



Design and Implementation of a Smart IoT-Based Wheelchair System: A Novel Approach to Assistive Technology for Mobility and Health Monitoring

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Abstract: Technology is being developed in different fields to reduce the human effort where systems are getting smart and autonomous. Different autonomous systems can perform tasks more accurately and efficiently than humans, reducing human interaction with the machine. Patients and disabled persons typically use wheelchairs, which are common but important objects. In a traditional wheelchair, human effort is required to operate. In some cases, patients are unable to manually operate the wheelchair by moving the wheel, necessitating additional support or assistance to push from the backside. Technologies are being used to make wheelchairs smart and autonomous now, where any external assistance is not required anymore. In this work, a framework for IoT-based smart wheelchairs has been proposed, where multifunctional designs with advanced operating features have been developed. The wheelchair can be controlled with hand gestures, where the user can operate the chair by moving hand position. Smart features like obstacle detection, GPS, fall detection, home appliance control, IoT-integrated features like

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IoT, and a remote alert system have been installed. The device can detect any obstacle and can move automatically to avoid it. GPS location helps to figure out the current location of the wheelchair. The user can control or operate the home appliance, like turning the light or fan on/off remotely from the wheelchair. IoT applications help to take the user's health data and send it to healthcare for a checkup. In case of any urgency, the wheelchair can communicate with the emergency contact to acknowledge the status of the user. The proposed device can serve as an effective solution, providing a seamless experience with smart operating features and multiple advanced functionalities.

Keywords: Wheelchair, IoT, Gesture control, Arduino, Embedded system, Smart mobility.

1. Introduction

With advances in technology, maintaining a good quality of life for people with impairments that affect their mobility has become much easier (Sahoo et al., 2023). According to the World Health Organization (WHO), about 75 million people worldwide rely on a wheelchair for daily mobility, and globally an estimated 1% of the population, or 1 in 100 people, uses a wheelchair at some point in their life (Fung et al., 2020; Ferreira et al., 2021). Their everyday lives are, in many cases, fraught with challenges related to independence, safety, and accessibility (Fu et al., 2013). At the forefront of this progress are smart wheelchairs that provide greater independence, mobility, and safety for users (Mahdin et al., 2022). By reducing the physical burden associated with an ordinary wheelchair, a smart wheelchair can significantly improve health and well-being, maintain better postural alignment, and enhance mobility (Li et al., 2023). Improved overall physical health can be achieved for people with varying levels of mobility impairments by reducing overexertion and avoiding secondary health complications associated with limited physical mobility, such as pressure ulcers and joint stiffness, when accessible, user-friendly control options are available (Zhang et al., 2022). The objective of this project is to develop a wheelchair instrumented with an Android app, enabling user flexibility and autonomy through gestures or app use across numerous settings. This enables gesture control, using sensors in a glove to provide a natural interface for those who are unable to use their hands or have a limited range of motion.

Safety is another key factor that makes smart wheelchairs particularly beneficial (Favey et al., 2021). Many wheelchair users are at higher risk of accidents due to

obstacles, uneven surfaces, or poor lighting (Zhang et al., 2024). The smart wheelchair has been designed to incorporate an ultrasonic sensor that detects objects at 30 cm to prioritize the user's safety. If an obstacle is detected, the system triggers a buzzer and automatically reverses the wheelchair to avoid a collision. This obstacle detection and avoidance system is essential, as it helps prevent accidents, particularly in dynamic environments such as public areas or crowded spaces. Furthermore, the system interfaces a light-dependent resistor (LDR) sensor to monitor lighting conditions. To support safer navigation in poorly lit environments, the sensor activates automatic lighting when ambient light is low. The research objectives are: (1) An extensive literature review has been conducted, in which related works in the same field have been studied thoroughly to identify the current strengths and limitations of state-of-the-art techniques. (2) A novel framework for a smart wheelchair has been proposed, featuring smart, innovative features and functionalities. (3) The framework has been developed with a versatile design, allowing a single device to be used for multiple applications. The aim is to develop a multifunctional smart wheelchair capable of meeting users' mobility, safety, and well-being needs, ensuring overall usability and satisfaction. The wheelchair incorporates remote control, gesture recognition, automatic obstacle avoidance, and adaptive lighting, providing a significant advancement over standard assistive mobility devices. The proposed framework incorporates IoT features, enabling remote access to healthcare services. This is expected to lead to a better understanding of how smart mobility solutions can enhance the quality of life for people with mobility impairments in the future.

Section 2 conducts a literature review, thoroughly reviewing existing works to assess the current state of development and its limitations. Section 3 presents the proposed methodology, including the terms and techniques used in its development. Section 4 presents the results of the evaluation of the developed prototype's performance. Section 5 concludes the discussion. A list of references has been added at the end to support the work.

2. Review of Literature

Many researchers have developed smart wheelchairs, each contributing new control systems and features designed for people with disabilities (see Table 1). A gaze-tracking control system using eye movements and auditory feedback for smart home automation is introduced by Vidyasagar et al. (2023) to control household appliances via the eyes and ears. Rao et al. (2022) also designed an EEG-based wheelchair using a non-invasive brain-computer interface implant to translate brain signals into movement directives via MATLAB and Arduino. Suganyadevi et al. (2023) have focused on introducing additional wheelchair features, including automatic mobility, bed-to-chair conversion, and an emergency alert system, for COPD patients. To analyze wheelchair maneuver patterns, Fu et al. (2013) used mobile cloud computing to collect and process real-time data from smartphones equipped with accelerometers and gyroscopes. Kaur et al. (2023) designed a biometric-authentication-powered gesture-detection system to enhance mobility safety. Udaya et al. (2022) designed an IoT system that enables wheelchair operation via eye-movement control. Wani et al. (2023) designed an automatic speed controller that enables free wheelchair movement. The researchers verified the correctness of both the math-based model and the MATLAB model simulation. To facilitate independent living for the elderly, sensors for monitoring vital signs have been integrated into a digital wheelchair by Dar et al. (2023), which transmit data to healthcare providers.

