

Research Article

Development of Smart Wheelchair to Support Hybrid Learning Accessibility in Smart Classes for People with Disabilities

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Article Info	Abstract
Article History	Students with physical disabilities often encounter significant mobility and accessibility challenges in hybrid learning environments, particularly in dynamic classroom settings where conventional wheelchairs lack adaptability and compatibility with hybrid classroom layouts and digital learning activities. This research developed and evaluated a smart wheelchair equipped with sensor-based automated navigation to enhance mobility, independence, and accessibility in hybrid classrooms. The research employed a Research and Development approach using the ADDIE model, integrating prototype development, functional testing, mechanical simulation, and expert validation. The system incorporated a joystick and smartphone-based control, ultrasonic and line sensors for obstacle detection, GPS-assisted positioning, and an auto-parking feature. Mechanical simulation results indicated structural safety with a high safety factor (7.47) and minimal deformation (0.0429 mm). Performance testing demonstrated stable navigation, responsive control with an average latency of 120 ms, and successful auto-parking in 90% of trials. Expert validation involving five specialists showed that the system achieved "highly feasible" ratings across efficiency, durability, aesthetics, precision, and safety indicators. The findings indicate that the proposed smart wheelchair effectively improves independent mobility and supports accessibility in hybrid learning environments. However, further refinement is required to enhance precision and safety performance for broader implementation.
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1. Introduction

Hybrid learning environments combine face-to-face instruction with digital learning activities and

therefore require students to interact with both physical classroom resources and technology-enabled teaching tools [1]. For students with physical disabilities, mobility barriers within dynamic classroom layouts can limit access to learning materials, reduce participation, and increase reliance on assistance. Although conventional wheelchairs provide basic mobility, they often lack adaptability to changing classroom arrangements and do not support reliable indoor navigation in busy learning spaces. As hybrid classrooms increasingly adopt flexible seating, shared devices, and interactive learning stations, there is a growing need for mobility solutions that can support independent navigation and safe movement in real classroom conditions [2].

Existing smart wheelchair technologies have primarily been developed for general mobility assistance or clinical and rehabilitation contexts [3]. While many systems include sensors for obstacle detection and alternative control interfaces, they are seldom designed around the practical demands of hybrid classrooms, such as navigating narrow aisles, adapting to frequent layout changes, and supporting smooth participation during learning activities [4]. This creates a gap between current assistive mobility technologies and the accessibility needs of inclusive hybrid learning environments.

To address this gap, this study develops and evaluates a smart wheelchair prototype tailored to hybrid classroom settings. The system integrates sensor-based navigation and obstacle detection, joystick and smartphone-based control, GPS-assisted positioning as a supplementary feature, and an auto-parking function to support controlled stopping within designated classroom zones. The prototype is developed using a Research and Development approach based on the ADDIE model, and it is evaluated through functional performance testing, mechanical simulation, and expert validation across key indicators (efficiency, durability, aesthetics, precision, and safety).

The objectives of this study are:

- To design and develop a smart wheelchair with sensor-based automated navigation tailored for hybrid classroom environments.
- To evaluate the prototype's structural, mechanical, and navigational performance through systematic testing.
- To assess expert-based feasibility across efficiency, durability, aesthetics, precision, and safety indicators.

The remainder of this paper is organised as follows. Section 2 reviews related work on smart

wheelchair systems and accessibility needs in hybrid learning. Section 3 describes the system design, development process, and experimental protocols. Section 4 presents result from simulation, performance testing, and expert validation, followed by discussion of scope and limitations. Section 5 concludes the paper and outlines future work.

2. Literature Review

Technological advancements continue to transform educational ecosystems, yet accessibility challenges persist for students with disabilities, particularly within hybrid learning environments [5]. While digital learning tools have expanded access globally, many students with disabilities still encounter mobility limitations that hinder their ability to interact effectively with instructional materials, navigate classroom layouts, and participate equally in learning activities [6]. Existing smart wheelchair technologies primarily focus on healthcare, rehabilitation, or general assistive mobility. However, these systems seldom address the pedagogical and spatial requirements of hybrid classrooms, where flexible seating arrangements, digital device integration, and dynamic learning interactions demand adaptive indoor navigation capabilities. As a result, a significant technological gap remains in supporting independent accessibility for students with disabilities in hybrid classroom environments.

In hybrid learning environments, accessibility barriers extend beyond digital content and include navigation through changing classroom layouts, access to shared learning stations, and safe movement during interactive activities. Existing assistive mobility solutions are often costly or not adapted to dynamic indoor learning spaces, which can reduce independent participation and increase reliance on assistance. These constraints motivate context-specific smart mobility solutions for inclusive hybrid classrooms.

