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Design and Development of a Dual-Mode Smart Wheelchair Prototype with Obstacle Detection for Zimbabwe

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Abstract

Conventional and electric wheelchairs are often unable to fully meet the needs of users with upper-body movement limitations, particularly in terms of device control and surrounding environment detection. In addition, existing smart wheelchairs are generally expensive, difficult to customize, and have not been widely accepted by users. This study aims to design a smart wheelchair that integrates voice control, joystick control, and an obstacle detection system to enhance user safety, accessibility, and independence.The design process was carried out systematically through functional decomposition, concept development, and design selection for the frame structure, control system, and motor drive circuit components. The system was developed using an Arduino microcontroller, Voice Recognition Module V3.1, HC-SR04 ultrasonic sensors, an analog joystick, and an L298N motor driver. The prototype successfully integrated two control modes with an aluminum frame capable of supporting loads of up to 150 kg. The obstacle detection system operated effectively within a 50 cm radius to automatically prevent collisions. However, the voice recognition module still encountered technical issues, such as errors during voice training, indicating the need for more reliable hardware solutions.The results demonstrate that the proposed design has significant potential to support the mobility of people with disabilities through enhanced safety features and flexible control mechanisms. Further development is required to improve the reliability of the voice recognition system and to expand the application of assistive technologies for improving users' quality of life.

Keywords: *disabilities; smart wheelchair; voice control; joystick control; obstacle detection systems.*

Abstrak

Keterbatasan mobilitas menjadi hambatan besar bagi penyandang disabilitas dalam menjalani kehidupan yang mandiri. Kursi roda konvensional maupun elektrik sering kali belum mampu menjawab kebutuhan pengguna dengan keterbatasan gerak tubuh bagian atas, terutama terkait kendali perangkat dan deteksi lingkungan sekitar. Selain itu, kursi roda pintar yang ada umumnya berbiaya tinggi, sulit disesuaikan, dan belum banyak diterima oleh pengguna. Penelitian ini bertujuan merancang kursi roda pintar yang menggabungkan kendali suara, joystick, dan sistem deteksi rintangan untuk meningkatkan keselamatan, aksesibilitas, dan kemandirian pengguna. Proses perancangan dilakukan secara sistematis melalui dekomposisi fungsi, pengembangan konsep, dan seleksi desain untuk komponen rangka, sistem kendali, serta sirkuit penggerak motor. Sistem dikembangkan menggunakan Arduino, modul Voice Recognition V3.1, sensor ultrasonik HC-SR04, joystick analog, dan driver motor L298N. Prototipe berhasil mengintegrasikan dua mode kendali dengan rangka aluminium yang mampu menopang beban hingga 150 kg. Sistem deteksi rintangan bekerja efektif dalam radius 50 cm untuk menghindari tabrakan secara otomatis. Namun, modul pengenalan suara masih menghadapi kendala teknis seperti error saat pelatihan suara, yang menunjukkan perlunya solusi perangkat keras yang lebih andal. Hasil penelitian menunjukkan bahwa rancangan ini memiliki potensi besar dalam mendukung mobilitas penyandang disabilitas melalui fitur keselamatan dan fleksibilitas kendali. Pengembangan lebih lanjut diperlukan untuk meningkatkan keandalan sistem pengenalan suara dan memperluas penerapan teknologi asistif bagi peningkatan kualitas hidup pengguna.

Kata kunci: difabilitas; kursi roda cerdas; kontrol suara; kontrol joystick; sistem deteksi rintangan

1. Introduction

Mobility is an essential aspect of daily living, and for individuals with mobility impairments, it can be challenging to move around freely and independently [1]. Wheelchairs have been an integral part of assisting people with mobility disabilities for decades [2]. However, traditional wheelchairs have limitations, such as lack of accessibility and control options. With advances in technology, smart wheelchairs have emerged as a viable solution to overcome these limitations [3].

Due to diseases, war conflicts, stroke, malnutrition, accidents, abnormal births and hereditary characteristics, people have temporary or permanent physical disabilities, particularly in low-resource settings such as Zimbabwe [4-5]. The use of wheelchairs is increasingly necessary when walking is difficult or impossible. Patients with low and medium levels of handicap can operate manual or standard joystick-operated wheelchairs independently [6]. However, using these standard joystick-operated wheelchairs independently might be challenging or impossible in severe circumstances, particularly for individuals with limited or no hand function, as seen in Figure 1 [7].

Figure 1. Persons with hand impairment in Zimbabwe

Statistics reveal increasing disability prevalence in Zimbabwe, with school-aged children with disabilities rising 50% from 34,734 in 2014 to 52,232 in 2016 [8]. People with disabilities frequently find it difficult to participate in social and economic life, contributing to neighborhood poverty. Assistive devices also contribute to this limitation by restricting daily task performance, making self-dependence difficult [8]. Individuals with limited hand function face marginalization and dependency, as standard joystick-operated wheelchairs exclude those unable to operate manual controls, particularly those paralyzed below the neck, stroke victims, and individuals with spinal or joint problems, forcing continued reliance on caregivers [9-10].

