Design and Implementation of Low-Cost Hybrid-Controlled Smart Wheelchair Based on PID Control Integrated with Vital Signs Monitoring

M. Sayed[1], MG Mousa[2], Ali A. S.[3], and T. Mansour[4]
Mechanical Engineering Department, Suez Canal University, Ismailia, Egypt[1, 3, 4]
Mechanical Engineering Department, Damietta University, Damietta, Egypt[2]
Maintenance Department, Methode Electronics, Cairo, Egypt[1]

***Abstract*—According to international organizations' statistics, the percentage of disabled people is considered not just a small percentage of the world's population. Improving the quality of life for people by using new technologies is one of the essential topics today. Although the wheelchair is the most common way of mobility for the disabled, this research aims to improve wheelchair use by creating other control methods, including speech recognition commands. A joystick, wireless remote control, and an additional port are available in addition to speech recognition commands to control the wheelchair. Researchers also studied and compared the effects of integrating a Proportional–Integral–Derivative (PID) controller with the normal controller during smart wheelchair operation in various normal usage scenarios. This research provides data based on a real experiment, not like most research that depends on mathematical models only for comparison. Adding the PID controller eliminated the overshoot of the smart wheelchair, reduced steady-state error, and reduced settling time. Furthermore, it contains a healthcare monitoring system to track the user's vital signs and object avoidance sensors to keep them safe. Also, a full motor selection calculation for the smart wheelchair has been provided, which is useful for mobile robot design. Additionally, the smart wheelchair features a power monitoring system. Finally, a voice-controlled wheelchair helps the user feel more private and independent. Using this kind of smart wheelchair and living this lifestyle will increase the user's morale.**

Keywords—Smart wheelchair; speech recognition; PID; healthcare; mobile robot

I. Introduction

The global population is experiencing rapid growth. The prevalence of physical disability is increasing due to ageing, accidents, and medical conditions such as quadriplegia and paralysis [1, 2]. Japanese demographic forecasts indicate that the percentage of adults aged 65 and above will attain 40% by 2050 [3]. Individuals may lose a limb or both legs due to sickness or accidents, resulting in incapacitation and dependence on others for daily necessities. They are unable to fulfill their responsibilities independently [2]. Contemporary civilization is characterized by individuals who are predominantly focused on their own lives, with an emphasis on competence and self-sufficiency. Individuals reliant on others are hardly discussed in this rapid era of materialism and modernization. In our society, it is hardly contemplated the requirements of individuals who are dependent. If all individuals could lead their lives autonomously, the world would be an exceptional place to inhabit [4].

Mobility impairment is a prevalent form of functional disability that hinders an individual's capacity for movement, frequently necessitating the use of walkers or wheelchairs. World Health Organization (WHO) research revealed that 75 million individuals experience mobility issues and necessitate the use of a wheelchair. Although wheelchairs enable individuals with limited mobility to navigate freely, users frequently experience degeneration, discomfort, or ulceration owing to extended usage and the physical characteristics of their surroundings [5]. New technology is introduced to the marketplace daily. The primary objective of technology is to simplify human life and reduce reliance on others [2]. Powered Wheelchairs (PWs) can accommodate the needs of individuals with mobility impairments [4].

The issue of population ageing escalates the need for healthcare services for the elderly and disabled, especially in nursing facilities or domestic settings [6]. The evaluation of a patient's condition is often conducted through observation and interpretation by qualified medical personnel. From a scientific research perspective, it is crucial to address the issues impacting the physical state of wheelchair users, providing technology and creative solutions to healthcare providers to optimize their treatments. Consequently, it is essential to augment conventional techniques with more objective and quantitative evaluation approaches, such as posture monitoring [5].

Individuals with cognitive, motor, and sensory impairments need Powered Wheelchair (PW) for mobility, whether because of disability or illness [7]. Additionally, several individuals suffer from motor paralysis that necessitates prolonged bed rest due to conditions such as Amyotrophic Lateral Sclerosis (ALS) or Spinal Cord Injury (SCI) [8]. They progressively diminish in muscle strength and often encounter difficulties in reaching and grabbing, rendering the driving device, such as a joystick, challenging to operate [9].

A Smart Wheelchair (SW) typically consists of either a standard PW base integrated with a computer and many sensors or a mobile robot base equipped with a seat [7]. Besides joystick control, many methods of controlling a PW employ entirely distinct interfaces [10]. The electrical impulses generated by our bodies enable connections to several applications in Human-

Machine Interface (HMI) and rehabilitation. Moreover, cognitive functions have been implemented to enhance their capabilities, rendering them beneficial for the daily lives of individuals with impairments [11]. One of the most challenging elements of developing a non-manual HMI for wheelchair operation is generating sufficient instructions that encompass left and right turns, forward and backward movements, acceleration, deceleration, and stopping [12].

Speech Recognition (SR) has been intensively explored since the 1950s, but recent improvements in computer and telecommunications technology have substantially improved its capabilities [13]. SR solves problems, enhances productivity, and changes the way we live. Voice control accomplishes almost all of the functionality of a pushbutton. An SR is a demanding undertaking since it involves a lot of procedures that need significant computational resources. The wide range of applications of automated SR systems, such as in Human–Computer Interactions (HCIs), telephony, and robotics, has powered a large scientific community during the last few decades. Automatic speech recognition is currently used in a wide range of goods and applications, including medical transcription, gaming control, contact center conversation systems, and information retrieval [14].

A SR technique is a computer tool that can analyse a human vocal signal and detect the information contained in it, translate it to text, or send orders that act on an action, in this case, turning the device on and off. To get a correct interpretation of the acquired auditory message, data from several sources of knowledge, such as syntactic, phonetic, pragmatic, lexical, acoustic, phonological, and semantic information, must be analyzed. With the introduction of Artificial Intelligence (AI) and intelligent assistants, the popularity and use of SRs have expanded. Recognizing the speaker can help to translate talk into systems that have been trained to recognize a specific person's voice, or it can be applied to authenticate or confirm a speaker's identification as part of a safety protocol [15].