Persons with disabilities in Indonesia and around the world often face challenges in accessing equal education. Despite efforts to create an inclusive educational environment, many facilities and technologies are still limited or unaffordable for persons with disabilities, especially in higher education [7]. In an educational environment that combines face-to-face and online learning (hybrid classrooms), students with disabilities often struggle to adapt to dynamic classroom layouts and existing learning technologies [8]. Limited mobility is one of the main obstacles to their moving independently in the classroom, accessing learning materials, and interacting with fellow students. Therefore, it is necessary to develop assistive technologies that improve their accessibility and mobility, enabling them to participate in the learning process in hybrid classrooms actively [9]. One potential solution is the development of smart wheelchairs

equipped with sensor-based automated navigation systems, which can make it easier for people with disabilities to navigate dynamic classrooms and support their engagement in learning.

Assistive technology is a term that encompasses assistive, adaptive, and rehabilitative tools for persons with disabilities and encompasses almost anything that can be used to compensate for certain disabilities [10]. Assistive/Adaptive disability technology includes hardware, software, and technological innovations specifically designed to help individuals with various disabilities [11]. Assistive technology includes mobility aids and digital tools that support independent participation in education.

Although several studies have explored smart wheelchair systems featuring sensor-based navigation, obstacle detection, and alternative control interfaces, most of these developments are designed for general mobility assistance or clinical applications; the majority of existing systems do not incorporate adaptive navigation tailored to dynamic classroom layouts, nor are they typically designed around hybrid classroom participation workflows that characterise hybrid learning models. This mismatch between current technologies and the accessibility needs of educational settings underscores the importance of designing a context-specific smart wheelchair solution for hybrid learning spaces.

Previous research on smart wheelchairs has mainly focused on assistive mobility, rehabilitation, and general navigation. Hartopo, et al. [12] reviewed AI-assisted wheelchair navigation but did not address learning environments. Dicianno, et al. [13] emphasised clinical usability without considering adaptive navigation for dynamic classroom layouts. Zhou [14] proposed Internet of Things (IoT) based wheelchair technology aimed at outdoor or general mobility rather than hybrid-learning contexts. These studies highlight clear gaps in indoor classroom navigation, hybrid classroom participation workflows, and accessibility support for hybrid learning. This research addresses these gaps by developing a classroom-oriented smart wheelchair with adaptive navigation.

3. Methodology

3.1. Research Design (ADDIE Framework)

The present study employed a Research and Development design using the ADDIE model: Analysis, Design, Development, Implementation, and Evaluation. The ADDIE framework was selected for its structured, iterative nature, enabling the systematic development, refinement, and validation of the smart wheelchair prototype [15]. Each stage provided a clear workflow for integrating technical engineering

processes with usability and feasibility assessment in hybrid classroom contexts. Although ADDIE is commonly used in instructional design, its structured phases are also suitable for hardware–software prototyping when combined with engineering practices. In this study, the ADDIE model was adapted as follows: the Analysis phase involved identifying accessibility needs in hybrid classrooms; the Design phase specified system architecture, sensor configuration, and mechanical layout; the Development phase focused on hardware assembly and programming; the Implementation phase involved prototype deployment and initial trials; and the Evaluation phase included expert validation, navigation tests, mechanical safety checks, and structural analysis.

3.2. Research Design and Data Collection

This research employed a Research and Development (R&D) approach using the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) to design, develop, and evaluate the smart wheelchair prototype. The research focused on prototype development, functional testing, and expert-based validation. The evaluation combined expert validation and technical performance testing; observations were used only to define design requirements. Data collection was conducted through structured observations, expert validation, and system performance testing. Observations were carried out to identify accessibility challenges in hybrid classroom environments and to define system requirements. The evaluation process involved five expert validators from relevant fields, including mechanical engineering, electrical systems, assistive technology, ergonomics, and inclusive education.

These experts assessed the prototype based on predefined indicators, namely efficiency, durability, aesthetics, precision, and safety. Each indicator was rated using a five-point Likert scale, where 1 = very poor, 2 = poor, 3 = fair, 4 = good, and 5 = very good. The obtained scores were converted into percentages using the formula:

$$\text{Feasibility percentage} = (\text{obtained score} / \text{maximum possible score}) \times 100.$$

The feasibility categories were interpreted as follows: 80–100% = highly feasible, 60–79% = feasible, 40–59% = moderately feasible, 20–39% = less feasible, and 0–19% = not feasible. Functional testing was performed to evaluate system performance, including navigation accuracy, response time, obstacle detection, and load-bearing capability. The results were analysed using descriptive statistics to determine system feasibility and performance reliability. This approach ensures that the evaluation is technically grounded and aligned with prototype-based engineering research.