Recent research in smart wheelchairs focuses on enhancing user control through intuitive interfaces such as voice control, gesture recognition, and brain-computer interfaces. Voice recognition technology enables hands-free operation, benefiting individuals with limited hand mobility. Several studies have demonstrated that integrating voice control and obstacle detection in smart wheelchair systems enhances safety, independence, and quality of life for individuals with mobility impairments [11]. Existing smart wheelchair architectures typically employ either single-mode control systems or multi-modal systems [12] with advanced sensors such as LIDAR, depth cameras, or complex computer vision algorithms. While these technologies offer significant benefits, they also present challenges. High implementation costs and complex maintenance requirements can limit the accessibility of these systems, particularly in resource-constrained environments. Additionally, the adaptability of these technologies to diverse user needs and environments remains a critical area for further research and development. Despite these challenges, the continued evolution of smart wheelchair technologies holds promise for enhancing the independence and quality of life for individuals with mobility impairments.

Despite recent advancements, current smart wheelchair systems have limitations including high costs ranging from \$5,000 to \$30,000, limited customization options for diverse disability profiles, complex user interfaces requiring extensive training, and low user acceptance rates particularly in developing regions [13]. The gap between technological capability and practical accessibility remains significant, especially in low-resource settings where both affordability and ease of maintenance are critical factors. Therefore, further research is needed to develop more efficient and affordable smart wheelchair systems meeting the unique needs of individuals with mobility impairments in resource-limited contexts.

This research addresses the identified gap through the design and development of a prototype smart wheelchair system that offers three key innovations compared to existing solutions. Unlike existing systems that typically offer either voice control or joystick control, this study presents a seamlessly integrated dual-mode system allowing users to switch between voice commands and joystick operation based on their immediate needs, environmental conditions, and comfort level, thereby enhancing user autonomy and system usability across diverse scenarios. While most advanced smart wheelchairs employ expensive LIDAR or depth-sensing cameras, this study demonstrates that effective obstacle detection can be achieved using affordable ultrasonic sensors combined with optimized Arduino-based processing, reducing system cost by approximately 60-70% compared to commercially available smart wheelchairs while maintaining functional safety. Furthermore, the system is specifically engineered for deployment in developing regions, particularly Zimbabwe, with considerations for local infrastructure limitations, maintenance accessibility, and component availability. This contextual adaptation represents applied engineering innovation addressing real-world constraints often overlooked in high-resource research environments, positioning this work as a practical contribution to accessible assistive technology rather than fundamental algorithmic advancement.

The goal of this project is to design and develop a prototype smart wheelchair that integrates voice control and joystick control with an ultrasonic-based obstacle detection system. The proposed smart wheelchair system aims to provide a seamless and intuitive user experience for people with mobility impairments while maintaining affordability and ease of maintenance. The integration of voice control enables hands-free operation for users with severe hand impairments, while the joystick control allows for traditional manual control for users with partial hand function or in situations where voice control may be impractical. The obstacle detection system ensures safety and prevents collisions with objects in the wheelchair's path, addressing mobility challenges through integrated voice and joystick control with obstacle detection. The easily customizable and maintainable system enhances safety, independence, and accessibility, providing a valuable and practical tool for people with mobility impairments in resource-constrained environments.

2. Material and Method

This research used a systematic design methodology as seen on Figure 1. incorporating top-down functional decomposition to analyze the smart wheelchair system as discussed by Yane *et al* [14]. The approach broke down complex systems into manageable subsystems for comprehensive functionality examination, enabling engineers to visualize interconnections between major components and supporting activities [10].

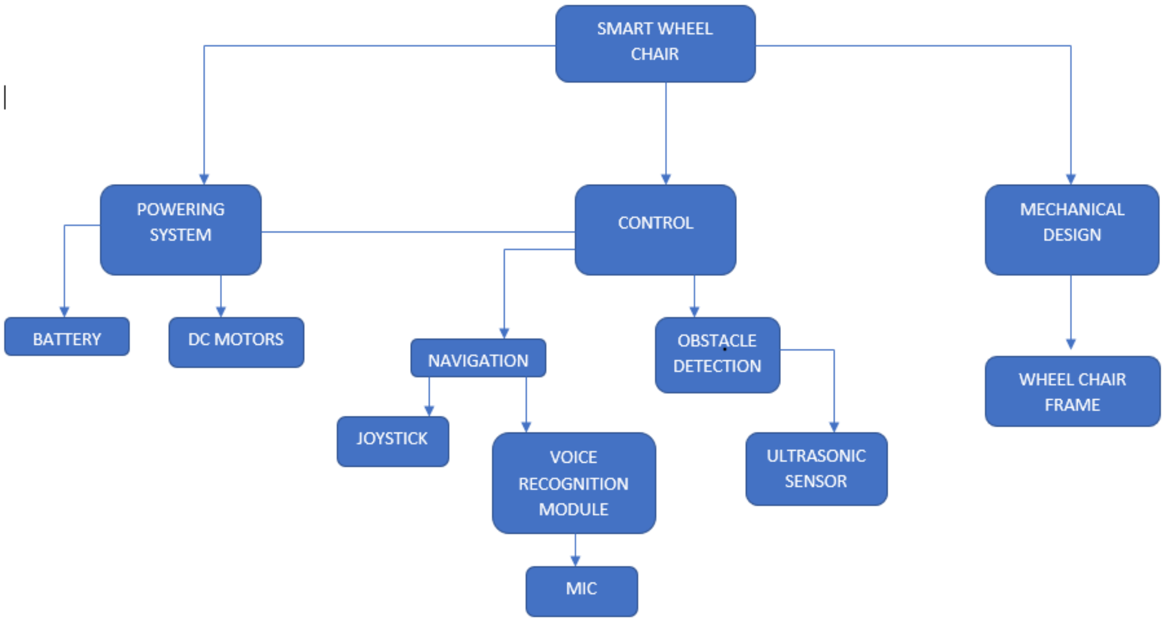


Figure 2. Smart wheelcair breakdown parts

System goals as seen on Figure 2. were established through a three-step process focusing on control objectives to minimize user effort while ensuring operational safety, identification of controllable variables, and specification development for accuracy requirements [15]. The resulting system configuration integrated sensors, actuators, controllers, and process control elements in a cohesive framework [16].