People suffered the loss of their arms or legs, whether temporarily or permanently, due to illness or an accident [2]. But since speech is the most natural means of communication, you may also use your voice to drive the wheelchair. It is evident that a wheelchair with SR is necessary to assist individuals with physical limitations who struggle to control their movements, particularly when using their hands independently [16].

The current number of PW users is estimated to constitute just about fifty percent of the potential user base. The number would increase if technology were available to enable anyone unable to operate a joystick or switch array to reliably and safely control a PW [17]. As the older population expands, the need for autonomous and intelligent healthcare services is escalating [18].

II. Related Work

Vaishali Jabade implemented a control system for the PW by using the technology of voice recognition through Google Assistant, which was integrated with a monitoring system for the user's health. Vaishali used Bluetooth as a type of communication to send the voice commands from the mobile to the controller of the PW. Direct wired communication is the recommended method for sending voice commands to the controller of the PW, as it offers greater safety [19].

SATYAVIR SINGH implemented a PW controlled by voice commands and integrated with a collision avoidance system based on an ultrasonic sensor. SATYAVIR used Bluetooth communication to send the voice commands to the controller, which increased the possibility of missing some commands. while using wired communications enhances user safety [20].

Jenina R. Amoguis modified a manual wheelchair to become a PW controlled by SR integrated with an ultrasonic sensor to increase the safety of the user while using the PW. Jenina R. Amoguis did not add any joysticks to the PW. Since adding a joystick to the PW that is controlled by any other controlling method increases the number of users of the PW [21].

Fida Hussain uses voice commands and a joystick to operate a PW, which makes it user-friendly for individuals with disabilities, including those who are deaf and equipped with ultrasonic sensors. She used the normal relay module to control the motors of the PW, and then she had a fixed speed all the time. While using driving boards for motors allows for changing the speed of the motor if required [22].

Mohammad Shahrul developed an intelligent PW controlled by speech recognition using convolutional neural networks to identify the required commands for operating the PW. He did not consider any kind of safety in his model, like, for example, when there is any obstacle in front of the PW. Integrating any proximity sensors that stop the PW if there is an obstacle increases the safety and satisfaction levels of the user [23].

Arsha designed a real PW, controlled by the commands from the voice recognition module integrated with ultrasonic sensors to avoid any accidents during the operation of the PW. M. S. Arsha used the standard relay board to operate the motors of the system. The recommended method for driving the motors of the PW is to use a motor driving board, as this allows the user to adjust the speed of the motors [24].

Divya Jennifer DSouza developed a smart-sensing wheelchair to monitor heart rate and blood oxygen levels and trigger an alarm system if the user's signals are not good. Divya Jennifer DSouza used a photoplethysmography sensor to monitor the heart rate. Unlike an electrocardiogram sensor, the photoplethysmography sensor does not provide an accurate heart rate reading [25].

Shailu studied using different algorithms for improving the speed regulation of an electric wheelchair as an application of the mobile robot. Shailu optimized the PID controller gains using firefly, genetic, particle swarm, and gray wolf algorithms and compared the results [26].

Sankardoss developed an economical implementation of a directional and speed controller for an electric wheelchair. He conducted a comparison using three different types of controllers: the intelligent neural network, fuzzy logic, and PID. His trials were based on improving the overshoot and settling time [27].

Rawiphon Chotikunnan applied a PID control system on a Mecanum wheelchair to regulate the movements of the motors, which leads to improved control accuracy. He employed the

Cohen-Coon tuning approach to figure out the gain of the PID controller [28].

III. Objectives and Methodology

This research aims to explore the full design and implementation of a real SW, which utilizes a four-wheel drive system and operates through standard joysticks, wireless remote controls, and voice commands. Additionally, the system integrates a healthcare monitoring system into the Graphical User Interface (GUI) of a Personal Computer (PC). To increase the safety level and satisfaction of the user, an obstacle avoidance system has been integrated with the SW from four directions to immediately stop the movement, if it detects an obstacle in the moving direction. Also, it measures some of the environmental parameters, like vibration and noise level. In addition, monitoring the responses of the operation of the motors of the SW in response to the commands that are received from the various methods of operation. A PID control has been included in the SW in order to control the speed at which the motors are operating.

To achieve the mentioned objective, a mechanical design of the SW has been carried out, including selecting the optimal dimensions of the wheelchair and the motor selection based on a real calculation and the availability of the market, and it will be discussed thereafter. By listing the required features of the SW, the required devices can be defined to add these features to the implemented SW, as shown in Table I.

TABLE I. SW Subsystems and their Required Devices

Subsystem	Feature	Required device
Operation Methods	Manual control of the wheelchair	Joystick
	Speed control, alarm, and Emergency stop	Dashboard
	A control tool for the helper	Remote-Control (RC) board
	Control the wheelchair by voice commands	SR Kit
	The ability to add an extra operating method	Extra control port
Healthcare System	Measuring the body temperature of the user	Body Temperature sensor
	Measuring the heart rate of the user	Electrocardiogram (ECG) sensor
	Measuring the emotional state of the user	Galvanic Skin Response (GSR) sensor
	Measuring the weight of the user	Load Cell
Safety System	Indicator for the alarm	Buzzer
	Measuring the noise around the wheelchair	Sound sensor
	Measuring the vibration of the wheelchair	Accelerometer
	Obstacle avoidance system in the four directions of the wheelchair	Infrared (IR) Range sensor
The SW Monitoring System	Changing the motor's speed	Motor driver board
	Monitoring the responses of the operation of the motors	Voltage sensor
	Monitoring the power of the SW	Current sensor
	Measuring the speed of the SW	Encoder system
Data Acquisition (DAQ) System	Make the link between the devices, control the wheelchair, and send the measured signals to the PC	Arduino Mega board
	Display the readings of the different sensors	PC

Based on the mentioned information above from the motors, required devices, and the electrical power supply, the electrical connections and interfaces of the SW have been defined, and it will be clarified thereafter. Fig. 1 shows a real photo of the implemented SW.