Kengale et al. (2021) designed a smart wheelchair with advanced navigation and perception capabilities to minimize the need for human assistance. To support safety, Mahdin et al. (2022) used deep learning for object detection and collision avoidance via GPS tracking. To improve patient safety through data collection and transmission, Khattak et al. (2023) proposed a multi-tiered communication system. A voice- and keypad-controlled wheelchair was presented by Pandiayan et al. (2022) that makes it

easy to interact with and to monitor health indicators. Kuppa et al. (2022) developed an accessible customized wheelchair controlled via the Android app and a joystick to increase user independence.

A gesture-controlled system for those with limited mobility was adopted by Niranjana et al. (2022), based in part on a microcontroller for real-time processing of hand gestures. MEMS sensors enabled hand-gesture control, along with an Android app, which Darshini et al. (2022) added to their system. For instance, Hou et al. (2021) integrated AI into their wheelchair design for comprehensive health monitoring, while Utaminingrum et al. (2022) achieved 87% accuracy in road-surface recognition using image data.

Later, Nguyen et al. (2013) presented a TIM wheelchair system equipped with advanced visual technology to improve perception of dimension and direction (depth perception). Ahmed et al. (2021) developed a smart wheelchair with fingertip and gesture control, as well as a heart-rate monitor for emergency alerts. Rockey et al. (2013) analyzed inexpensive sensors for use with mobility aids and identified their usefulness in wheelchair systems. Basak et al. (2021) developed a hands-free smart wheelchair that uses gestures to send emergency alerts. This versatile wheelchair system, which includes home control via joystick, voice, or gesture, was proposed by Nijhum et al. (2023) and implemented using an Android application. Additionally, Alam et al. (2022) developed an advanced health monitoring system employing various sensors to enhance patient safety, and Giri et al. (2023) investigated vital sign monitoring using IoT technology. Ngo et al. (2021) implemented a semi-automatic control system based on EEG signals and a graphical user interface to improve mobility for disabled individuals. A smart wheelchair with voice control was developed by Iskanderani et al. (2021), featuring a visual user interface for movement control. Intuitive wheelchair navigation was done by Gayathri et al. (2022) using eye-blink sensors, while Amin et al. (2021) developed an Android-based system for active wheelchair engagement. Sreevatsav et al. (2023) proposed an affordable smart wheelchair with IoT features for safe navigation across different terrains. Kim et al. (2022) investigated autonomous robotic wheeled chairs for smart hospitals, equipped with sensors for obstacle detection and data transmission. Collectively, these studies demonstrate innovations to further improve wheelchair functionality and user autonomy, as well as to enhance wheelchair safety. Table 1 summarizes the review works.

Table 1 Review summary of the existing related works.

Authors	Proposed Technique	Findings/ Benefits	Limitations	User Interaction	Safety Features	Control Method	Target Users	Sensors Used	Cost
Vidyasagar et al. (2023).	Gaze tracking-based smart home automation for wheelchair users	Allows control of smart home appliances using eye tracking and sound output	Requires constant gaze tracking, which may be tiring for users	Eye-tracking interface	No collision detection	Gaze tracking and sound commands	General wheelchair users	Eye-tracking sensor	Moderate
Rao et al. (2022).	EEG-based wheelchair with non-invasive brain-computer interface (BCI)	Enables wheelchair control through brain signals, offering independence for severely disabled individuals	High cost, requires extensive training and precision	Brain-controlled movement via EEG	No obstacle detection	EEG signal control	Individuals with severe physical impairments	EEG sensor	High
Adevi et al. (2023).	Smart wheelchair for COPD patients with oxygen tank holders and multiple features	Provides automated mobility, emergency alerts, and medical support for COPD patients	Designed for a specific group (COPD patients), limited general applications	User control with emergency sound alerts	No specific collision detection	Automatic movement, convertible bed feature	COPD patients	Buzzer Sensor	High
Fu et al. (2013).	Mobile cloud computing to analyze wheelchair maneuver patterns	Real-time data collection and analysis of wheelchair movements via smartphones	Dependent on internet connection for cloud-based data storage and analysis	Smartphone interface for user input	No collision detection	Smartphone-based data collection and processing	General wheelchair users	Accelerometer, gyroscope	Moderate
Kaur et al. (2023).	Biometric-powered hand gesture detection system for wheelchair mobility	Secure and efficient hand gesture-based wheelchair control with biometric authentication	Complex biometric verification setup and potential false positives	Hand gesture control with biometric authentication	No obstacle detection	Hand gesture control system	General wheelchair users	Fingerprint scanner, hand gesture sensors	High
Rani et al. (2022).	Gesture-controlled and eyeball-based wheelchair system	Hands-free wheelchair control using ocular movement, allowing easier mobility for handicapped patients	Complex setup, depends on accurate image processing	Eye-tracking interface	No obstacle detection	Ocular movement detection	Handicapped individuals	Eye-tracking sensor	High

Table 1 Review summary of the existing related works.