3.3. System Overview and Classroom Integration

The Smart Wheelchair developed is an ordinary wheelchair equipped with a special module/tool, making it an Automatic Wheelchair [16]. This innovation was developed to improve the accessibility of tools for persons with disabilities [17]. The following is a scheme for implementing Smart Wheelchair aids in the hybrid class. The following is the Smart Wheelchair development scheme. Figure 1 below illustrates the integration of a smart wheelchair into a hybrid smart classroom environment for students with disabilities. The system supports both in-class and remote learning by enabling automatic remote control, mobile-based speed and direction settings, Global Positioning System (GPS) tracking, and auto parking features. The smart wheelchair functions as a core component of the smart hybrid class model, combining hardware and software innovations to provide effective, flexible, and inclusive assistive technology that supports independent mobility and active participation in hybrid learning environments.

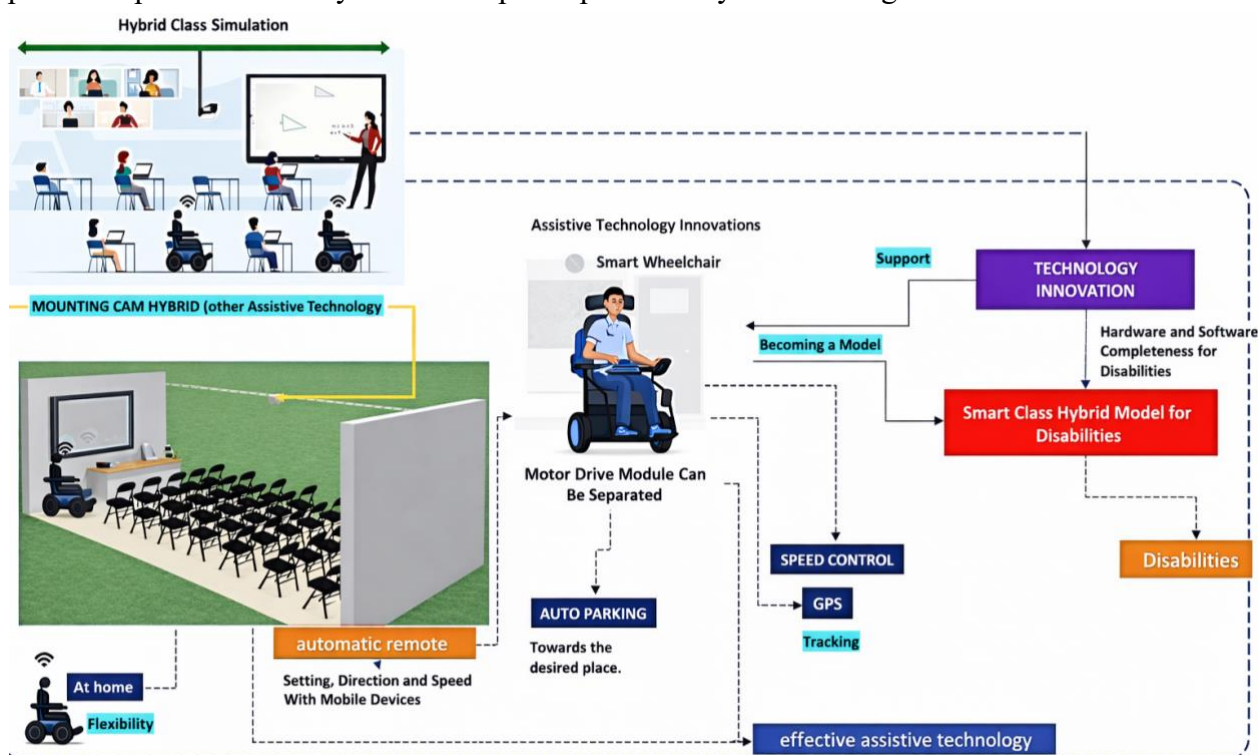


Figure 1. Smart wheelchair innovation scheme

The smart wheelchair innovation developed in this study is very important. To the best of the authors' knowledge, existing smart wheelchair systems primarily address general mobility or clinical contexts, while context-specific solutions tailored to the dynamic requirements of hybrid learning classrooms remain limited and underexplored in the current literature. Hybrid learning, which combines face-to-face and online learning, poses a major challenge for people with disabilities, especially regarding mobility and accessibility in dynamic classrooms [18]. Existing conventional wheelchairs lack automatic navigation and

the ability to adapt to changing classroom layouts, which are urgently needed in flexible, interactive classrooms. With this smart wheelchair innovation, people with disabilities can move independently, avoid obstacles, and access learning materials more easily without depending on others. In future work, the prototype may be extended to interface with additional disability-support tools and classroom systems; however, this study focuses on the validated features reported in the Results.