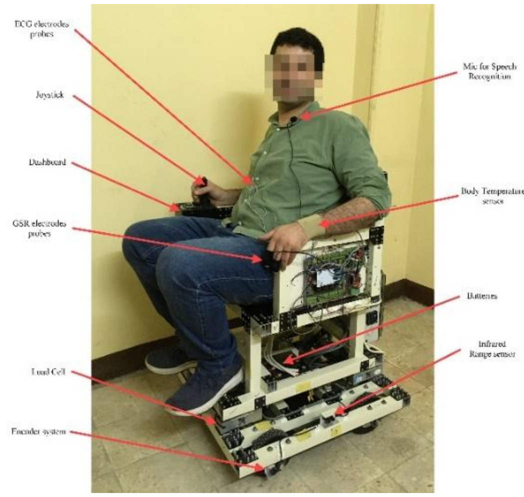

Fig. 1. The implemented SW

By thoroughly understanding the required mission of the SW mentioned in this research, the proper link between all its sub-systems can be established and converted into a programming structure on the Arduino boards, enabling all the devices to communicate and work in harmony. Fig. 2 describes using different operation methods for operating the SW. Furthermore, to implement a monitoring system for healthcare for the user and the measured signals from the SW integrated with limits for the measured signals and making an alarm if required, a GUI has been executed on the PC.

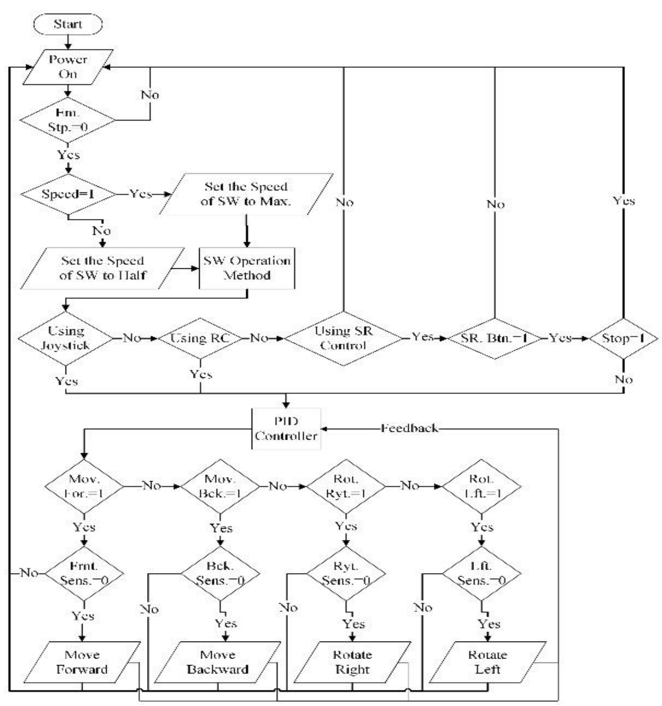

Fig. 2. The flowchart diagram describes using different operating methods of the SW.

IV. Design and Selection

In this section, the mechanical and electrical design of the implemented SW will be introduced, which adheres to the international standards for wheelchairs. Additionally, each step involved in selecting the components of the SW is going to be demonstrated to ensure they fulfill their intended functions.

A. *Mechanical Design*

The SW will rely on batteries to power all its motors and systems. As a result, reducing the weight of the wheelchair's body structure will reduce the power needed for the motors to support the wheelchair's weight. In addition, it has been planned to set a maximum payload of 100 kg for the wheelchair user. According to the previous data, it has been found that the structure should be as light as possible and rigid to withstand the applied forces. Taking all of this information into account, it has been determined that using aluminium sections joined together by small sheet metal assemblies held together by bolts and nuts was the best solution. According to the previous idea and the standard range of PW dimensions, the design of the wheelchair has been implemented by using the CAD software. As a result, the CAD software calculated the weight of the designed wheelchair to be 40 kg.

After taking into account all the parameters of the wheelchair's structure, the next step involves assigning the power to the drive motors. The four-wheel drive system has been selected for the SW based on its advantages, ensuring each wheel has its own driving motor. One of the most important dimensions that needs to be taken into consideration is the height of the wheelchair from the ramp, with a maximum incline angle that can be worked with, as shown in Fig. 3. This dimension is directly reflected in the selection of the wheel diameter of the SW. Consequently, the diameter of the wheel on the SW will directly affect its linear speed. The diameter of the wheel, after considering all the necessary data for selection, was 15.24 cm.

1) Motor selection. Based on the previous information about the structure, it has been determined that the maximum weight of the SW, including the user, would be 140 kg. The wheel diameter would be 15.24 cm, and the wheelchair would have a four-wheel drive system. Additionally, it has been determined that the SW should have a maximum linear speed of 0.5 m/s to ensure user safety, as recommended by references [29, 30]. The maximum inclination angle of the ramp that our SW can operate with has been defined as 7.125 degrees, as referenced in [31]. While all the required information is available, applying the force analysis for each wheel can be defined as shown in Fig. 3.

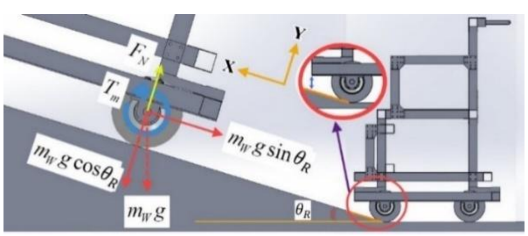

Fig. 3. CAD drawing shows force analysis for each wheel and the distance between the ramp and the SW.

where,

- F_N is the normal force (N).
- T_m is the torque of the motor for each wheel (N.m).
- m_W is the applied mass on each wheel (kg).
- θ_R is the maximum inclination angle of the ramp (°).
- g is the gravitational acceleration (m/s^2).
- Vmax is the maximum linear speed of the wheelchair (m/s).
- r_W is the radius of each wheel (m).
- ω_{max} is the angular speed for each wheel (rad/s).
- N_{max} is the maximum RPM of each motor (RPM).
- a is the wheelchair acceleration (m/s^2).
- t is the time of motion (s).
- V_0 is the initial speed (m/s).
- P_m is the power for each motor (W).
- ΣF_x is the total force in the X axis (N).
- F_m is the generated force by each motor (N).