Authors	Proposed Technique	Findings/ Benefits	Limitations	User Interaction	Safety Features	Control Method	Target Users	Sensors Used	Cost
Wani et al. (2023).	Intelligent controller for smart wheelchair motion control	Improved speed control of the wheelchair through intelligent algorithms	Requires sophisticated mathematical modeling	Joystick and controller interface	No specific obstacle detection	Controller-based speed and motion control	General wheelchair users	Motion controller sensors	Moderate
Dar et al. (2023).	IoT-powered wheelchair for elderly healthcare monitoring	Allows independent mobility with real-time health monitoring	Requires stable internet connection for data transmission	Voice control and real-time healthcare monitoring	No obstacle detection	Voice control system	Elderly patients and healthcare monitoring	Heart rate, blood pressure, lung function sensors	High
Khattak et al. (2023).	Wheelchair with Thread protocol for boosting patient safety	Smooth data sharing between wheelchair and healthcare providers	Requires a complex communication system	Seamless data transmission between wheelchair and healthcare network	No specific obstacle detection feature	Thread-based communication control	Patients in healthcare environments	Communication modules	High
Ahmed et al. (2021).	Effective wheelchair with gesture and fingertip control	Provides a user-friendly control system with real-time medical condition monitoring	Limited accuracy in gesture and fingertip control	User-friendly interface, real-time health monitoring	No obstacle detection	Fingertip and gesture control system	General wheelchair users	Heart rate sensor, fingertip sensors	Moderate
Niranjana et al. (2022).	Gesture-controlled smart wheelchair with PIC microcontroller	Facilitates wheelchair movement using simple hand gestures	Limited gesture recognition accuracy	Hand gesture interface	No obstacle detection	Gesture recognition via PIC microcontroller	People with limited mobility	Hand gesture sensors	Moderate

3. Methodology

3.1 Embedded System and IoT

An embedded system is a combination of software and hardware designed to perform specific tasks. Generally, there are three primary components to develop a basic embedded device: sensors, microcontrollers, and actuators. The sensor receives an environmental signal and sends it to the microcontroller. The microcontroller, which is considered the heart of the embedded system, receives the signal from the sensors and processes it according to predefined logics. The microcontroller processes the signal and then sends it to the actuators for output. Figure 1 shows the basic architecture of an embedded device.

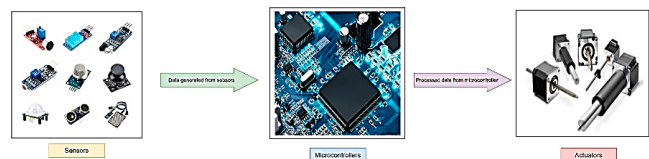


Figure 1. Basic workflow of an embedded system.

IoT is a computing concept in which each device is treated as a node interconnected with other devices through the internet. As of today, IoT is being used across different fields where autonomous devices are operated remotely, and human interaction is becoming less common. In many cases, there is no need for human interaction. Medical

applications widely utilize IoMT (the Internet of Medical Things) to access remote medical services. Patients do not need to go to the hospital for a medical checkup, where health data can be sent to the physician automatically, and the required advice/treatments can be received remotely. This work employs an IoMT application that attaches a pulse oximeter sensor to the wheelchair. The sensor will continuously monitor the user's pulse rate and oxygen level. If the sensor detects any abnormality, it will notify the concerned parties and transmit the medical data to the healthcare services.

3.2 Hardware and Software

- **Arduino:** A microcontroller platform that is open-source and used to build electronic projects based on the computer code that is uploaded to it. It can read inputs and operate outputs.
- **Bluetooth Module:** A short-range wireless device that enables a microcontroller and a computer or smartphone to communicate wirelessly over the Bluetooth protocol. Common modules include HC-05 and HC-06.
- **Ultrasound Sensor:** This module sends out ultrasonic waves and then measures the period of time it takes for their echo to return so that it can determine the distance. Frequently used for detecting objects and avoiding obstacles.
- **LED (Light Emitting Diode):** A tiny thing with two legs, which emits light when current flows through it. It produces light. This LED is applied as an identifier or for illuminating on specific regions of a project.
- **Brushed Motor:** A brush-making electric motor that runs on direct current. It is simple, reliable, and widely used in applications requiring rotating motion.
- **Gyroscope Sensor and MPU6050 Accelerometer:** A sensor unit detects direction changes, acceleration, and angular velocity by combining three-axis accelerometer and three-axis gyroscope components. It operates perfectly for robots together with other motion-sensing applications.
- **ESP8266:** The Wi-Fi module provides internet connectivity for Arduino microcontrollers and their family of microcontrollers. The module provides wireless network connectivity to support Internet of Things (IoT) applications.
- **Heart Rate Sensor and MAX30100 Pulse Oximeter:** A device that contains blood oxygen sensors, which analyze oxygen absorption to measure heart rate with simultaneous blood oxygen level determination (SpO₂).
- **GPS (Global Positioning System):** The module provides location information through signals obtained from space-based satellites. This technology supports the functioning of tracking and navigation applications.
- **Rechargeable 12V Battery:** This energy storage device can be recharged multiple times while maintaining energy within its storage capacity. Portable and mobile electronic projects frequently use this power technology as their power source.
- **Buzzer:** A little audio device that emits sound when electricity is supplied. It is utilized in a variety of projects for notifications, alerts, and alarms.
- **LDR Sensor (Light Dependent Resistor):** A light-sensitive component whose resistance decreases with increasing light intensity. It is used in light-sensing applications like automatic lighting control systems.