Meanwhile, quantitative data were collected during the trial of the intelligent wheelchair system in a hybrid class setting, which involved measuring technical performance and evaluating indicators such as tool efficiency, tool durability, and system safety [19]. The results of this trial were analysed using descriptive statistics to determine the percentage of conformity to the predetermined criteria. Performance outputs and expert ratings were summarised using descriptive statistics.



Figure 2. Smart wheelchair smart system design

3.4. System Components

The smart wheelchair system was developed using an integrated hardware architecture consisting of input, processing, communication, output, and safety components. The input components include a joystick, a smartphone-based control application, ultrasonic sensors, and infrared line sensors, which provide user commands and environmental data. The processing unit is based on an ESP32 microcontroller [20], which functions as the central controller responsible for real-time data processing, decision-making, and system coordination. For communication, the system uses a Bluetooth module (HC-05) for short-range wireless control between the smartphone and the wheelchair, and a Global System for Mobile Communications (GSM) module (SIM900) to transmit location data to external devices. Additionally, a GPS M8N module is used to provide spatial positioning and coordinate tracking, particularly for outdoor or extended navigation scenarios. The output or actuation components consist of a motor driver and DC

motors that execute movement commands, such as direction and speed control. For safety, the system incorporates ultrasonic sensors for obstacle detection and collision avoidance during navigation. These components operate in an integrated manner to ensure reliable, responsive, and safe wheelchair operation within hybrid classroom environments.

The system was developed to run a wheelchair using an Android device via a Bluetooth module (HC-05), a joystick, and GPS integrated with smartphones. The design of this tool can be described using diagram blocks as follows. Figure 3 below shows three stages: the input unit, the process unit, and the output unit. The input unit uses components including a smartphone, a line sensor, a joystick for control, and a GPS for coordinating input. The process unit uses ESP32 board components. Meanwhile, the output unit uses a DC motor, and coordinate position information is transmitted to the smartphone via the SIM900 module.

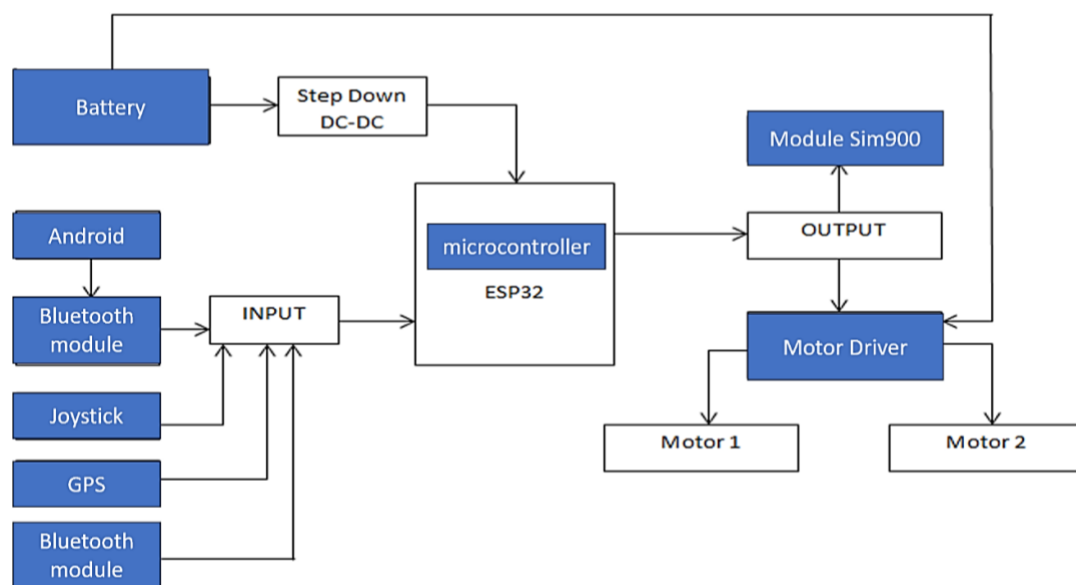


Figure 3. System block diagram

At this stage, the entire wheelchair system is designed mechanically and electrically. In this case, designing a microcontroller-based wheelchair and an Android-based joystick. In designing and manufacturing the device, several electronic components are used, including a power supply, a Smartphone, a Bluetooth module (HC-05), an ESP32 microcontroller, a motor driver, a 12-volt DC motor, a joystick, a GPS M8N, and a step-down converter.

3.5. System Architecture and Data Flow

The smart wheelchair system was developed using a modular hardware architecture combining microcontroller-based automation, sensor-driven navigation, and wireless communication. The system

integrates ESP32 as the central processing unit, supported by ultrasonic sensors, infrared line sensors, a GPS M8N module, and an HC-05 Bluetooth module. This configuration enables responsive navigation, obstacle detection, remote control, and spatial positioning within hybrid classroom environments.