2) Calculations for motor selection. In this section, the mathematical calculations that define the specifications for each motor in the implemented SW will be presented. It is worth noting that these calculations apply to any mobile robot.

– RPM Calculations:

By using the equation of the relation between the linear speed and the angular speed to calculate the angular speed shown in Eq. (1) and (2):

$$\omega_{max} = \frac{V_{max}}{r_W} \quad (1)$$

$$\omega_{max} = \frac{0.5}{0.0762} = 6.562\ rad/s \quad (2)$$

Applying the equation for the relationship between the angular speed and the RPM to calculate the maximum RPM of each motor shown in Eq. (3) and (4):

$$N_{max} = \frac{60}{2\pi} \cdot \omega_{max} \quad (3)$$

$$N_{max} = \frac{60}{2\pi} \cdot 6.562 = 62.64 \approx 63\ RPM \quad (4)$$

– Torque Calculations:

From the First Equation of Motion, to calculate the acceleration shown in Eq. (5) and (6):

$$a = \frac{1}{t} \cdot (V_{max} - V_0) \quad (5)$$

Assume that $t = 1\ s, V_0 = 0$

$$a = 0.5\ m/s^2 \quad (6)$$

From the force analysis for each wheel as shown in Fig. 3, the total force in the X axis can be calculated as shown in Eq. (7):

$$\because \sum F_x = m_W \cdot a = F_m - m_W \cdot g \cdot sin(\theta_{max}) \quad (7)$$

And considering the equation that represents the relationship between force and torque, to calculate the torque is as shown in Eq. (8) to (11):

$$F_m = \frac{T_m}{r_W} \quad (8)$$

then,

$$T_m = m_W \cdot r_W \cdot (a + g \cdot sin(\theta_{max})) \quad (9)$$

$$T_m = 35 * 0.0762 * (0.5 + 9.81 * sin(7.125)) \quad (10)$$

$$T_m = 4.579\ N \cdot m = 46.677\ Kg \cdot cm \quad (11)$$

– Power Calculations:

By using the equation between the power and the torque as shown in Eq. (12):

$$P_m = T_m \cdot \omega_{max} = 4.579 * 6.562 = 30.05\ W \quad (12)$$

According to the mechanical structure, force analysis, and four-wheel drive system of the wheelchair, the suitable motor torque was 47 Kg.cm, the motor power was 30 W, and the motor RPM was 63 RPM for each motor of the SW.

B. *Electrical Structure*

In this section, the process of defining each component of the SW's electrical system will be demonstrated. At the beginning, all the required functions of the SW will be reviewed, as mentioned in Table I. It has begun by selecting each necessary device, sensor, kit, or board to perform a specific task within the SW. Next, the quantity and types of digital inputs, digital outputs, analog inputs, analog outputs, and communication connections within the SW have been determined. Due to the large number of inputs and outputs and our consideration of cost, the Arduino Mega Board has been selected as the controller for the SW. Given the high number of inputs and outputs, it has been determined that two Arduino Mega Boards would meet our requirements.

1) *Schematic overview*. Once all the necessary devices for the SW have been defined, including motors, sensors, kits, and boards, then their electrical power supply and connections can be specified. As previously mentioned, the large number of inputs and outputs necessitated the use of two Arduino Mega boards in the electrical system of the SW. The electrical system has been separated into two primary sections, each utilizing one Arduino Mega board. The first section collects all signals related to the SW's operating devices and sends the necessary electrical power to the motors, while the second section primarily collects signals from lifecare sensors. The first side, known as the Control side, controls and operates the SW, while the second side, known as the Data Acquisition (DAQ) side, communicates with the PC to process and display all the collected signals on the GUI. Serial communication connects both sides, enabling communication between them. The electrical schematic diagram of the SW is shown in Fig. 4, and the Control and DAQ sides will be described in the next section.

2) *Control interface circuit board*. As previously mentioned, the control side of the SW's electrical system primarily relies on the first Arduino Mega Board, also known as the Control Arduino Mega Board. The mediator between the Control Arduino Mega Board and the other devices is the Control Interface Circuit Board. The Control Interface Circuit Board is responsible for managing the input signals from the joystick, dashboard, RC board, proximity sensor for speed measurement, voltage sensors, and current sensors. It also provides a free terminal block that serves as an additional control port. Additionally, it facilitates communication with the SR Kit, manages the output signal for the buzzer, and communicates to the DAQ Interface Circuit Board. The board also serves as an interface between the Arduino Mega Board and the motor driver boards, ensuring that the motors receive the necessary electrical power based on the output signal from the Arduino Mega Board. The electrical system contains two motor driver boards, and each board can handle two different motors. The Control Interface Circuit Board provides all the electrical supply to all the devices and subsystems in the SW. The real connections and interface of the Control Interface Circuit Board, the Arduino Mega Board, the RC board, and the motor driver boards are shown in Fig. 5.

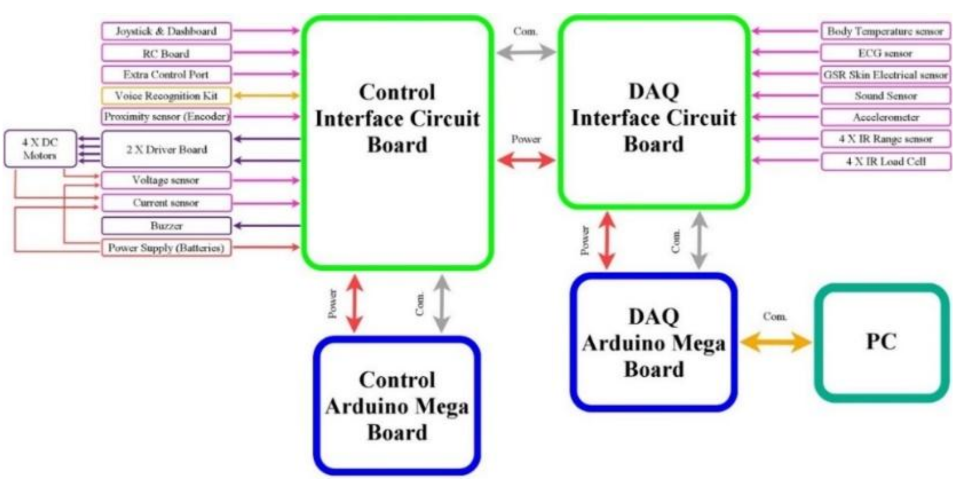

Fig. 4. The electrical schematic diagram of the SW.