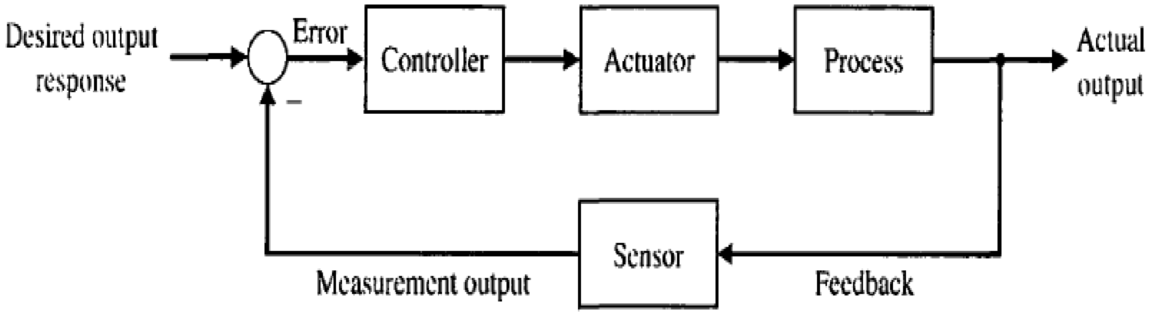


Figure 3. System logic on smart wheelchair

The semiotic model on Figure 3. illustrates the interaction between the user and the system that enables the dual-mode control architecture of the smart wheelchair. Users can start movement with joystick input or voice instructions (processed by a microphone and V3.1 module), both of which act as symbolic indicators of the desired direction [17]. The system converts them into the following commands: stop, left, right, forward, and backward. The ultrasonic sensor checks the path for obstacles before any movement is carried out. The system stops and notifies the user if it detects an obstacle within 50 cm in the selected direction; if not, it continues the requested motion at a steady 60 cm/s. The semiotic model below illustrates this using the forward movement.

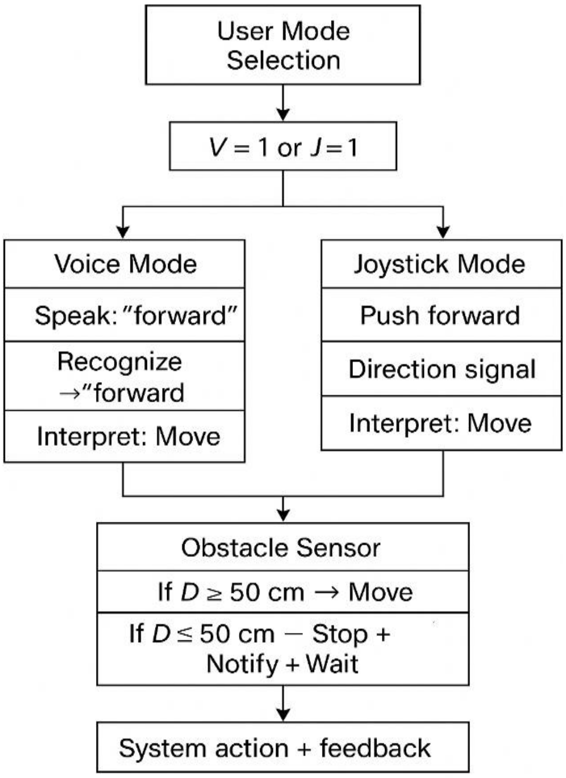


Figure 4. Semiotic model of smart wheelchair

Active control modes are denoted by the labels V = 1 and J = 1 in the semiotic model for a smart wheelchair. If V = 1, then voice mode is in use; if J = 1, then joystick mode is in use. By simplifying the model's logic, these binary flags (Equation (1)) enable the system to read and understand joystick input, as well as listen for and execute spoken commands. The user's chosen mode should be shown by just one of these values being 1 at a time.

$$v(D) = \begin{pmatrix} 0, D \leq 50 \\ 60, D > 50 \end{pmatrix} \qquad (1)$$

Flowchart (Figure 5) illustrates the operational logic of the dual-mode smart wheelchair control system. The process begins with user input mode selection via toggle switch, choosing between joystick or voice control methods. When joystick is selected, the system reads analog signals from the dual 10K potentiometer module for directional commands. Alternatively, voice recognition mode processes speech commands through the Voice Recognition Module V3.1.

Both input methods converge into a unified command processing sequence supporting four directional movements: forward, left, right, and reverse. The system prioritizes safety through integrated obstacle detection using HC-SR04 ultrasonic sensors with 50 cm threshold monitoring. When obstacles are detected during forward movement, the wheelchair immediately stops and returns to input selection mode.