Table 2 shows the component details used in the framework; Figure 2 shows the characteristics and quantities of the components. Arduino IDE 1.8.5 was installed on the PC. After designing the logic through code, both Arduino boards have been programmed by uploading the code. The Arduino Bluetooth control app (version: 1.4.5) was installed and connected with the device to control it remotely.

Table 2. List of components with quantities.

Components	Type/feature/model	Unit
Arduino	Uno	1
Arduino	Mega	1
Bluetooth module	HC-05	2
Ultrasonic Sensor	HCSR-04	1
LED	RGB	2
Brushless Motor	12v DC	1
Accelerometer and gyroscope	MPU6050	2
WIFI module	ESP8266	1
Pulse oximeter	MAX30100	1
GPS module	NEO6M	1
Rechargeable Battery	9-12v and 25v L-ion	2
Motor driver	L298N H-bridge	1

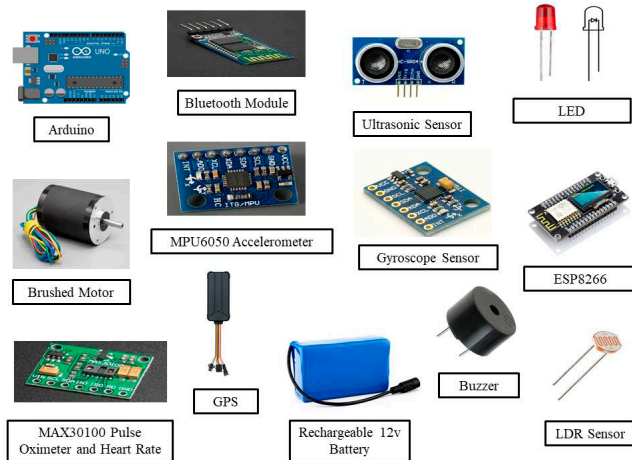


Figure 2. Components used in the proposed framework.

3.3 Optimal Placement of the Gesture Control Module.

For the smart wheelchair to function effectively, the gesture control module must be positioned optimally to ensure accurate detection, seamless communication, and quick execution of movement commands. To assess its real-world performance, the module was physically integrated into the wheelchair, and its response time was evaluated under different conditions. The gesture control module, comprising the MPU6050 accelerometer and gyroscope along with the HC-05 Bluetooth module, was strategically positioned to maximize accuracy and minimize interference. After multiple placement trials, the armrest was identified as the best location. This placement allows users to make natural hand movements without excessive strain while ensuring that the sensor captures gestures precisely. Additionally, the Arduino microcontroller, which processed the gestures, was hidden beneath the armrest to minimize the system footprint. The L298N H-Bridge motor driver, installed close to the wheel, helped reduce signal transmission delays and enhance motor response times.

Placing the sensor on both the lap and the wrist was evaluated as an alternative location, but it yielded inadequate results. These placement positions frequently allowed accidental movements that led to erroneous gesture detection. The sensor on the armrest provided stability, enabling reliable input recognition without discomfort for users.

3.4 Power Requirements for the Smart Wheelchair

The power system remains a fundamental element of an IoT-based smart wheelchair because it affects

performance quality, as well as reliability and usability. The 12V LiPo (Lithium Polymer) battery serves as the power source for the microcontrollers, along with sensors, a motor driver, and communication modules in the prototype. Testing the operation's validity is achievable with this battery, but the system requires a more powerful, higher-capacity battery for real-world use to deliver consistent results across different operating conditions.

The system components require specific electrical power levels for operation. Two main controllers from the Arduino Uno and Mega regulate wheelchair functions using 5V power that draws between 50–70mA at a time. Power consumption for these wireless communication modules (Bluetooth HC-05 and Wi-Fi ESP8266) ranges from 30 mA to 200 mA, depending on the data transmission load and operating voltage (3.3V to 5V). Both parts, namely the HCSR-04 ultrasonic sensor and the MPU6050 sensor, which utilizes accelerometer and gyroscope functionality, obtain power from 5V and draw 15 mA and 3.6 mA, respectively. The GPS module (NEO6M) and pulse oximeter (MAX30100) also operate at 3.3V–5V, with power consumption of 50 mA and 600–800 μ A, respectively. The most power-demanding component is the 12V DC brushless motor, which requires 3A to 5A, depending on terrain and load. Additionally, the L298N H-Bridge motor driver dissipates 2–3W, while LED indicators contribute an additional 20 mA per color channel at 5V. Although the 12V LiPo battery is effective for prototyping, a higher-capacity power source would be more suitable for real-world implementation. A 24V or 36V Li-ion battery pack with a 10Ah–20Ah capacity would provide longer runtime, reduce the need for recharging, and support higher power demands. To improve power management, integrating a Battery Management System (BMS) can help regulate energy distribution, prevent overcharging, and extend battery lifespan. Additionally, a DC-DC converter can be used to efficiently step down the voltage to 5V and 3.3V for low-power components, ensuring minimal energy waste. For even greater efficiency and sustainability, solar charging modules could be explored as an alternative or supplementary power source, increasing the wheelchair's mobility range.

While the 12V LiPo battery works well for the prototype, real-world deployment would benefit from a higher-capacity 24V–36V Li-ion battery pack, combined with a smart power management system to enhance efficiency, reliability, and long-term usability. By optimizing energy consumption and incorporating advanced power solutions, the smart wheelchair can provide a seamless and uninterrupted experience for users.