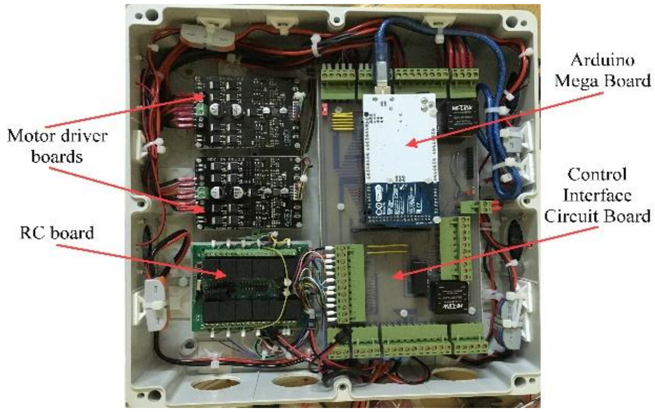

Fig. 5. The Control Interface Circuit Board, the Arduino Mega Board, the RC board, and the motor driver boards.

3) DAQ Interface Circuit Board. The DAQ side, the second side of the SW's electrical system, houses the second Arduino Mega Board, also known as the DAQ Arduino Mega Board. The Control Interface Circuit Board supplies electrical power to the DAQ Interface Circuit Board, which then distributes the necessary power to the connected devices. The DAQ Interface Circuit Board is organizing the analog inputs from the body temperature sensor, ECG sensor, GSR sensor, sound sensor, Accelerometer, IR range sensors, and Load Cells. Also, it is managing serial communication with the Control Interface Circuit Board. The board also contains the required signal conditioning circuits for the connected devices, sensors, and boards. In addition to the DAQ Interface Circuit Board, it contains the electric power filters and regulators to supply each device, sensor, and board connected to it with the required input voltage based on its datasheet. So, it contains the connection pins for the Control Arduino Mega Board. The implemented connection with the DAQ Interface Circuit Board, ECG board, GSR board, sound sensor, Accelerometer, and the Arduino Mega Board is shown in Fig. 6.

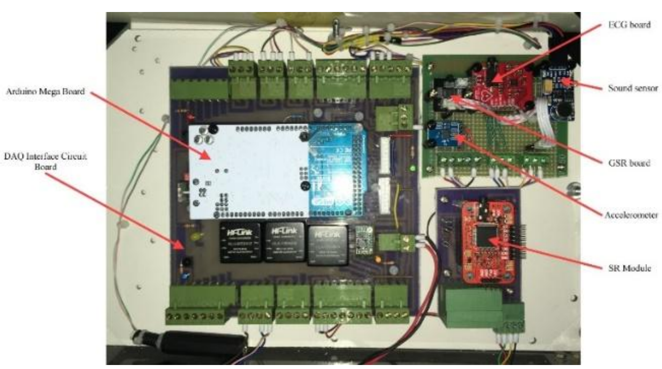

Fig. 6. The DAQ Interface Circuit Board, ECG board, GSR board, sound sensor, Accelerometer, the Arduino Mega Board, and the SR Module.

V. Operation and Hardware

This section will discuss various methods for controlling the SW, as well as the various options integrated into it to enhance its functionality. The goal is to increase the user's comfort by adding useful functions that will make their life easier. Additionally, the hardware utilized to implement these functions in the aforementioned SW will be discussed.

A. Operation Methods of Wheelchair

Here, the techniques used to drive and operate the SW will be discussed, as well as how the user can activate and deactivate some of its features.

1) Voice commands control. The wheelchair has incorporated a speech recognition system to broaden its user base. This system enables individuals with upper limb issues or poor hand control to navigate the necessary area independently, eliminating the need for assistance. Based on the user's voice input, the speech recognition system sends commands to the SW's controller, which then uses these commands to control the wheelchair's movements. The user's voice served as the training source for the speech recognition system.

2) Manual control. The PW's main feature is the normal manual control, which uses a joystick to allow the user to navigate the area and move the wheelchair. The joystick control incorporates a dashboard with functional buttons to provide the user with additional options and assistance during operation. The dashboard includes buttons for various functions, including an emergency button for stopping the SW in emergency situations, a speed control button for adjusting its speed, a voice command operation button for enabling and disabling, and a button for turning on and off the alarm.

3) Wireless remote control. The SW now includes a wireless remote control to simplify operation and control for the user's helper. Additionally, regular users can utilize the wireless remote control if they prefer not to use the traditional manual control with a joystick while resting their hands on their thighs. The wireless remote control is equipped with several buttons that perform the same functions as the manual joystick and dashboard, including wheelchair movement, speed control, and activation and deactivation of certain SW functions.

B. Healthcare and Vital Signs Monitoring

The wheelchair feels like a close friend to its user. Individuals who are handicapped, elderly, experience difficulty in their lower limbs, or sustain injuries depend on their wheelchair for their daily activities. Users spend most of their time using the wheelchair for navigation, reaching specific locations, assisting with tasks, or enjoying meals. Therefore, adding more options to the wheelchair will enhance its users' happiness, satisfaction, and self-confidence. It has implemented and integrated a Vital Signs Monitoring system with the aforementioned SW to monitor the user's vital signs and provide an indication if any of them are not functioning well. The SW's controller sends all measured signals to the PC for display on the GUI. Fig. 7 shows the implemented GUI of the healthcare system for the SW, which contains a live display of the user's body temperature, GSR, and ECG readings.