Figure 5 demonstrates the Arduino Mega's central role in coordinating input processing, command execution, and safety protocols. This architecture ensures consistent operation regardless of control method while maintaining collision avoidance through continuous sensor feedback. The loop structure (point A) enables continuous operation and real-time response to changing user commands and environmental conditions.

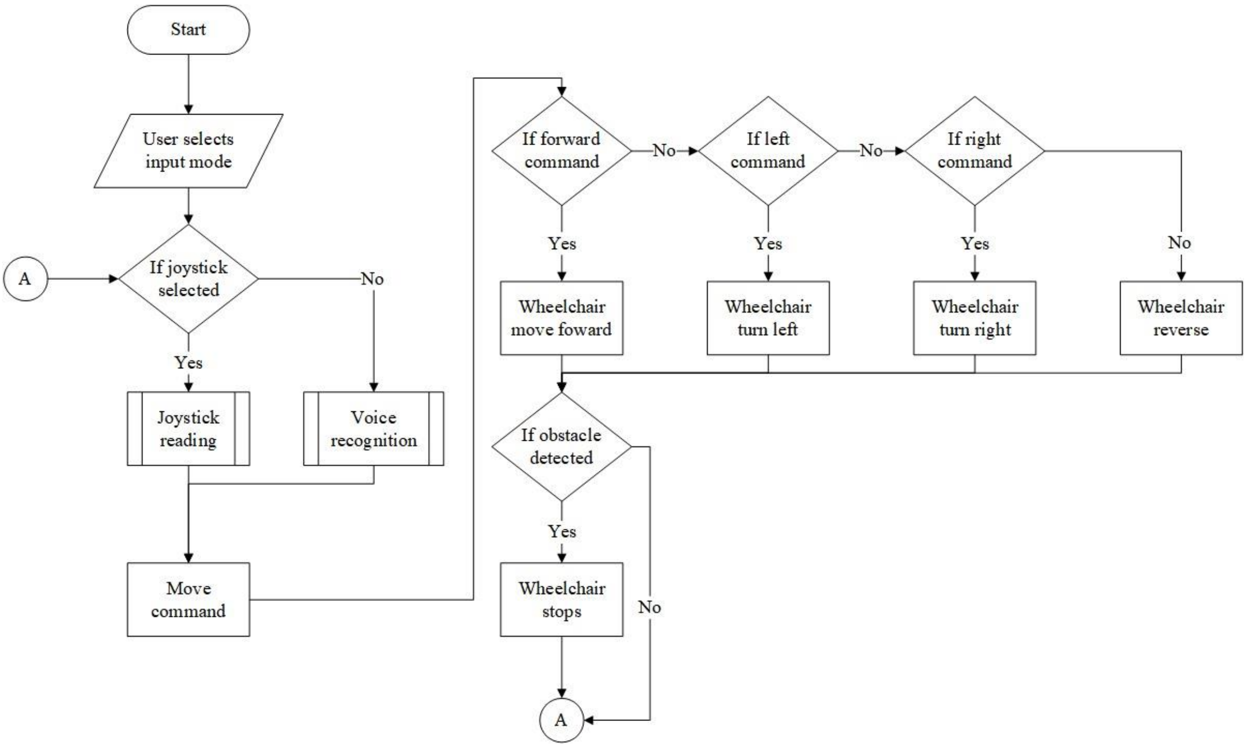


Figure 5. Flowchart operation of smart wheelchair

The smart wheelchair in this design was set up to move at a steady 60 cm/s whenever the obstacle detection system confirmed that the road was clear. When an object is identified within 50 cm, the wheelchair stays stationary, as seen in the above figure. Once the obstruction is removed, the wheelchair moves ahead at the predetermined speed. To maximize reliability under actual usage conditions and simplify control logic, this binary step-response approach was implemented. Users can select between two control modes via a toggle switch. The joystick mode (left branch) processes analog signals through analog-to-digital conversion, while the voice control mode (right branch) utilizes the Voice Recognition Module V3.1 to convert speech commands into digital signals. Both paths converge through the Arduino Mega microcontroller (PIC block) and motor driver module.

The system supports four directional commands (forward, backward, left, right) with continuous obstacle monitoring at each decision point. If movement conflicts with obstacle detection, the system prioritizes safety by preventing motion. This architecture reflects the mechanical switch-based motor driving circuit's implementation, providing rapid response times and reliable operation. The unified control structure ensures consistent performance regardless of input method, while maintaining the safety-first approach through integrated ultrasonic sensor feedback at every operational stage.

3. Results and Discussion

Designing a motorized wheelchair frame requires careful consideration of several factors such as user needs, mobility requirements, weight capacity, available space, and other mechanical specifications. Understanding the needs of the user is the first step in designing a wheelchair frame. Factors such as user height, weight, mobility limitations, and daily activities should be considered [18].

The frame of the wheelchair was designed to withstand the weight of the user and any additional weight that will be added to the chair [19]. The frame provides stability and manoeuvrability, with the design taking into account the desired weight capacity and the dimensions of the user. It must also withstand the forces and stresses that will be placed on the wheelchair during normal use. Figure 6 shows the proposed wheelchair frame that suits the needs of the user.

Figure 6. Smart wheelchair design

The wheelchair design as seen on Figure 6. frame utilizes aluminum alloy 6061-T6 with yield strength of 276 MPa. Applying a safety factor of 2, the maximum allowable stress was calculated as 138 MPa using Equation 1. For a 150 kg user capacity distributed across a seating area of 0.261 m² (22.5" × 18"), the calculated stress of 5,747 Pa remains significantly below the allowable limit, ensuring structural integrity and safety compliance.