3.5.1. Communication Modules and Data Flow

The smart wheelchair system employs three main communication modules: a Bluetooth module (HC-05), a GSM module (SIM900), and a GPS module (M8N), each serving distinct and complementary functions within the system architecture. The Bluetooth module (HC-05) is used for short-range communication between the smartphone application and the ESP32 microcontroller, enabling real-time transmission of user control commands such as direction, speed, and navigation modes. The ESP32 processes these commands to control the motor driver and execute wheelchair movement. The GPS M8N module functions as a positioning system that continuously provides geographic coordinate data (latitude and longitude). This data is utilised for location tracking and navigation monitoring, particularly in extended or outdoor scenarios where spatial awareness is required.

The GSM module (SIM900) transmits location data from the GPS module to external devices, such as smartphones, via cellular networks. This enables remote monitoring of the wheelchair's position. The data flow within the system follows a structured sequence: user commands are sent from the smartphone to the ESP32 via Bluetooth; the ESP32 processes sensor and positioning data; the GPS module generates coordinate data; and the GSM module transmits this information to external devices. This explicit communication flow ensures reliable system operation and eliminates ambiguity in data transmission. The ESP32 microcontroller serves as the primary controller due to its dual-core processing, low-latency performance, and integrated Wi-Fi/Bluetooth modules. Its high processing speed enables real-time handling of sensor data and navigation decision-making. The microcontroller receives input from ultrasonic and line sensors, as well as Bluetooth commands, and processes it to control the motor drivers that drive the movement and make directional changes. Ultrasonic sensors were installed on the wheelchair's front, left, and right sides to detect obstacles and ensure safe navigation. These sensors measure distance by transmitting ultrasonic waves and detecting reflected signals. Infrared line sensors were used to support path guidance, enabling the wheelchair to follow predefined visual markers on classroom floors when necessary. The combination of both sensor types enhances navigation accuracy and reliability. The HC-05 Bluetooth module enables remote control functionality, allowing the wheelchair to be operated manually

via a mobile device when automated navigation is not suitable.

Bluetooth commands are processed by the ESP32, which adjusts motor output accordingly. Latency tests showed an average response time of 120 ms, indicating stable wireless control. Latency testing was conducted by sending directional control commands from the Android application to the wheelchair controller under indoor classroom conditions. The response time was measured as the interval between command transmission and motor activation. A total of 20 repeated trials were performed, yielding an average response latency of 120 ms (± 15 ms), indicating stable and responsive wireless control. The GPS M8N module was integrated to support spatial awareness and location logging during hybrid learning activities. Although GPS accuracy is limited indoors, it provides supplemental data for broader campus navigation scenarios. In hybrid learning contexts, GPS serves as an auxiliary system, while ultrasonic and infrared sensors perform primary indoor navigation tasks.

3.5.2. Control and Instrumentation

The wheelchair can be controlled using the joystick attached to the wheelchair and an Android application. A plug-in controller that has eight directions of motion, namely forward, backwards, left, right, front right oblique, front left oblique, rear right oblique, rear left oblique. A controller is connected to an Arduino controller device that has been classified as a joystick and Android controller [21]. The wheelchair's control system uses a joystick or Bluetooth on an Android device to turn the wheelchair left or right and reverse its direction. The wheelchair drive uses a 24 Volt DC motor. In controlling the speed and direction of rotation of a DC motor, a Motor Driver regulates the source voltage or current flowing to the DC motor. In principle, the Motor Driver circuit functions as a regulator, controlling voltage and current to adjust the motor's speed and direction.

3.6. Experimental Setup and Test Protocols

Testing of the tool was conducted to evaluate whether the developed system operated as planned. The tests were conducted in several stages, including mechanical performance, connectivity, and load-bearing evaluation.

3.6.1. Mechanical and Connectivity Trials

In this study, tests were repeated under the same classroom conditions to assess control reliability and connectivity stability. This was conducted to evaluate the success rate of voltage data readings and also

control using the remote on smartphones, joysticks and line sensors on wheelchairs. The data were collected during the wheelchair performance process while controlling wheelchair movement. The mechanical testing process and controller connection are carried out in stages, starting with testing the performance of each mechanical device, such as actuators, gears and chains, as well as testing the wheelchair's electrical system. Mechanical testing is carried out by measuring and observing changes in the circuit's output in response to the input. Next, software testing followed. This test aims to verify the transmission of data from the Android application to the device and the time it takes for the tool to receive it on this smartphone. The transmitted data consists of control commands that determine wheelchair movement: this electric wheelchair can move forward, backwards, turn left, turn right, and stop. After the device is connected, testing continues using the Joystick as a manual control tool. The next trial is to add a load to the wheelchair, up to 80 kg, using the joystick control system or an Android smartphone application.