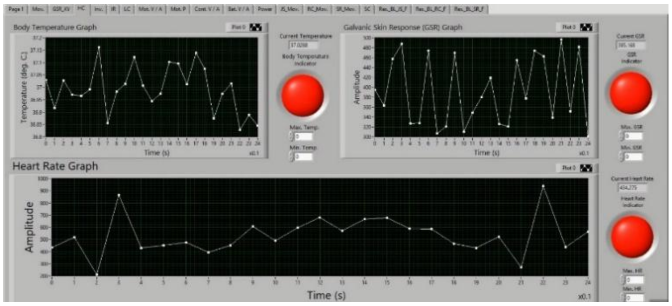

Fig. 7. The implemented GUI of the healthcare system for the SW.

1) Body temperature monitoring. The SW incorporates a body temperature sensor to measure the user's body temperature, which is a crucial indicator of their health condition. The sensor used to measure the body temperature is an NTC thermistor, specifically designed to measure 2.25K ohms at 25 degrees Celsius. A voltage divider circuit has been designed to measure the resistance change of the body temperature sensor, reflecting the body temperature, and send its output to the wheelchair controller. The Vital Signs GUI plots and displays the body temperature and other vital signs, incorporating upper and lower limits that can trigger an indicator if the measured signal exceeds these limits.

2) ECG monitoring. The ECG signal is a good indicator of the user's heart activity. The ECG monitoring system consists of three electrode pads that can be stuck to the user’s chest to transfer the ECG signals to the ECG sensor kit, which converts them to an analog signal to be sent to the controller board of the SW. Then the received signals are being processed and sent to the PC that has the GUI of the ECG monitoring to display a live situation of the ECG of the user.

3) GSR monitoring. The SW integrates a GSR sensor to monitor the user's emotions. The concept of a GSR sensor relies on the user's emotional sweating. As the user's emotions fluctuate, the amount of sweat they secrete alters, influencing the conductivity between two fingers in their hand. This change in conductivity leads to a corresponding change in the resistance between the two fingers. This change has been measured, which refers to the emotional status of the user, by connecting two electrodes to two different fingers on the user’s hand and measuring the resistance between them by using a GSR sensor board, and then the analog signal is sent to the controller of the SW. The SW's controller transmits the processed sensor signal to the PC for monitoring via the GSR's GUI.

C. Safety Implementation

As the safety level of the SW increases, the user will experience greater satisfaction during use, thereby elevating their morale. The SW has integrated an obstacle avoidance system. While the product is designed to assist individuals with disabilities in using and operating the wheelchair, it would be beneficial to provide them with awareness notifications while they are operating the SW. Moreover, the use of voice commands for wheelchair operation by individuals with disabilities leads to an increase in accidents and a decrease in user safety and satisfaction. Therefore, incorporating an obstacle avoidance system into our SW is crucial. The integrated Obstacle Avoidance System in the SW employs four IR sensors, positioned on the front, rear, right, and left sides of the wheelchair, to detect any obstacles in its vicinity. The Obstacle Avoidance System halts the SW's movement if any of its four sensors detects an obstacle in its path. It will continue to operate in this direction until the obstacle moves and the user commands it to continue. The signals from the four sensors of the Obstacle Avoidance System are given the utmost priority in the program structure of the SW's controller, thereby reducing delays, waiting times, and stoppages, thereby enhancing user safety.

VI. PID CONTROL DESIGN FOR SW

While the linear speed of the SW is one of the important factors that affect the user’s safety and satisfaction, a PID control has been implemented to sustain the speed of the SW. The design of the PID controller has started by finding the transfer function of the used motor. The following section outlines the process of determining the transfer function of the DC motor for use in speed control of the SW. Fig. 8 shows the equivalent circuit of the DC motor that was used to figure out the transfer function.

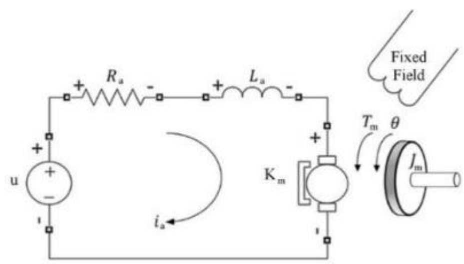

Fig. 8. The equivalent circuit of the DC motor [32].

where,

- Jm is the moment of inertia of the rotor (Kg.m2).
- C is the motor viscous friction constant (N.m.s).
- Km is the motor torque constant and the back emf constant (N.m/A), and (V/rad.sec-1).
- Ra is the electric resistance of the coil (Ohm).
- La is the electric inductance of the coil (H).
- θ is the angular displacement of shaft in radians (rad).
- ω is the angular velocity of shaft (rad/s).
- ia is the armature current (A).
- u is the armature voltage (V).
- Tm is the motor torque (N.m).

The relation between the back emf and the angular velocity and the relation between the armature voltage and the back emf voltage can be defined based on Kirchhoff's voltage law. Also, the relationship between the motor torque and the armature current too. In addition, the motor torque based on Newton's 2^{nd} law and applying the Laplace transformation, the relation between the input voltage and the output angular velocity can be defined as shown in Eq. (13):

$$\frac{\Omega(s)}{U(s)} = \frac{K_m}{L_a J_m s^2 + (L_a C + R_a J_m)s + R_a C + K_m{}^2} = \frac{K_m}{(J_m s + C)(L_a s + R_a) + K_m{}^2} \quad (13)$$

By substituting at the transfer function of the DC motor of the SW [Eq. (13)] with the values of the parameters of the system (J_m, C, K_m, R_a, and L_a) as the below values:

$$J_m = 9.19 * 10^{-4} \quad \text{Kg.m2}$$

$$C = 9.19 * 10^{-5} \quad \text{N.m.s}$$

$$K_m = 0.75 \quad \text{(N.m/A), and (V/rad.sec-1)}$$

$$R_a = 3 \quad \text{Ohm}$$

$$L_a = 0.1 \quad \text{H}$$

The open-loop transfer function of the DC motor of the SW will be as shown in Eq. (14):

$$\frac{\Omega(s)}{U(s)} = \frac{0.75}{0.0000919s^2 + 0.00276619s + 0.5627757} \quad (14)$$

Using the system's open-loop transfer function in Eq. (14), Fig. 9 shows the system's output prior to the addition of the PID controller. However, there is an overshoot of about 53.8% from the input value, and the system could not achieve the required value.