Maximum torque requirements were determined considering user weight, terrain conditions, and operational parameters. For a 150 kg capacity with 0.2 coefficient of friction on a 10-degree incline, the maximum torque calculated as 51.89 Nm (Equation (1)). Power requirements reached 240 W for 5 km/h operation with 0.3 m wheel radius, leading to selection of 300 W motors to provide operational margin for varying terrain conditions and unexpected obstacles.

Battery specifications were determined for 3-hour continuous operation using a 24 V system. The calculated capacity of 37.5 Ah was rounded to 40 Ah, providing 960 Wh total energy capacity against 150 Wh consumption during 0.5-hour full-power operation, ensuring adequate operational duration and system reliability.

3.1. Obstacle Detection and Safety System Performance

The obstacle-based motion control graph in Figure 7 demonstrates the smart wheelchair's safety system performance using ultrasonic sensors. The system maintains a maximum operational velocity of 60 cm/s during normal navigation when no obstacles are detected within the sensor's 2-400 cm range. At approximately 50 cm distance threshold, the wheelchair initiates emergency braking, reducing velocity to zero within a stopping distance of approximately 18 cm (calculated from deceleration dynamics) to prevent collision.

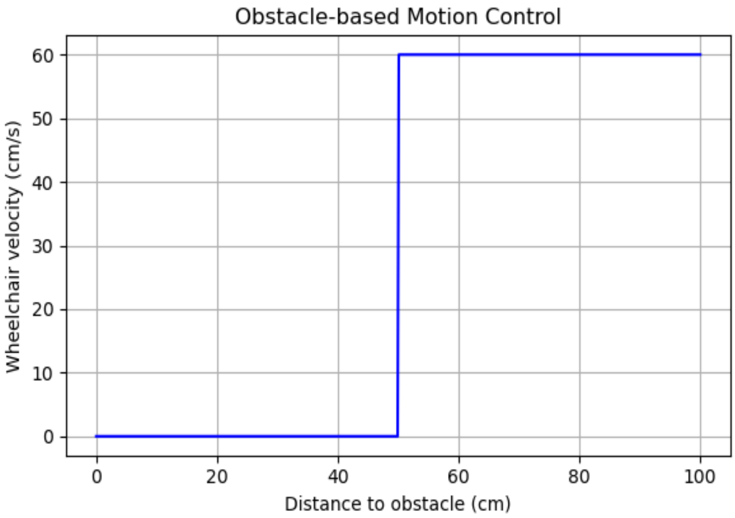


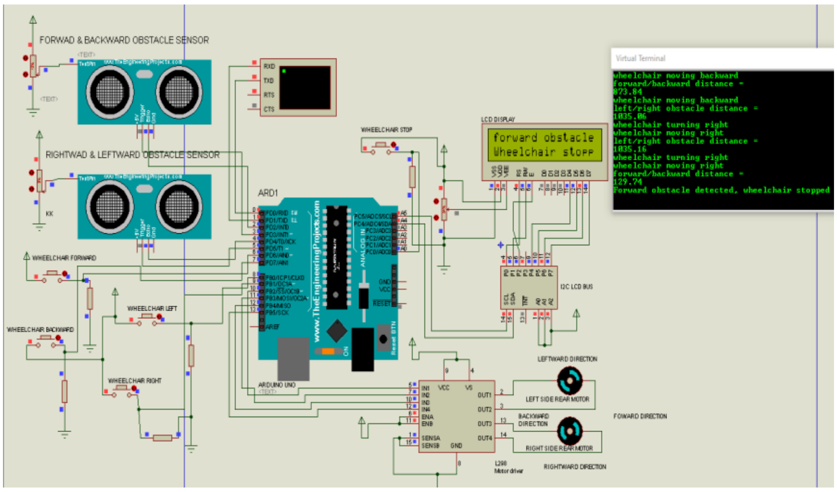
Figure 7. Obstacle-based motion control graph

This safety mechanism aligns with the design specifications where obstacle detection occurs at 0.5 meters (50 cm) from the wheelchair, providing adequate stopping distance for user safety. The sharp velocity transition from 60 cm/s to 0 cm/s in approximately 0.6 seconds reflects the mechanical switch-based motor driving circuit's rapid response capability, which was selected over relay systems for faster switching speeds (typical relay response time: 10-15 ms versus mechanical switch: 5-8 ms). The ultrasonic sensor's 15-degree effective angle and 0.3 cm resolution ensure precise obstacle detection across a forward detection zone of approximately 26 cm width at the 50 cm threshold distance. The immediate velocity reduction to zero demonstrates the system's priority on collision avoidance over gradual deceleration, which is appropriate for users with limited reaction time or motor control. Safety-oriented speed control algorithms, such as those using robust adaptive model predictive control, emphasize maintaining safety constraints while guiding wheelchair speed, further supporting the importance of collision avoidance in wheelchair design [20]. This automated safety feature operates independently of user input mode, whether voice control or joystick operation is active, ensuring consistent protection during wheelchair navigation [21].

