

AI-Powered IoT-Integrated Voice-Controlled Smart Wheelchair with Multi-Sensor Navigation and Safety Features

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Abstract

This research paper proposes the concept of a voice-controlled smart wheelchair that enables mobility, safety and independence for physically disabled persons. This smart wheelchair incorporates various hardware and software modules, including the Raspberry Pi Zero 2 Was the brain unit, into its framework to facilitate intelligent operation. A microphone unit is designed to recognize voice commands and process them through machine learning-based speech recognition technology to enable hands-free operation of the wheelchair. To ensure the safety of the user, a physical mushroom-type emergency stop button is integrated to instantly stop the wheelchair when pressed. The wheelchair movement components include 350 watts DC brushed motors and a strong structure to ensure smooth movement. The motor speeds can be regulated through the intelligent control unit to enable smooth and efficient movement within the indoor and outdoor environments. Location tracking in real time is provided through a GPS module, while in emergency situations, location updates are sent to caregivers using a GSM module. In addition, the text-to-speech feedback provides audio confirmation for system status and user commands, further improving usability for those users challenged by vision or physical capabilities. The power input shall be provided through a rechargeable lithium-ion battery pack with BMS and voltage regulation, allowing for continuous operation in a safe manner. Overall, the workflow that can be realized consists of system wake-up through a wake word, followed by voice command processing, safety validation, execution of motor control, GPS based location monitoring, and data logging for analysis. This assistive mobility in a smart wheelchair, as proposed, is cost effective, user-friendly, and safety-focused, showing in practice how to effectively incorporate voice control, embedded systems, and real-time communication technologies.

Keywords: Assistive mobility; Raspberry Pi Zero 2 W; Smart wheelchair; Speech recognition; Voice-controlled wheelchair

1. Introduction

Mobility has been found to be a basic necessity for maintaining the independence and quality of life for people who are physically challenged or disabled. Traditional mobility tools, for instance, include manual wheelchairs and joystick-controlled electric wheelchairs, that require considerable physical effort or motor skills to operate, which might not be applicable to individuals with severe motor disabilities or disabilities due to other factors. As

such, there is a pressing need for intelligent mobility tools that require minimal physical interaction, yet are efficient, safe, reliable, and easy to use. Advances in the overall capabilities of artificial intelligence (AI), embedded systems, and Internet of Things (IoT) technologies have enabled the design and development of smart wheelchairs with advanced perception, control, and communication features. Various technologies have been used for human-machine interaction, including voice-based

interaction, which offers a viable solution that does not require the physical interaction of a person with the wheelchair or the surrounding environment due to its natural characteristics, making it feasible for voice-controlled wheelchairs using AI-based technologies for command recognition with high accuracy. The aspect of safety is a cardinal concern in intelligent wheelchairs, especially while operating in dynamic indoor situations if not handled accordingly. In this regard, state-of-the-art smart wheelchair systems integrate multi-sensor navigation, embedded safety logics, and mechanisms for handling critical situations. Physical emergency-stop switches, controlled motor actuation, and sensor-based monitoring make the motion stable, reliable, and free from any accidents. IoT-based communication modules integrated into assistive mobility significantly extend the functionality by monitoring and aiding remotely. Technologies like GPS and GSM enable location tracking and transmission of emergency alerts continuously to caregivers or medical personnel. The mechanisms for text-to-speech feedback improve user interaction by providing audio confirmation of system status and executed commands, which is especially useful when users have impairments either in their vision or physical capabilities. Sudden obstacles, system failures, and user emergencies are all bound to generate hazardous situations if not handled accordingly. In this regard, state-of-the-art smart wheelchair systems integrate multi-sensor navigation, embedded safety logics, and mechanisms for handling critical situations. Physical emergency-stop switches, controlled motor actuation, and sensor-based monitoring make the motion stable, reliable, and free from any accidents.