3.6.2. GPS Drift Test

The GPS drift test was conducted using a stationary evaluation method, in which the wheelchair remained idle at a fixed position throughout the experiment. Positional data obtained from the GPS module were continuously recorded and compared with reference coordinates from Google Maps. Data collection lasted approximately 30 minutes, and coordinates were transmitted to the smartphone via the SIM module. The analysis revealed an average positional deviation ranging from 2.5 to 3.8 meters under indoor conditions, reflecting the inherent limitations of GPS accuracy in enclosed environments. Therefore, the GPS module was utilised as a supplementary positioning system rather than the primary indoor navigation mechanism.

3.6.3. Auto-Parking Test

This wheelchair is equipped with a line sensor under the wheelchair that automatically parks at a designated point, as illustrated in the following picture. Figure 4 below shows that the wheelchair is designed to park in a designated area using a black track line 5 cm wide and a red parking box measuring 60 x 60 cm. The width and colour of this track are the standards set by the researcher, who has adjusted the wheelchair's lines. The auto-parking function was tested through 10 repeated trials following the predefined track and parking box configuration. The system completed automatic parking in 9 out of 10 trials, with an average stopping deviation of less than 5 cm from the target position. One failure occurred due to sensor

misalignment, which was addressed during subsequent calibration.

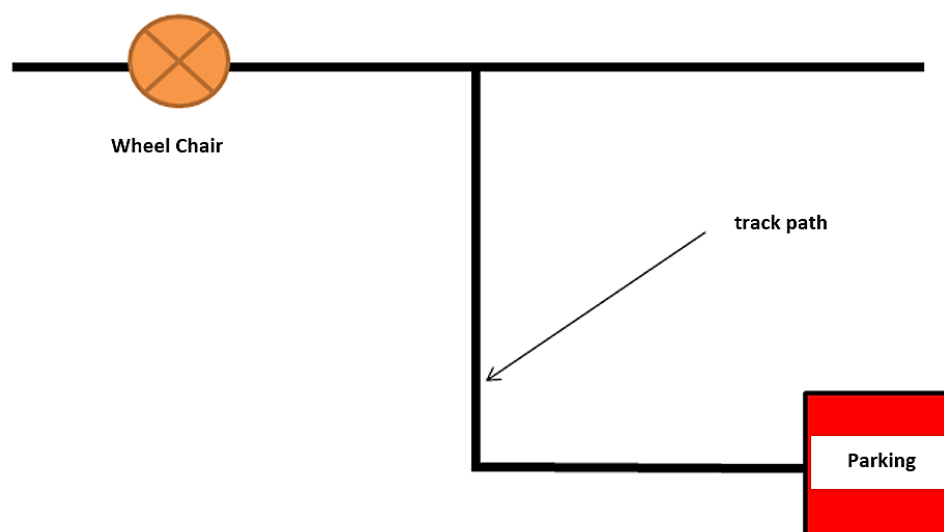


Figure 4. Illustration of an automatic parking track

4. Results and Discussion

4.1. Needs Analysis Summary

Based on classroom observations and expert consultation during requirements analysis, it was found that students with disabilities currently face various obstacles to participating in hybrid learning. Many of them find it difficult to adapt to the dynamics of flexible classrooms, especially regarding mobility and access to learning materials. Classroom observations and expert consultation indicated that conventional wheelchairs do not adequately support independent mobility in dynamic classroom layouts. In addition, observations also show that people with disabilities have difficulty accessing existing learning technologies, such as digital whiteboards and projectors, due to mobility limitations. Therefore, this research has developed a tool to meet these needs: smart wheelchairs equipped with automatic navigation systems that can adapt to changing classroom layouts. This tool is specifically designed to facilitate the mobility and accessibility of students with disabilities, especially in hybrid learning, so they can participate more actively and equally in the learning process.

4.2. Prototype Design Outcomes

Based on the Needs Analysis conducted through classroom observations and expert consultation with various parties and observations of Smart classes for persons with disabilities, it is necessary to develop assistive devices in the form of Smart Wheelchairs. Development begins with the creation of a Smart Wheelchair assistive device design [22]. The design uses SolidWorks applications to obtain precise 2D,

3D, and simulation visualisations of the developed tools. The following are the results of the tool design.