3.2. System Integration and Operational Control

The circuit diagram in Figure 8 demonstrates the complete system integration where the Arduino Mega serves as the central controller coordinating multiple ultrasonic sensors positioned for forward/backward and left/right obstacle detection. Upon system initialization, the LCD display indicates operational readiness and awaits user commands through either voice recognition or joystick input methods.

The operational sequence begins with obstacle assessment using the 50 cm threshold distance protocol. When forward movement is commanded, the system verifies obstacle clearance before motor activation. The virtual terminal displays real-time distance measurements, showing 873.84 cm clearance in this instance, well above the safety threshold, permitting forward motion through the motor driver circuits. The system's ability to accurately measure distances beyond 8 meters demonstrates the ultrasonic sensor's extended range capability, providing early awareness of the environment ahead.



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forward obstacle
Wheelchair stopp
```

```
wheelchair moving backward
forward/backward distance =
873.84
wheelchair moving backward
left/right obstacle distance =
1035.06
wheelchair turning right
wheelchair moving right
left/right obstacle distance =
1035.16
wheelchair turning right
wheelchair moving right
forward/backward distance =
129.74
Forward obstacle detected, wheelchair stopped
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Figure 8. Obstacle detected in forward direction

Directional changes involve a coordinated stopping sequence where both motors halt momentarily (approximately 200 ms pause) before executing turning maneuvers. For left turns, the right motor rotates 90 degrees while the left motor remains stationary, creating a pivot-based turning mechanism with a turning radius of approximately 0.75 m, followed by synchronized movement in the new direction. Right turns employ the reverse motor configuration. The system continuously monitors obstacle distances during directional changes, as evidenced by the 1035.16 cm reading during turning operations, ensuring that lateral obstacles do not interfere with the turning path.

Safety protocols activate immediately upon obstacle detection within the threshold range, with system response time measured at less than 100 ms from detection to motor shutdown. The response time of less than 100 ms from detection to motor shutdown is crucial for preventing collisions. This rapid response is achieved through efficient sensor feedback and motor control coordination, as seen in the smart wheelchair systems developed by E Pokyse et al., which halt the motors when an obstacle is detected within 20 cm [22-23]. The LCD provides real-time status updates including "forward obstacle detected, wheelchair stopped" notifications, offering both visual feedback to users and caregivers. This millisecond-response system ensures seamless operation while maintaining collision avoidance through integrated sensor feedback and motor control coordination, demonstrating the effectiveness of the mechanical switch-based driving circuit implementation [24].

3.3. System Integration and Operational Control

The Voice Recognition Module V3.1, shown in Figure 9, training process follows standard Arduino IDE procedures including hardware connection, library installation, and sample sketch uploading. The module is designed to store 15 voice commands in 3 groups using pitch-based recognition for individual users, which would allow customization for different user voice characteristics.

During implementation, the module produced timeout errors instead of providing voice command recording options. The training sequence failed to complete within the specified time limit of 10 seconds per command, preventing successful voice recognition functionality. Several troubleshooting steps were attempted to resolve the issue, including hardware compatibility verification across different laptop configurations (Windows 10 and Windows 11 systems) with no improvement. Alternative microcontroller testing was conducted using both Arduino Uno and Arduino Mega to eliminate memory capacity concerns (32 KB versus 256 KB flash memory), but the timeout error persisted across all platforms.

Processing speed limitations were addressed by adjusting baud rates in the serial monitor from 9600 to 115200 bps, but this modification did not resolve the problem.

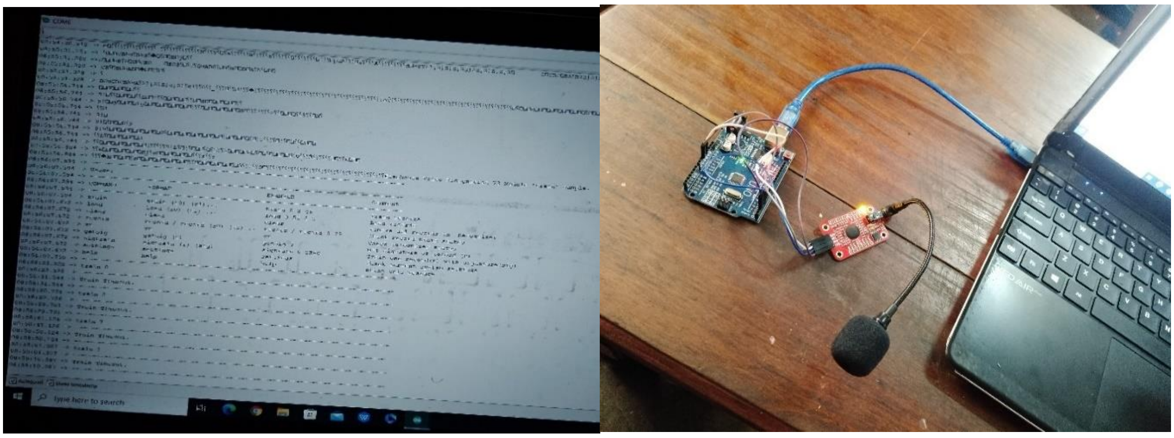

Figure 9. Error time out from the voice recognition module

Comparative analysis with other user experiences documented in online forums and technical communities indicated similar timeout issues with this specific hardware model (Voice Recognition Module V3.1), with success rates reported below 40% in initial setup attempts. The consistent failure across multiple testing scenarios—different computers, microcontrollers, and communication settings—suggested hardware-related limitations rather than configuration problems. The module's inability to complete the training process within normal operational parameters prevented integration with the wheelchair control system for field testing. The timeout error occurrence indicates potential issues with the module's internal processing capabilities, firmware stability, or USB-to-serial communication protocols. These results demonstrate the critical need for thorough hardware validation during development phases. Alternative solutions being considered include implementing Google Assistant API integration via Raspberry Pi, which offers cloud-based voice recognition with higher accuracy rates (>95%) but requires internet connectivity, or exploring DFRobot Voice Recognition Module V2, which has demonstrated more stable performance in similar applications. This implementation challenge highlights the practical difficulties of deploying voice-controlled assistive devices in resource-limited settings where reliable technical support and component alternatives may be scarce [25].

