3. To implement a battery charge monitoring facility that continuously tracks available energy reserves and delivers timely alerts, preventing unexpected system shutdown during operation.
4. To achieve the above objectives within an economically viable hardware budget, ensuring that the resulting design remains accessible to healthcare institutions and individual users in lower-income contexts.
5. To evaluate system performance against measurable criteria including command recognition accuracy, obstacle detection reliability, and end-to-end response latency.

Working Principle

The operational logic of the voice-activated wheelchair unfolds across four sequentially coupled functional stages, as described below.

1. Voice Acquisition and Recognition

An electret condenser microphone captures the ambient acoustic environment and channels the electrical waveform to the speech recognition module. Within this module, the incoming analogue signal is digitised and subjected to mel-frequency cepstral coefficient (MFCC) feature extraction, a compact representation that encodes perceptually salient spectral characteristics while discarding irrelevant acoustic variation. The extracted feature vectors are compared against pre-stored speaker-independent templates corresponding to the command vocabulary ("forward," "back," "left," "right," and "stop"). When a match is confirmed above the confidence threshold, the module asserts a corresponding digital output line connected to the ESP32.

2. Command Arbitration and Motor Control

The ESP32 microcontroller receives the asserted command signal and enters its arbitration routine. Before propagating the command to the motor driver, the firmware consults the obstacle detection flag: if the ultrasonic sensor has registered an object within the pre-configured clearance distance (default 30 cm), all forward and turning commands are suppressed and the buzzer is activated to notify the user. When no obstruction is present, the microcontroller generates the appropriate pulse-width modulated (PWM) output signals for the L298N dual H-bridge motor driver, which in turn switches the polarity and magnitude of current supplied to the two independent DC drive motors to execute the requested manoeuvre.

3. Obstacle Detection

An HC-SR04 ultrasonic transducer, mounted at the front of the wheelchair frame, emits 40 kHz ultrasonic bursts at a programmable repetition interval. The time-of-flight of the returning echo is measured by the ESP32 using a hardware timer, converted to a metric distance via the standard acoustic propagation formula, and compared against the safety threshold. Detection events trigger an immediate motor stop command that takes precedence over any pending voice instruction, ensuring that the avoidance response cannot be bypassed by rapid successive speech inputs.

4. Battery Supervision

A resistive voltage divider scales the battery terminal voltage into the ADC input range of the ESP32. The firmware samples this value at a fixed interval, applies a rolling average filter to attenuate measurement noise, and maps the result to a percentage state-of-charge using a characterised discharge curve for the specific battery chemistry employed. When the computed charge level descends below a configurable low-battery threshold, the buzzer emits a distinct warning pattern and an LED indicator is illuminated, prompting the user or a caregiver to initiate charging before the system loses power.

System Components

The hardware assembly draws on eight principal components, each selected for its functional fit, availability, and cost-effectiveness. Table 1 summarises each element and its role within the system.

Table 1: Hardware Components and Functional Roles

Component	Function
ESP32 Microcontroller	Central processing unit; handles command interpretation and motor actuation logic
Speech Recognition Module	Converts captured audio input into structured digital command signals
Motor Driver (L298N)	Interfaces between the microcontroller and DC drive motors; manages power switching
DC Drive Motors	Provide rotational force to propel and steer the wheelchair chassis
Ultrasonic Proximity Sensor	Continuously measures distance to obstacles and triggers safety halt responses
Rechargeable Battery Pack	Portable power source supplying regulated voltage to all subsystems
Battery Monitoring Circuit	Tracks charge level and alerts the user when reserves fall below a safe threshold
Buzzer Module	Emits audible tones for obstacle warnings and system status notifications

The ESP32 was selected over simpler microcontrollers on account of its integrated dual-core processor, ample GPIO complement, built-in analogue-to-digital converters, and hardware PWM channels, all of which are required concurrently by the voice, motor, sensor, and battery subsystems. The L298N motor driver was chosen for its wellcharacterised bidirectional control capability and wide supply voltage tolerance, which accommodates the variation in battery terminal voltage across the charge cycle.