3.5 Working Functionalities

Two Arduino boards (1 Uno, 1 Mega) have been used as the system's main microcontrollers. The Arduino Mega has been used in the main device, and the Arduino has been used in the gesture controller.

Figure 3 shows the connection diagram of the main device, where the Arduino Mega serves as the system's heart, and other components are connected to it. Arduino and other components get power from a 25V battery. A power adapter has been used to properly distribute power to the Arduino and motor driver. The connected components get power from the Arduino itself.

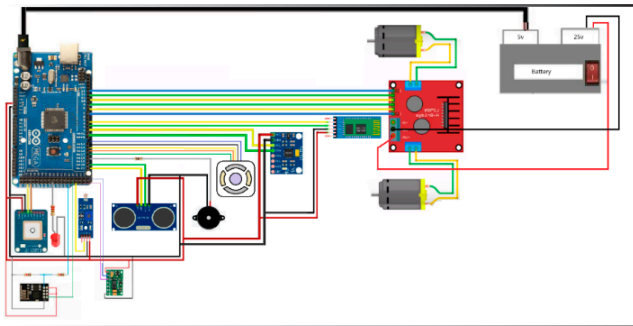


Figure 3. Connection diagram of the proposed wheelchair framework.

Figure 4 shows the connection diagram for the gesture controller, in which sensors and other components are connected to the Arduino UNO. The controller establishes a connection with the main device through the Bluetooth module. The attached gyroscope sensor measures the x-, y-, and z-axis values and sends the signals to the main device to move accordingly.

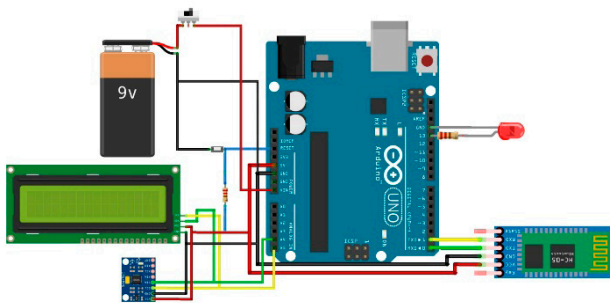


Figure 4. Connection diagram of the gesture controller module.

Figure 5 shows the workflow diagram of the proposed system, in which the flow of actions for the main device (wheelchair) is shown. The installed control panel allows manual wheelchair control, while the gesture controller enables remote control. The microcontroller receives the signal from the controller, processes it, and generates an output to move the motors. The main microcontroller (Arduino) connects to the input devices/components to receive the signal. The figure depicts the defined logic and conditions that generate the output.

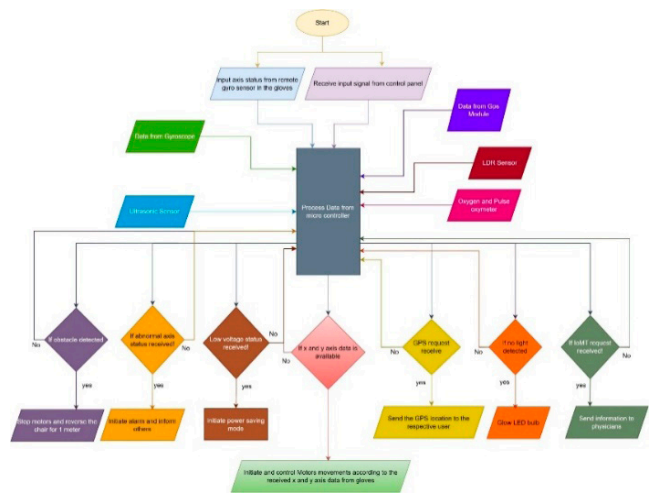


Figure 5. Workflow diagram of the proposed framework.

3.6 Designed algorithms

Algorithm 1: Arduino-based motor control system with multiple functionalities

Start

1. DECLARE pins for LDR sensor, LED, motors, ultrasonic sensor, buzzer, and Bluetooth communication
2. DECLARE speed variables for left and right motors
3. INITIALIZE Bluetooth communication and serial monitor
4. SETUP pin modes for inputs and outputs
5. FUNCTION setup():
 - 6. Configure motor pins as OUTPUT
 - 7. Configure the LDR sensor, the ultrasonic sensor, and the buzzer as INPUT/OUTPUT
8. Start Serial and Bluetooth communication

```

9.      Call the STOP() function to ensure motors are
        off at the beginning
10.     FUNCTION loop():
11.         IF Bluetooth data is available:
12.             Read LDR sensor state
13.             IF LDR detects light:
14.                 Turn LED ON
15.             ELSE:
16.                 Turn LED OFF
17.         Measure distance using ultrasonic
        sensor:
18.             Trigger pulse for ultrasonic
        sensor
19.             Read the echo response
20.             Calculate distance from
        duration
21.             IF distance ≤ 30 cm:
22.                 STOP motors
23.                 Activate the buzzer in
        an alert pattern
24.         Resume movement after alerts
        Read Bluetooth command:
25.             IF 'F' received:
26.                 Call FORWARD()
        function
27.             IF 'B' received:
28.                 Call BACKWARD()
        function
29.             IF 'L' received:
30.                 Call LEFT() function
31.             IF 'R' received:
32.                 Call RIGHT() function
33.             IF 'S' received:
34.                 Call STOP() function
35.         FUNCTION FORWARD():
36.             Set motor speeds
37.             Move motors forward
38.         FUNCTION BACKWARD():
39.             Set motor speeds
40.             Move the motors backward
41.         FUNCTION LEFT():
42.             Set motor speeds
43.             Rotate vehicle left
44.         FUNCTION RIGHT():

```

```

46.             Set motor speeds
47.             Rotate vehicle right
48.         FUNCTION STOP():
49.             Stop all motors

```

END

Algorithm 2: Gesture-based transmitter with 3-axis gyroscope sensor.