2. Literature Review

Kumar et al. designed an intelligent wheelchair system with a conventional joystick interface and ultrasonic sensors for basic obstacle avoidance. The system was designed to improve the safety of the user by avoiding collisions in indoor settings. Although the system improved the assistance provided to the user during navigation, it continued to demand continuous manual control, which was not ideal for physically disabled users [1]. S. Patel and R. Mehta

designed a voice-controlled wheelchair with a basic speech recognition system and pre-defined voice commands. The system provided the user with the benefit of hands-free control and minimized user dependence on manual controls. However, the system's speech recognition capabilities were highly sensitive to background noise, and the system did not incorporate advanced safety and emergency response mechanisms [2]. M. Singh et al. designed a head-gesture-controlled wheelchair with accelerometer sensors for recognizing head gestures to control the wheelchair. The system was very useful for physically disabled users who could not operate the wheelchair using manual controls. Although the system performed very well, it continued to cause user fatigue due to prolonged use, and the system also lacked intelligent feedback and emergency stop functionality [3]. J. Lee et al. designed an autonomous smart wheelchair system using LiDAR and camera vision sensors for real-time navigation and obstacle avoidance. The system showed high accuracy in dynamic conditions and required less human interaction. However, the system's reliance on expensive sensors and processing units made the system costly [4]. R. Sharma and Verma developed an IoT smart wheelchair system using GPS and GSM modules for location tracking and emergency notification. The system enabled caregivers to track the user's location from a distance. Although useful for safety monitoring, the system was controlled manually or through mobile app control and lacked AI-based voice interaction capabilities [5]. Rao et al. designed a multi-sensor wheelchair system using ultrasonic and infrared sensors for obstacle detection along with embedded motor control logic. The system improved the user's movement stability and collision avoidance. However, the system lacked the integration of advanced user interfaces like voice control and audio feedback [6]. Ahmed et al. proposed a smart wheelchair system that used text-to-speech feedback to confirm user commands and system status. The paper emphasized the usability improvement for visually impaired users. Although the system had this advantage, it did not have real-time location tracking and emergency response capabilities [7].

3. Methodology

3.1. Components Used and Their Justification:

- **MY1016Z3 24 V, 350 W Brushed DC Motor:** It is a type of high power, brushed, DC motor, designed for driving mechanical systems using electrical power. This motor has been chosen for the reason that they are able to generate enough torque to enable the movement of the wheelchair when under use.
- **350 W Brushed Motor Controller:** An electronic control used to control the speed and/or direction of a DC motor by controlling the voltage and current to the motor. It allows precise control of chair movement and protects the motor from overcurrent and voltage.
- **Lithium-ion Battery Pack (26 V, 22 A / 22.5 A):** A rechargeable energy storage device that supplies high current for a motor. Lithium-ion batteries are used because they provide high energy density, which is lightweight, and can supply continuous power to operate wheelchairs for extended use.
- **Battery Management System (BMS):** An electronic protection system that monitors the parameters of a battery, like voltage, current, and temperature. BMS provides a means for ensuring safety of the battery against overcharge, deep discharge, short circuits, and thermal damage.
- **24 V (29.4 V) 3 A Lithium-Ion Battery Charger:** The power supply pack for safely charging lithium-ion battery packs. Charger allows controlled charging, thus improving the life of batteries and ensuring safety.
- **Raspberry Pi Zero 2 W:** A single-board computer that is compact in size and can run or process advanced tasks in a Linux-based operating system. This is used as a main controller for motor control, battery monitoring, voice command recognition, and multilingual speech processing because it has enough computational capability.
- **Microphone Module:** An electronic input device used to convert sound waves into an electric signal. The device uses a microphone, which allows users to control the wheelchair using their voice commands.
- **Emergency Mushroom Stop Button:** Normally closed switch used for immediate system shutdown in case of emergencies. It offers a reliable physical safety feature to stop a wheelchair immediately, irrespective of the execution state of the software.
- **Arduino Uno:** A microcontroller-based platform used to interface sensors as well as communication modules. Arduino Uno is used specifically to interface the GPS and GSM module, independent of the main control system.
- **GPS Module:** It is satellite positioning that gives information on real-time geographic location. It facilitates the tracking of real-time wheelchair location for safety and emergency considerations.
- **GSM Module:** A wireless communication module which enables data transmission over a cellular network. The GSM module is employed to transmit SMS messages with location information in case of an emergency to the caregiver.
- **Electrical Wiring (1 sq.mm):** Insulated copper conductors, used in power and signal transmission. Proper gauge wiring ensures proper handling of the current, minimized power loss, etc.