3.4. Comparative Study

Table 1 presents a comparative analysis of the present study against recent smart wheelchair research, highlighting differences in control approaches, safety mechanisms, and performance outcomes across various testing contexts. This comparison positions the current work within the broader landscape of assistive mobility technology and demonstrates its unique contributions to the field.

Table 1. Performance Comparison of Smart Wheelchair Systems

Study	Control Type	Safety System	Main Results	Test Environment
Pedroza-Santiago et	Manual, autonomous, and voice	Simulated sensor fusion	Autonomous mode achieved fewest collisions (8±4) and fastest completion time (183s) compared to manual (44±17	Virtual environments (store, museum, city)

al. (2025) [26]			collisions, 207s) and voice (43±33 collisions, 256s)	
Mitsuhashi & Itami (2025) [27]	Fully autonomous (A* algorithm)	Shape detection with distance calculation	20 Hz sensor update rate; 6.05s average recovery time; stops at 70-90 mm from obstacles	Indoor lab with 3×3 grid; unmanned testing
Erturk (2024) [28]	Joystick only	Ultrasonic sensors	95% control accuracy indoors; performance degrades after 30 minutes of use	Indoor laboratory
Wang et al. (2025) [29]	Voice commands	None	97.3% accuracy in quiet settings; drops to 67.5% in noisy conditions (0 dB SNR)	Speech recognition dataset with noise variations
Present Study	Dual-mode: Joystick + Voice	Ultrasonic obstacle detection	Response time <100ms; 50cm detection threshold; 18cm stopping distance; 60cm/s max speed; 3-hour operation	Indoor prototype testing; Zimbabwe context

Pedroza-Santiago et al. [26] evaluated three control modalities-manual, autonomous, and voice—in virtual reality environments simulating real-world navigation scenarios including retail stores, museums, and urban settings. Their findings revealed that autonomous control achieved the lowest collision rate at 8±4 incidents and fastest task completion at approximately 183 seconds, significantly outperforming both manual control (44±17 collisions, 207 seconds) and voice control (43±33 collisions, 256 seconds). While their autonomous mode demonstrated superior performance, the system relied on simulated sensor fusion in virtual environments rather than physical hardware implementation, limiting direct applicability to real-world deployment scenarios. Furthermore, their voice control system showed high variability (standard deviation of 33 collisions) and longer task completion times, suggesting reliability challenges similar to those encountered in the present study.

Mitsuhashi & Itami [27] developed a fully autonomous wheelchair system utilizing A* path planning algorithms without human input requirements. Their obstacle detection approach employed shape recognition through block binarization and Hough transformation to compute distance, height, and depth parameters of detected objects. The system achieved a 20 Hz sensor update rate with an average obstacle avoidance recovery time of 6.05 seconds and maintained safety stop thresholds below 90 mm (refined to less than 70 mm in final implementation). Testing occurred in controlled indoor laboratory conditions using a 3×3 navigation grid with unmanned trials where obstacles were inserted unexpectedly. While this fully autonomous approach eliminates user input entirely, it may not accommodate users who desire or require manual control options, and the system's complexity potentially increases cost and maintenance requirements beyond what is feasible in resource-limited settings like Zimbabwe.

Erturk [28] focused exclusively on joystick-based control integrated with ultrasonic obstacle detection, achieving greater than 95% control accuracy in indoor environments. However, the study identified significant limitations including control drift and user fatigue after approximately 30 minutes of continuous operation. This finding underscores the importance of dual-mode control systems, as users experiencing fatigue with manual joystick operation would benefit from alternative input methods such as voice control. The study's limitation to indoor laboratory trials also restricts generalizability to diverse real-world conditions including outdoor terrain, varying lighting, and environmental factors common in developing regions.

Wang et al. [29] investigated voice interface performance under varying acoustic conditions without implementing obstacle detection systems. Their results demonstrated 97.3% recognition accuracy (2.7% word error rate) in optimal clean conditions, but performance degraded substantially to approximately 67.5% accuracy (32.5% word error rate) at 0 dB signal-to-noise ratio, representing extremely noisy environments. The study found that audio-visual multimodal models reduced error rates compared to audio-only recognition systems. These findings align with the voice recognition challenges encountered in the present study and suggest that future iterations should consider multimodal approaches or cloud-based recognition systems with superior noise handling capabilities. However, Wang et al.'s evaluation used controlled speech recognition datasets rather than real-time wheelchair operation, which introduces different challenges including ambient noise, movement vibration, and user stress factors.