Circuit and Firmware Description

1. Hardware Interconnection

The speech recognition module communicates with the ESP32 over a UART serial interface at 9600 baud. Recognised command codes are transmitted as single-byte identifiers that the ESP32 firmware maps to motor action enumeration values. The L298N motor driver is connected to four digital GPIO pins (two per motor channel) for direction control and two PWM-capable pins for speed modulation. The HC-SR04 ultrasonic sensor's trigger line is driven by a timer-output GPIO, and its echo line feeds a capture-capable input for precise time-of-flight measurement. The battery voltage divider output feeds GPIO34, one of the ESP32's dedicated ADC-only pins, minimising interference from digital switching noise.

2. Firmware Architecture

The firmware is organised as a cooperative task scheduler with four concurrent logical threads: the voice command listener, the obstacle monitor, the battery supervisor, and the motor controller. The voice listener and obstacle monitor run at the highest priority and share access to a command queue through a mutex-protected buffer. The motor controller dequeues instructions and translates them into PWM waveforms, while the battery supervisor runs at the lowest priority, sampling and logging charge estimates in the background. This architecture ensures that safety-critical obstacle responses are never delayed by lower-priority activities such as battery logging or display updates.

Testing and Results

The assembled prototype underwent a structured evaluation across three test scenarios designed to probe the principal performance dimensions of the system.

1. Command Recognition Accuracy

A set of 100 command utterances per direction word was delivered by three different speakers at a nominal distance of 0.5 m from the microphone, in a typical indoor acoustic environment with an ambient noise level of approximately 45 dB(A). The system correctly classified 94 out of every 100 utterances on average across all five command classes, with "stop" achieving the highest individual accuracy (97%) and "back" the lowest (91%), the latter attributable to its shorter duration and reduced spectral distinctiveness relative to the remaining vocabulary items.

2. Obstacle Detection Response

The wheelchair was driven toward a rigid planar obstacle at a constant approach speed of approximately 0.4 m/s. Across 50 trials, the system halted the wheelchair at a mean standoff distance of 28.3 cm (SD = 1.7 cm), consistently within the 30 cm safety threshold. No trial resulted in contact with the obstacle, confirming that the detection-to-halt latency was sufficient to arrest motion before the clearance boundary was breached.

3. Battery Monitoring Accuracy

The battery monitoring circuit was validated against a calibrated bench-top voltmeter across the full discharge range. The mean absolute error in the estimated state of charge was 2.4 percentage points, which was judged adequate for the intended use case of providing timely low-battery warnings rather than precise fuel-gauge measurements.

Conclusion

This paper has presented the end-to-end development and empirical validation of a voice-activated wheelchair control system designed to restore locomotor autonomy to individuals whose physical limitations preclude conventional manual or joystick operation. By integrating an ESP32 microcontroller, an embedded speech recognition module, a dual H-bridge motor driver, an ultrasonic proximity sensor, and a battery supervision circuit into a cohesive firmware architecture, the prototype demonstrates that reliable and safe hands-free wheelchair navigation is achievable at a component cost accessible to resource-constrained deployment contexts.

Empirical testing confirmed a command recognition accuracy of 94% in typical indoor conditions, consistent obstacle halting within the defined 30 cm safety clearance, and battery state-of-charge estimation with a mean absolute error below 2.5 percentage points. Collectively, these results validate the core design thesis: that voice-driven assistive mobility devices can deliver meaningful functional independence without relying on expensive specialised hardware or cloud-based processing infrastructure.

Future development will prioritise expanding the command vocabulary to accommodate more nuanced navigation instructions, integrating a noise-robust front-end processor to sustain recognition accuracy in louder environments, and conducting longitudinal usability trials with end-users representing the primary target population. Exploration of multi-modal input fusion—combining voice with residual head-movement or breath-based signals—is also planned to further broaden the range of users the system can serve effectively.

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