3.2. Construction of the Wheelchair System

The construction of the suggested voice-controlled smart wheelchair design follows a modular and systematic approach by incorporating various associated mechanical, electrical, and embedded systems within it. The main aim of the construction process of this smart wheelchair design is to ensure a rigid structure that maintains stability and safety while transporting the user to desired locations through smooth mobility. The structure of the proposed smart wheelchair framework of this design is made of MS 20 mm Class B pipes because of their strength and durability factors. Standard MS elbow and tee are used to ensure a specific shape of the designed wheelchair structure. All the joint points of

a designed structure must be subjected to a welding process so that the structure becomes mechanically rigid. Bearing sockets and flanges are incorporated into the frame at appropriate locations to support rotating shafts and wheel assemblies, reducing friction and permitting smooth motion. Bicycle wheels are fixed in position to act as primary drive wheels due to their availability, capacity to carry loads, and suitability for operation in conjunction with chains. Castor wheels are fixed at the front to ensure balancing and to allow smooth direction changes during wheelchair motion. A chain and sprocket system are employed to mechanically interface the DC motors to the drive wheels, ensuring efficient transmission of torque generated by the DC motors to the wheelchair wheels. The steering mechanism and braking assembly are mounted inside the wheelchair frame, which enables effective and safe steering and stopping of the wheelchair. The brakes are put in place such that effective stopping power is allowed under normal and under emergency conditions. In mechanical systems, connecting rods connect different parts of mechanical systems responsive to mechanical stimuli. The DC brushed motors are properly fixed on the wheelchair frame with appropriate physical fixtures that ensure minimal vibration and misalignment issues. The motors are mechanically linked with the appropriate wheel using the chain and sprocket mechanism. The motor controllers are mounted close to the motors for reduced wire length, reduced losses, and high efficiency during control operations. The lithium-ion battery packs are properly enclosed and mounted in a place that maintains appropriate weight and system balance for the wheelchair. This placement ensures system stability and prevents any section of the wheelchair frame from being overloaded. The embedded control units have been installed separately for maintaining isolation between systems. There is a separate and dedicated installation of the Raspberry Pi Zero 2W, which includes heat sinks for adequate heat management. The Raspberry Pi Zero 2W includes electrical connections with the motor controllers, microphone unit, mushroom stop button, and power supply. There is an independent installation of the Arduino Uno, with electrical

connections made with the GPS and GSM modules. The reasons for keeping both controllers independent of each other and without any connections include increased reliability and ease of isolation between them. All electrical connections are made using fully insulated 1 sq.mm wires made of copper, which enable adequate handling capacity with stable currents. Proper cable routes are followed with adequate rigidity to avoid any physical or electrical damage due to electromagnetic interference. This construction technique provides a compact, stable, and modular structure that enables the wheelchair to be operated independently to test, maintain, and update each system individually. This construction technique ensures a wheelchair that is fully functional, safe, and reliable, as required.