Start

```

1.  FUNCTION setup():
2.      Initialize MPU6050 sensor
3.      Start Serial communication at a 9600 baud
    rate
4.      Start Bluetooth communication at 38400
    baud rate
5.  FUNCTION loop():
6.      READ motion data from MPU6050 (ax, ay, az,
    gx, gy, gz)
7.      SET data[0] = map(ax, -17000, 17000, 300, 400)
    // X-axis for forward/backward
8.      SET data[1] = map(ay, -17000, 17000, 100, 200)
    // Y-axis for left/right
9.      PRINT data[0] to Serial Monitor
10.     PRINT data[1] to Serial Monitor
11.     IF data[0] > 380:
12.         SEND 'F' via Bluetooth // Move
        Forward
13.     ELSE IF data[0] < 340:
14.         SEND 'B' via Bluetooth // Move
        Backward
15.     IF data[1] > 180:
16.         SEND 'R' via Bluetooth // Turn Right
17.     ELSE IF data[1] < 110:
18.         SEND 'L' via Bluetooth // Turn Left
19.     IF data[0] BETWEEN 330 & 360, data[1]
        BETWEEN 130 & 160:
20.         SEND 'S' via Bluetooth // Stop Movement

```

END

Algorithm 1 shows the program structure of the Arduino-based motor control system for the proposed smart wheelchair, where Algorithm 2 shows the pseudocode for the MPU6050-based transmitter system.

The Arduino-based motor control system takes these commands and translates them into real-world motion. After initializing the motor driver pins, Bluetooth module,

and Serial communication, the Arduino continuously listens for incoming signals. If it receives a Forward ('F') command, both motors move forward; a Backward ('B') command makes them reverse. For turns, the system adjusts the speed of individual motors, allowing the robot to pivot left or right. When a Stop ('S') command arrives, all movement ceases. This seamless interaction enables real-time wireless motor control, making it ideal for gesture-controlled robots, assistive devices, and smart automation systems. Together, the transmitter and receiver create a natural, hands-free way to navigate and control robotic systems, making technology more interactive, accessible, and user-friendly.

Through the MPU6050-based transmitter system, users control robotic devices using basic hand gestures due to the accelerometer and gyroscope sensors. At the beginning of the operation, the system initializes the MPU6050 sensor, along with the Bluetooth module and Serial communication features. During operation, the system tracks tilts in both the X and Y directions continuously. The device sends a Forward (F) command when users tilt it forward, and it produces a Backward ('B') command following device backward tilting. A left or right tilt produces respective Left ('L') and Right ('R') protocol signals. A Stop ('S') signal prevents accidental movement from the device when it remains fixed in its neutral position. These commands are then transmitted wirelessly via Bluetooth, allowing a robot to be controlled simply by tilting a handheld device. This technology has exciting applications in gesture-controlled wheelchairs, robotic arms, and smart home automation, offering a more intuitive and accessible way to interact with machines.

Figure 6 illustrates the extended capabilities of IoT, enabling a wheelchair to connect to remote devices via the internet. IoT applications make it more effective and convenient for patients, allowing remote medical services to be received. The user's health data is sent over the internet to the respective healthcare server, and respective responses can be received accordingly. The device's live location can be tracked at any time from anywhere. Smart devices can control a wheelchair from any location via the internet. For emergencies, a remote communication feature is available, allowing one to communicate with the user, control the device, and obtain the user's alert status.

4. Results and Discussions

This section deals with the performance evaluation, experimental status, results, and analysis. The proposed

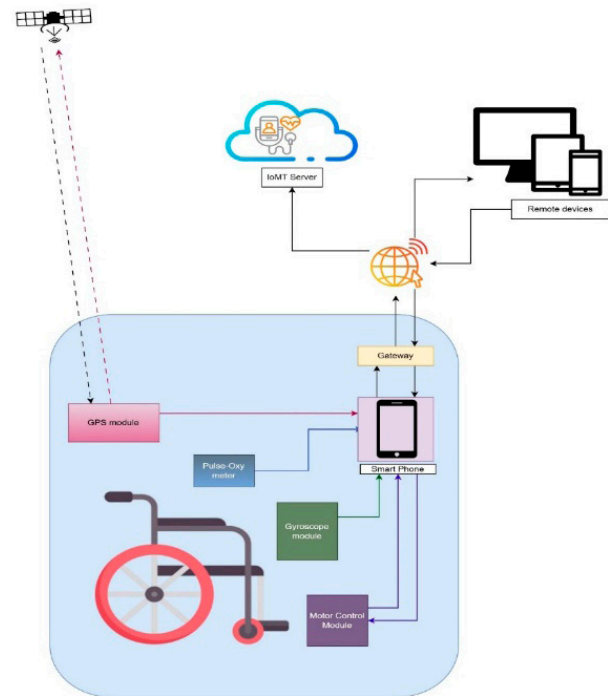


Figure 6. IoT-integrated functionalities of the proposed framework.

framework has been developed as a prototype to support the concept; the prototype has been designed using the terms and techniques mentioned in the methodology section. The prototype model has been tested through multiple trials to assess its strengths and limitations and has been modified accordingly.