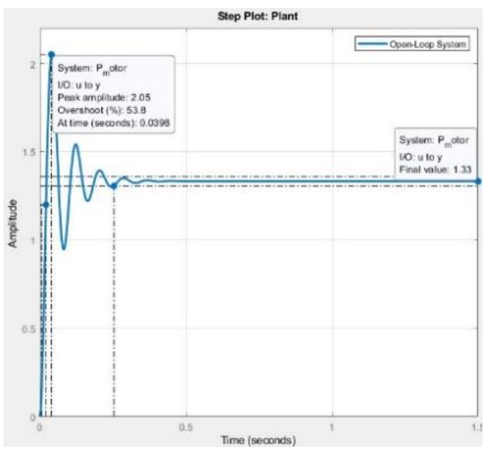

Fig. 9. The open-loop system response without the PID controller.

Fig. 10, illustrates the addition of a PID controller to enhance the system's output response. Also, the tuning was done using the PID Tuner function in MATLAB software. This is an automatic tuning function based on a proprietary tuning algorithm that uses a model-based tuning technique to set the PID controller parameters as: $K_p = 0.1181$, $K_i = 5.2143$, and $K_d = 6.6921*10^{-4}$.

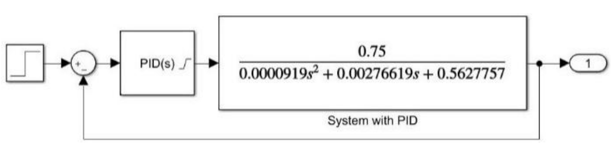

Fig. 10. The closed-loop system with the PID controller.

The addition of the PID controller to the system, as illustrated in Fig. 11, has improved the system's output response. Furthermore, the system could achieve the required value with a Rise time of 0.342 seconds and a Settling time of 0.615 seconds.

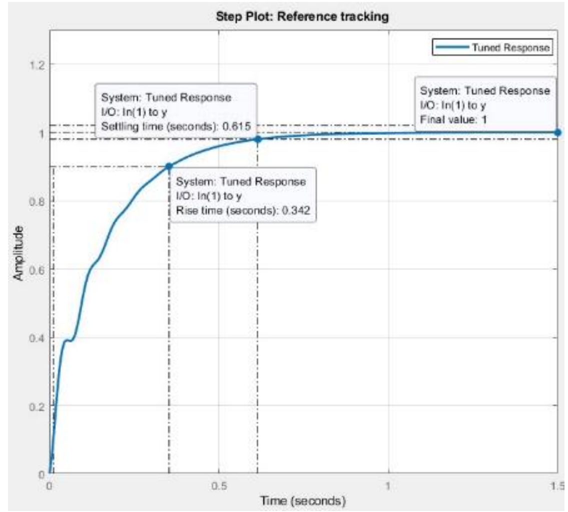

Fig. 11. The closed-loop system response with the PID controller.

VII. Results

A fixed response from the wheelchair impacts the user's satisfaction, subsequently influencing their morale. Ten trials were done to see how the wheelchair responded to step input from the SW operation device in a variety of situations, as shown in Table II. The goal was to make sure the controller worked properly after the tuning process. The main idea of the trials is to have a comparison of the implemented wheelchair response without using the PID controller and with using the PID controller to be able to figure out the change in the response during different situations that can happen for the wheelchair during normal usage. Trials one and two involved hanging the SW and moving its wheels without contacting the floor. And trial number three and four were based on moving the SW on the floor without any payload. And trials numbers five and six were based on moving the SW on the floor with a payload. And trial number seven and eight were based on moving the SW on a ramp that has the standard specs for the wheelchair ramps with a slope by ramp height of 1:8.2 and incline angle of 7 degrees without any payload, as shown in Fig. 12. And trial number nine and ten were based on moving the SW on the mentioned ramp previously with a payload.

TABLE II. THE TRIALS AND THEIR DESCRIPTIONS

Trial No.	Description
1	Move the SW while hanging without the PID controller
2	Move the SW while hanging with the PID controller
3	Move the SW on the floor without a payload without the PID controller
4	Move the SW on the floor without a payload with the PID controller
5	Move the SW on the floor with a payload without the PID controller
6	Move the SW on the floor with a payload with the PID controller
7	Move the SW on the ramp without a payload without the PID controller
8	Move the SW on the ramp without a payload with the PID controller
9	Move the SW on the ramp with a payload without the PID controller
10	Move the SW on the ramp with a payload with the PID controller

Fig. 12. The SW on a wheelchair ramp with standard specs.

Fig. 13 shows a good comparison by using the average of each speed reading for the trials from 1 to 6 under their conditions, while considering their steady state without and with the PID controller. The black curve of each graph shows the step input for the SW with a set value of 0.23 m/s. As shown in Fig. 13(a) for trials 1, 3, and 5, the SW system responded to the conditions that have been discussed earlier without using a PID controller. Some trials had overshoot, meaning that most had a high steady-state error, even though the settling time values varied. Fig. 13(b) illustrates the response of the SW system for trials 2, 4, and 6 under the previously mentioned conditions, utilizing a PID controller, exhibiting minimal overshoot, reduced steady-state error, and varying settling time values. It has also been noticed that the damping of the SW system is increasing with the increase of the load, and this phenomenon is a normal behavior for the system.

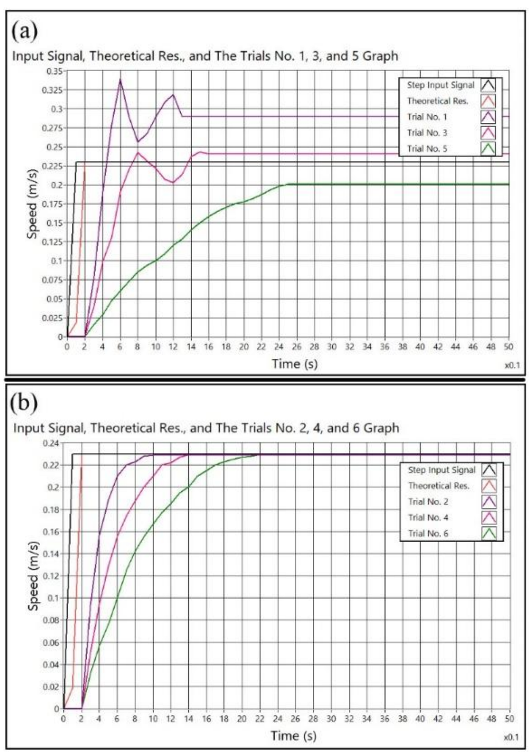

Fig. 13. Results graphs of the trials from 1 to 6 in response to the step input by using the average speed of each trial: a) Results graph for trials 1, 3, and 5 while not using a PID controller; b) Results graph for trials 2, 4, and 6 while using a PID controller.