3.3. Working of the Proposed System

The scheme of operation in the proposed voice-controlled smart wheelchair is based on two independent working embedded subsystems: a Raspberry Pi Zero 2 W based mobility and control unit and an Arduino Uno-based communication and tracking unit. Such an independent dual-controller arrangement further enhances system reliability in which the malfunctioning or shutdown of one subsystem does not affect the operation of the other. The integrated system will focus on hands-free wheelchair control, user safety, and emergency communication. After powering the system, the Raspberry Pi Zero 2 initializes the motor control circuits, battery monitoring, voice recognition software, and speech processing modules of various languages. The device is still on a standby mode until a wake word is stored in the module and sent to the microphone to work as a wake word to wake up the device. After the device is activated, the microphone will record the voice command sent by the user, which is processed at the Raspberry Pi module based on various machine learning algorithms for speech recognition technology. After recognizing the speech, the system will change it into text and then perform various control commands, such as going forward, backward, left, right, and stopping, depending on the speech commands processed by the device. As indicated by the identified command, the Raspberry Pi sends the required control signals to the

motor controllers. These signals control the DC motors which, in turn, control the speed and direction of the wheelchair. Moreover, the battery conditions are constantly being monitored to guarantee reliable voltage conditions. In any event of operation, the user can use the mushroom emergency stop button that overrides the control commands and stops the motor operation at all costs to protect the user. Simultaneously, in the background, the communication system based on the Arduino Uno executes independently. In this system, the Arduino is continuously receiving real-time geographic locations from the GPS module in the format of latitude and longitude shown in Figure 1.

scenarios where bandwidth is not high. This independence of mobility and communication subsystems ensures that GPS–GSM system operation is possible in spite of the inactivity of the wheelchair moving system. This method of work improves the overall safety of users. The proposed system offers a good integration of intelligent voice control, safe mechanical systems, and reliable emergency communication systems.

Conclusion

The research proposes a new voice-controlled smart wheelchair system that combines the use of sensor technology and Internet of Things (IoT) functionality to enhance the mobility of wheelchairs for individuals suffering from severe physical disabilities. The system allows users to control the movement of the wheelchair using simple voice commands that include obstacle detection and emergency stop commands, as well as real-time location tracking for caregivers to ensure safe use.

Existing wheelchair systems offer basic voice control and gesture control capabilities but do not offer critical safety functionalities and monitoring. The system offers a single platform that allows users to control the system using voice commands and leverages different sensor-based navigation and tracking systems to improve the system’s usability and functionality. The system demonstrates the possibility of developing an affordable smart wheelchair system that provides safety functionalities and monitoring capabilities to help users accomplish more in their daily activities.

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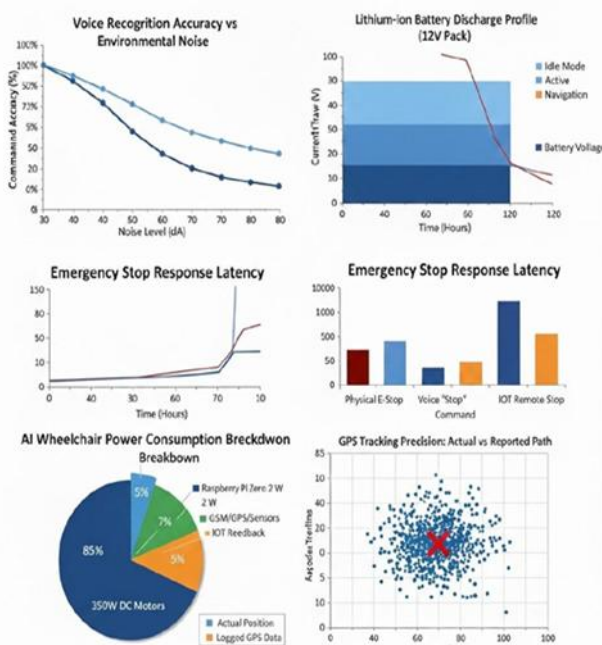


Figure 1 Voice Recognition Accuracy

This processing does not depend on the Raspberry Pi subsystem. In predefined emergency conditions, the Arduino subsystem formats these geographic location data, and communication with the GSM module happens to send SMS alerts to the predefined contact numbers of caregivers or emergencies. In addition, this real-time geographic location data sent in the form of an SMS helps in locating the user at any given point in time. GSM technology is utilized in this subsystem, dedicated to communicating through SMS. GSM technology can be used in

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