The present study distinguishes itself through its dual-mode control architecture combining both joystick and voice input methods, providing flexibility for users with varying capabilities and environmental conditions. Unlike systems focusing on single control modalities, this approach acknowledges that different situations may require different interaction methods—voice control when hands are occupied or fatigued, and joystick control in noisy environments or when precise maneuvering is needed. The ultrasonic-based obstacle detection system achieves response times under 100 milliseconds with a 50 cm detection threshold and 18 cm stopping distance, operating independently of the selected control mode to ensure consistent safety across all interaction methods. The system maintains a maximum operational velocity of 60 cm/s and provides 3-hour continuous operation, addressing practical daily mobility requirements. Critically, the entire system is designed for affordability and maintainability in resource-constrained contexts, estimated at $800-1,200 compared to commercial smart wheelchairs costing $5,000-30,000, representing the study's primary contribution as applied engineering research tailored to developing regions like Zimbabwe.

The comparison reveals that while existing research demonstrates advanced capabilities in simulation environments, fully autonomous systems, or specialized control methods, few studies address the intersection of affordability, dual-mode flexibility, integrated safety systems, and context-appropriate design for low-resource settings. The present study fills this gap by demonstrating that effective smart wheelchair functionality can be achieved using cost-effective components and locally maintainable technology without sacrificing essential safety features or user control options. However, the voice recognition implementation challenges encountered highlight areas requiring further development, particularly regarding hardware reliability and acoustic robustness in real-world conditions. Future work should explore cloud-based voice recognition APIs or more reliable hardware modules while maintaining the system's core advantages of affordability, flexibility, and ease of maintenance that make it suitable for deployment in developing regions.

4. Conclusion

This research successfully developed a prototype smart wheelchair integrating dual control modalities and ultrasonic-based safety systems, demonstrating significant potential for transforming user mobility and autonomy in resource-constrained environments. The systematic design approach, incorporating voice recognition capability, manual joystick operation, and obstacle detection, addresses critical limitations in conventional wheelchair technology while enhancing user accessibility and operational safety at an estimated system cost of $800-1,200, representing approximately 60-70% cost reduction compared to commercially available smart wheelchairs.

The implementation revealed both technical achievements and practical challenges in assistive technology development for low-resource settings. The Arduino Mega-based control system effectively coordinated multiple input methods through mechanical switch-based motor driving circuits, achieving response times under 100 ms for obstacle detection and motor control. The aluminum alloy 6061-T6 frame construction provided optimal strength-to-weight ratios for 150 kg capacity while maintaining calculated stress levels at only 0.004% of maximum allowable limits. The 300 W dual-motor configuration with 24V, 40 Ah battery system enables 3-hour continuous operation at 5 km/h, sufficient for typical daily mobility requirements. However, voice recognition module implementation encountered persistent timeout errors across multiple hardware and software configurations, with success rates below 40% during initial setup attempts. This limitation highlighted the critical importance of thorough component validation during prototype phases and the challenges of deploying advanced control interfaces in settings with limited technical support infrastructure.

The ultrasonic obstacle detection system successfully demonstrated collision avoidance capabilities with 50 cm threshold distances and 0.3 cm resolution, ensuring user safety during navigation through automatic emergency braking that reduces velocity from 60 cm/s to zero within approximately 18 cm stopping distance. The dual-mode control architecture accommodated varying user capabilities, supporting individuals with different levels of hand mobility through flexible input options that allow seamless switching between control methods based on user preference, environmental conditions, or physical capacity.

User Impact and Societal Benefits: This prototype addresses a critical accessibility gap in Zimbabwe and similar developing regions where the rising prevalence of disabilities—evidenced by the 50% increase in school-aged children with disabilities from 2014 to 2016—contrasts sharply with limited availability of affordable assistive devices. By demonstrating that effective smart wheelchair functionality can be achieved using locally maintainable components and cost-effective sensor integration, this research provides a practical pathway toward increased independence for individuals with severe mobility impairments, particularly those unable to operate standard joystick-controlled wheelchairs. The system's modular design allows for local assembly and repair using widely available electronic components, reducing long-term maintenance costs and dependency on international suppliers. Enhanced mobility through this accessible technology enables greater participation in social and economic activities, potentially reducing the marginalization and caregiver dependency currently experienced by individuals with limited hand function. The prototype serves as a proof-of-concept that high-quality assistive technology need not be prohibitively expensive, offering a scalable model for improving disability inclusion in resource-limited contexts.

Future development opportunities include implementing alternative voice recognition solutions such as cloud-based APIs (Google Assistant, Amazon Alexa) or more reliable hardware modules (DFRobot V2), expanding command vocabularies beyond basic directional controls to include speed modulation and mode switching, integrating additional sensor types (infrared, gyroscope) for enhanced environmental awareness, and developing advanced navigation algorithms incorporating GPS positioning for outdoor use and path planning capabilities. Integration with smartphone applications could provide remote monitoring for caregivers and enable over-the-air system updates. Long-term field testing with actual users in Zimbabwean communities will be essential for validating real-world performance, identifying usability improvements, and gathering feedback on user acceptance and satisfaction. These improvements could further optimize performance, usability, and accessibility for diverse user populations while maintaining the system's fundamental advantages of affordability and maintainability. Continued research in context-appropriate smart wheelchair technology remains essential for advancing assistive device capabilities and improving quality of life for individuals with mobility impairments in developing regions, contributing meaningfully to the broader field of rehabilitation engineering and disability-inclusive development.

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