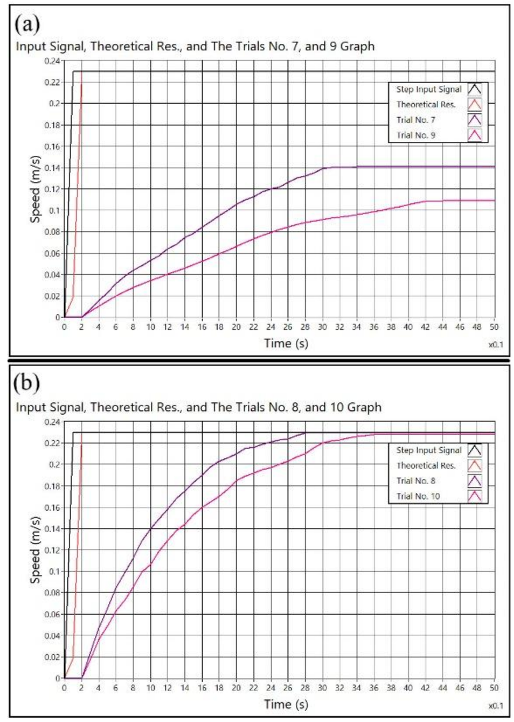

Fig. 14. Results graphs of the trials from 7 to 10 on the wheelchair ramp in response to the step input by using the average speed of each trial: a) Results graph for trials 7 and 9 while not using a PID controller; b) Results graph for trials 8 and 10 while using a PID controller.

Fig. 14 shows the output graphs for trials 7 to 10, comparing the average speed readings with and without the PID controller on the wheelchair ramp. In Fig. 14(a), trials 7 and 9 show that as the load increases, the SW's damping increases, leading to a higher steady-state error for the SW when the PID controller is not used, which is not acceptable performance. Fig. 14(b) depicts the response of the SW system during trials 8 and 10, demonstrating an increase in damping as the load increases. The PID controller's efforts are evident as it improves the steady-state error of the SW system and maintains the set value.

Table III summarizes the outcomes of all the trials conducted for the SW, both with and without the PID controller, under various scenarios that may arise during normal wheelchair usage, in response to a step input with a set value of 0.23 m/s. The results indicate that there are overshoot values when the system operates without the PID controller, with a maximum percentage of 47.51% under specific conditions, and no overshoot when the PID controller is used. In addition to using the SW system without the PID controller, which gives a high steady-state error with a maximum percentage of 52.60% under certain conditions, using the SW system with the PID controller produces a very low steady-state error with a maximum percentage of 0.81% under certain conditions. Moreover, using the SW with the PID controller shows an improved settling time compared to using the SW without the PID controller. Under certain conditions, the maximum settling time for the SW with the PID controller is 2.93 s, while the maximum settling time for the SW without the PID controller is 3.91 s. Additionally, as the load increases, the damping ratio of the SW system also increases.

TABLE III. THE RESULTS OF ALL THE TRIALS

Criteria / No.	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Overshoot (%)	47.51	0	5.78	0	0	0	0	0	0	0
Steady-State Error (%)	26.09	0.57	4.47	0.36	12.61	0.2	38.66	0.34	52.6	0.81
Settling Time (s)	1.25	0.67	1.36	1.08	2.27	1.66	2.87	2.27	3.91	2.93
Damping Ratio	0.51	1.28	0.81	1.52	1.2	1.78	1.5	2.05	2	2.31
Step Input Set Value (m/s)	0.23									

VIII. CONCLUSION AND FUTURE WORK

Feeling more independent and safe boosts the wheelchair user's morale, which in turn improves their health condition and lessens the burden on their helper. Our solution effectively integrates traditional joystick control with voice command functionality and wireless remote control, providing improved accessibility and autonomy for users. Furthermore, using the integrated vital signs monitoring system provides live data about the user's health, which enhances user health management. Combining an obstacle avoidance system with our SW increases the user's safety. Additionally, the results of a comparison between using the normal control system and the PID control system while operating the implemented SW in different situations can be observed for the wheelchair during normal usage, which has proved an improvement for the wheelchair's response and stability, thereby increasing user satisfaction. While the trials have proved that using the PID controller with $K_p = 0.1181$, $K_i = 5.2143$, and $K_d = 6.6921*10^{-4}$ has eliminated the overshoot of the system from 47.51%. In addition, decreasing the steady-state error percentage from 52.60% to 0.81% as a maximum also improved the settling time from 3.91 s to 2.93 s as a maximum compared to using the normal control system to operate the SW. Adding the PID controller to the SW has improved its performance and stability.

The findings of our study illustrate the advantages of integrating the PID controller while using hybrid and combined control systems in assistive devices, focusing on their capacity to improve the lives of handicapped people. The full calculations for motor selection for our SW have been illustrated, which is also very useful during the design of any mobile robot. Our hybrid-controlled SW signifies an important advancement in assistive technology, providing improved mobility and health monitoring. Keep improving in such a field; it plays a significant role in improving the quality of life for users.

Since this study is just the beginning, several more studies can be conducted in the future. These include replacing the wheelchair's traditional wheels with Mecanum wheels. New healthcare sensors and devices can be added to provide more details about the user's health, such as blood pressure, breathing rate, and so on. Improve the GUI for healthcare monitoring to include the readings from the new sensors and devices. The system stores the collected data in a database for the doctor's analysis. The system can send alarms about the user's health status through Short Message Service (SMS) if it's an urgent matter, and it can also send a daily report via email to the doctor.

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