4.1 Designed algorithms

The performance of the wheelchair and gesture controller has been measured separately; Table 3 shows the performance evaluation of the main device (wheelchair), and Table 4 shows the performance of the gesture controller.

The efficiency of a gesture-controlled smart wheelchair largely depends on how quickly it responds to user commands. Figure 7 provides an overview of the gesture control module's response time across movement directions—Forward, Top, Down, and Stop—over multiple trials. For the experiment, 100 runs were conducted per direction, and the response duration was plotted on the x-axis, with the y-axis spanning from 1 to 2.5 seconds.

The variables in the scatter plot show minimal variation, sustaining a steady rate range. The system maintains a consistent command registration process while avoiding unnecessary delays, indicating reliable operational behavior. The system speed measurements demonstrate

Table 3. Performance evaluation of the main module.

Input 1	Input 2	Results	Response Delay	No. of Trials	No. Of accurately Recognized Command	Number of accurately received command in Noisy Environment	Avg. Accuracy (%)	
Zero	One		Ri-ght	100 ms	100	88	82	85
One	Zero		Left	100 ms	100	89	81	85
One	One		Forwa-rd	100 ms	100	87	84	85.5
Zero	Zero		St-op	-	100	88	86	87

Table 4. Evaluation status of the gesture control module.

Results	Response Delay	No. of Trials	No. of accurately generated Command	Avg. Accuracy (%)
Right	80ms	100	88	85
Left	80ms	100	89	85
Forward	80ms	100	87	85.5
Stop		100	88	87

an execution time of no longer than 2.5 seconds, regardless of circumstances, indicating sufficient speed for practical wheelchair applications. Research outcomes demonstrate consistent performance of the gesture control system, positioning it as an effective control method for smart wheelchair users. Every system keeps space available for enhancement. Improving the gesture recognition code and sensor precision will decrease operational delay variations, so the system operates even more efficiently. AI-based predictive algorithms could be developed in the future to improve the response consistency according to these findings.

The results demonstrate that the developed smart wheelchair exhibits excellent responsiveness and efficiency for user-friendly operation. The system demonstrates potential to advance into a modern assistive technology solution that enhances the experience of people with mobility limitations.

4.2 Response Time Analysis of the Hardware Module Under Varying Conditions

The IoT-based smart wheelchair depends on the hardware module’s response time to deliver smooth, efficient operation. Microcontrollers with sensors, along with

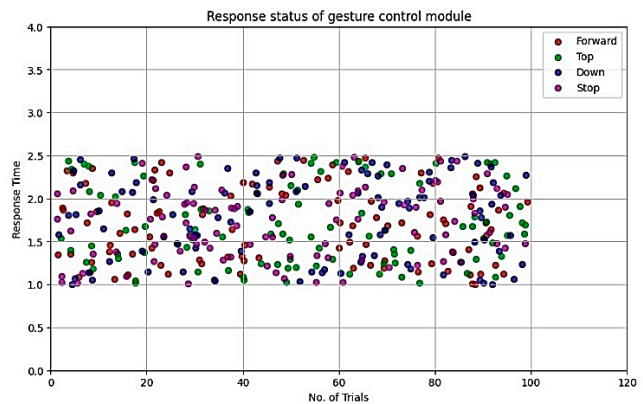


Figure 7. Response status for different gesture movements.

communication modules and motor drivers, execute user commands to move the wheelchair. Response times of the system shift depending on terrain types, along with obstacles, in addition to the connectivity status. This part shows the hardware’s behavior across different scenarios and highlights areas that require optimization.

Several factors determine the speed at which a wheelchair reacts to contact from users and changes in its environment:

Data processing and execution in the wheelchair function are managed by the Arduino Uno and Mega microcontrollers. The wheelchair takes longer to respond as the number of concurrent tasks processed increases.

The data transmission work of the wheelchair depends on both Bluetooth (HC-05) and Wi-Fi (ESP8266) modules as communication channels. The wheelchair experiences delays when executing commands because interference creates weak signal transmission problems.

The MPU6050 (accelerometer and gyroscope) together with MAX30100 (pulse oximeter) and HCSR-04 (ultrasonic

sensor) are significant elements that determine gesture detection and obstacle identification. The wheelchair responds less quickly when sensor data delivery shows any delay.

The L298N H-bridge driver controls the wheelchair's 12V DC brushless motor to power its movements. The wheelchair will slightly delay its response time when power supply from Li-ion batteries (9-12V and 25V) experiences fluctuations or when going over different types of terrain.

Performance testing of the wheelchair took place throughout various environments for practical evaluation:

Laboratory assessments on flat indoor surfaces demonstrated excellent quality of operation for this wheelchair. The wheelchair executed gesture commands efficiently, responding within 1.0 to 2.5 seconds.

The MPU6050 sensor required additional stabilization time and created delay in the response period when navigating across uneven terrain that included grass or gravel paths or outdoor paths. The wheelchair exhibited small adjustments in responses each time it changed surfaces during movement.

Obstacles required the system to take more time between detection and processing movements for avoiding them. The HCSR-04 ultrasonic sensor served as a vital detection tool but the system needed extra time for movement path recalculation due to this function.

Bluetooth and Wi-Fi devices near each other caused occasional delays in wireless signal transmissions in the testing area. Occasional wireless signal interferences caused delays in the speed of gesture command processing.

The system requires the implementation of following improvements to enhance its responsiveness:

Precision sensor readings become more dependable through the application of correct calibration procedures together with noise reduction techniques. Enhancements in power management and optimization of motor powers and microcontroller supplies help decrease execution delays of movements. The wheelchair system able to modify its response through adaptive control algorithms which depends on the detected terrain conditions.

From AI models and predictive obstacle detection systems the system becomes able to identify obstacles beforehand thus creating early adjustments to lessen sudden delays.

Physical tests of response time show that the hardware subsystem maintains high speed performance in

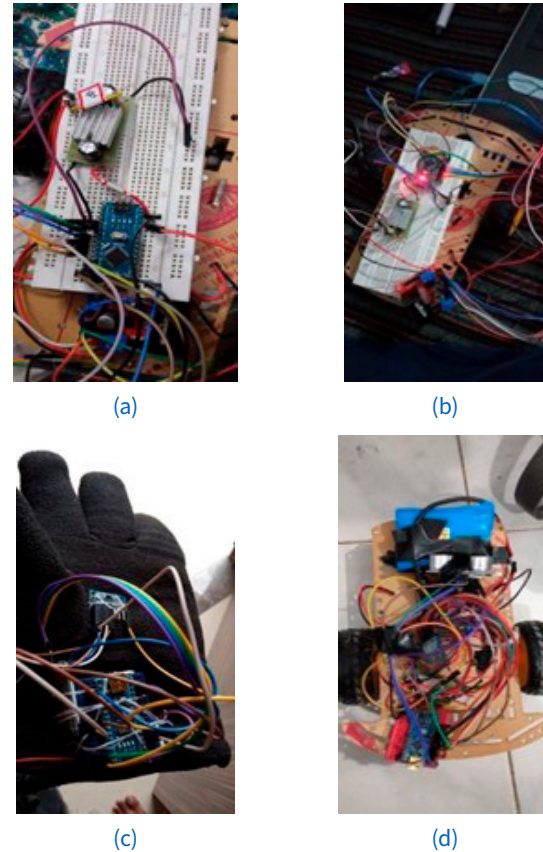


Figure 8. Development phase of the prototype model: (a) Component installation; (b) Connection and programming; (c) Gesture control gloves development; (d) Main module testing.

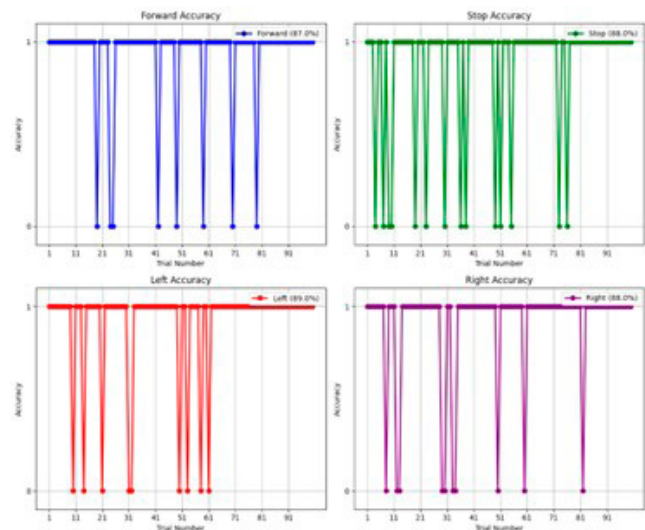


Figure 9. Accuracy status for different direction command.

all relevant operational environments. The system operates proficiently in smooth indoor spaces but terrain conditions and obstacles together with wireless interference result in slight fluctuations in response times. By implementing AI-driven optimizations, improved sensor calibration, and adaptive control strategies, the system can become even more responsive, providing users with a smoother and more intuitive wheelchair experience.

The prototype model has been carefully developed, tested, and modified, with a systematic procedure followed during the implementation and testing phases. Figure 8 shows the development-to-testing phase.

The component installation phase involves finalizing and installing the required components. The next phase is related to connection and programming, where the connection of each component with the microcontroller was established, and programming was done and uploaded to the microcontroller. The gesture control module was designed to wirelessly control the main module via gestures. In the final phase of development, testing was done to check the output of each component.

Figure 9 shows the accuracy of the left, right, forward, and stop commands; the accuracy for each direction is shown separately, along with the number of trials. It can be observed that the proposed device performed well for each direction.

5. Conclusion

In conclusion, the smart wheelchair represents a major advancement in assistive technology, with meaningful improvements in the quality of life for people with mobility barriers. The integration of two control systems—an Android app and gesture recognition—achieves a high level of flexibility and autonomy. This innovation enables people with varying mobility levels to use a wheelchair independently, making them more confident and freer in their daily lives. The wheelchair has other safety features, such as ultrasonic sensors for obstacle detection and automatic lighting provided by the LDR sensor. These technologies improve navigation in crowded and low-light conditions, providing users with a secure and reliable experience. Smart wheelchairs not only relieve physical strain but also prevent problems associated with limited mobility, such as pressure sores or injuries from collisions. On a global scale, smart wheelchair technology has the potential to make a big difference to global accessibility. In regions without common mobility solutions, these innovations can provide access to millions of

people who need it, thereby overcoming barriers to social or economic inclusion. Furthermore, these technologies give users greater freedom than a wheelchair, thereby alleviating carer burden and allowing wheelchair users to engage more fully in educational, professional, and social activities.

Conflict of interest

The authors have no conflict of interest to declare.

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