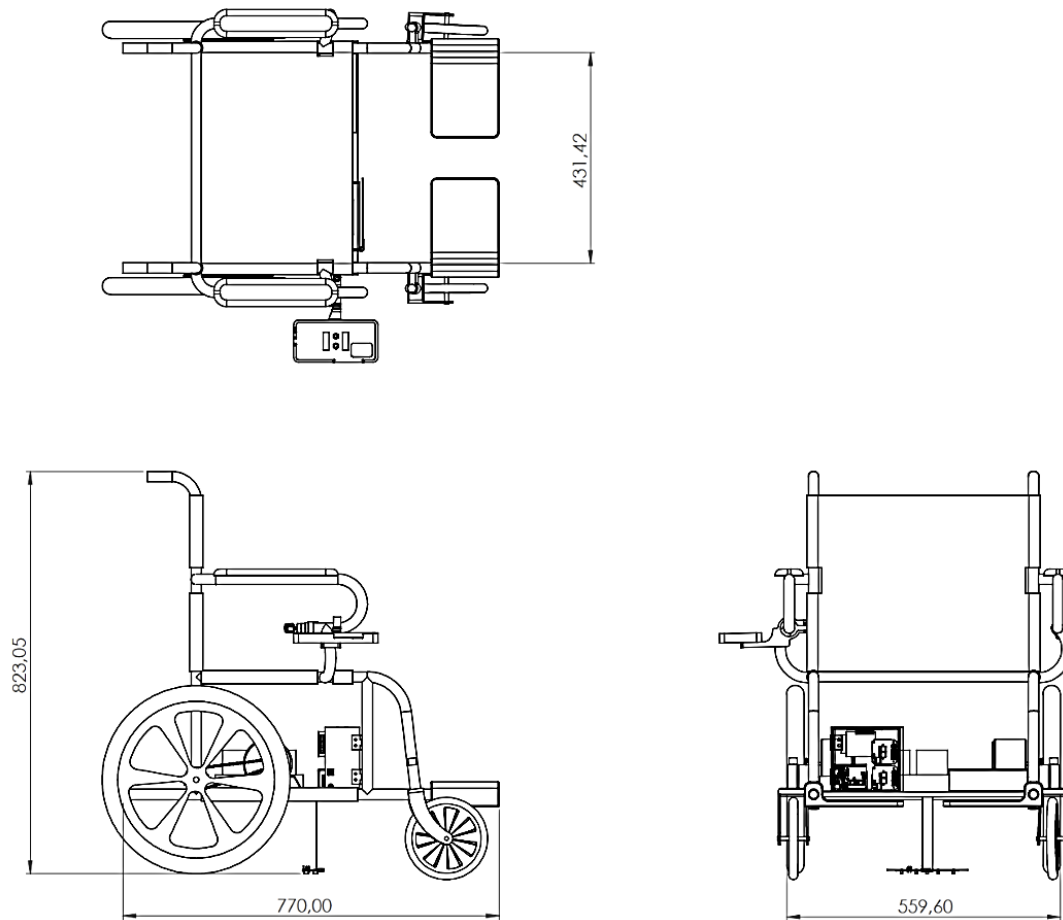


Figure 5. Two-Dimensional design of aids

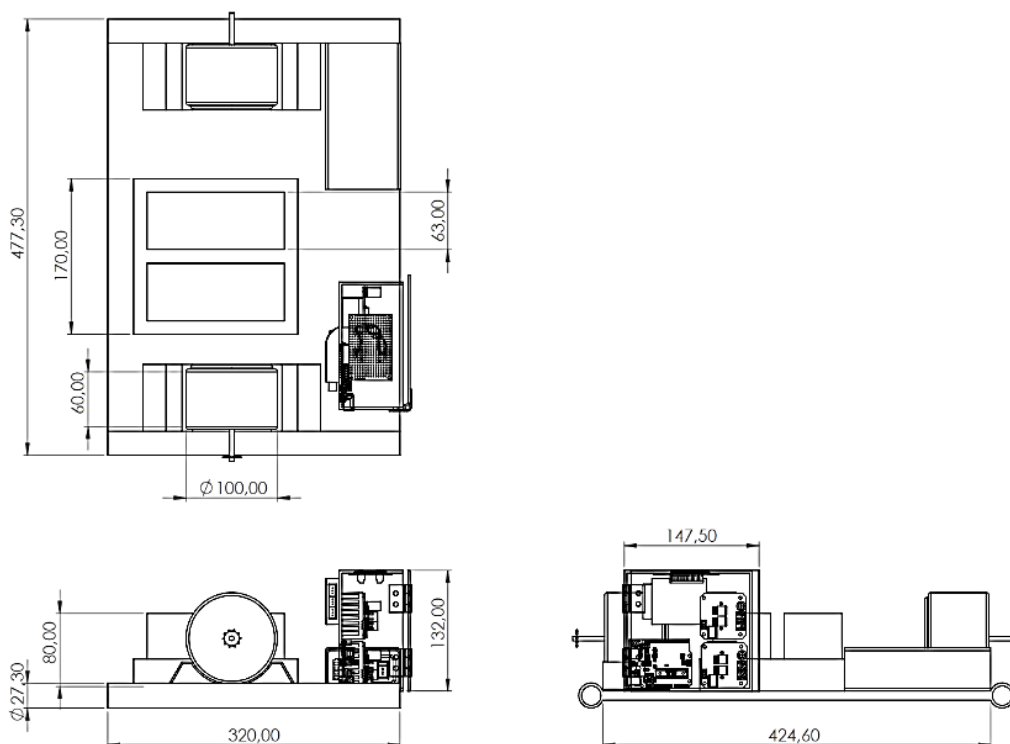


Figure 6. Smart wheelchair module layout design

Structural safety was evaluated using SolidWorks simulation. Outputs included von Mises stress, displacement, strain, and factor of safety under the defined load case.

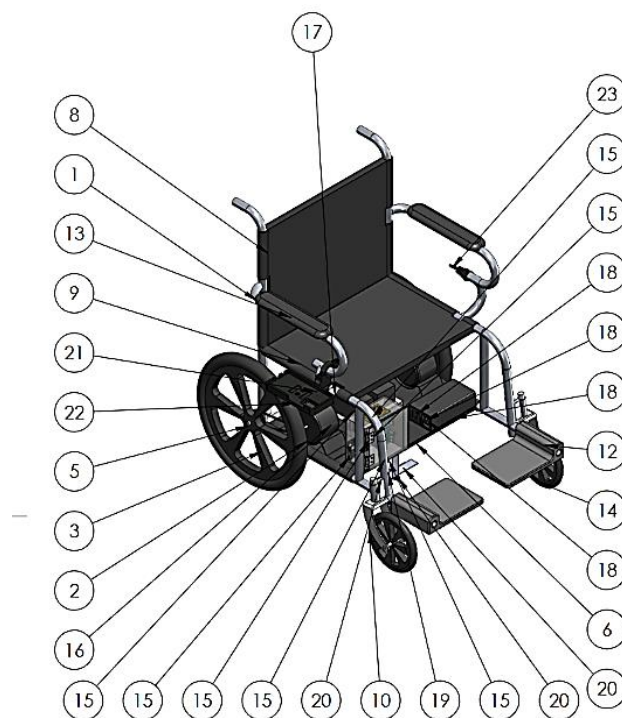


Figure 7. Smart wheelchair design intact

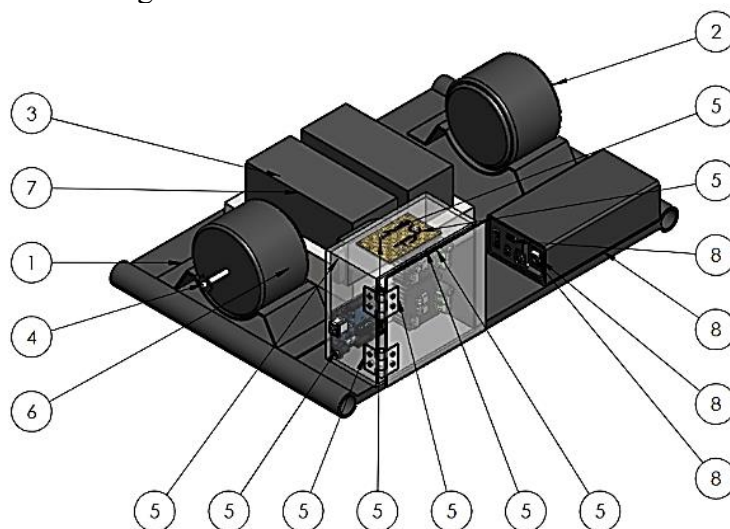


Figure 8. Smart wheelchair module design

4.3. Simulation Setup and Assumptions

Table 1 provides context for the safety factor values commonly used in mechanical design. In this study, the wheelchair structure achieved a safety factor of 7.47, exceeding the typical range for structural steel components in daily-use equipment, indicating a high margin of safety.

The main components of a 3D wheel model are the frame, backrest, and seat. These components are

arranged with accurate geometry to determine the current state using the simulation's default configuration. The 3D wheelchair image is shown in Figure 9.

Table 1. The safety factor values for some of the machine constructions

Equipments	Factor of Safety (FOS)
Aircraft components	1.5 - 2.5
Boilers	3.5 - 6
Bolts	8.5
Cast-iron wheels	20
Engine components	6 - 8
Heavy-duty shafting	10 - 12
Lifting equipment - hooks	8 - 9
Pressure vessels	3.5 - 6
Turbine components - static	6 - 8
Turbine components - rotating	2 - 3
Spring, large heavy-duty	4.5
Structural steel work in buildings	4 - 6
Structural steel work in bridges	5 - 7
Wire ropes	8 - 9

The simulation model uses grey cast iron as the frame material. The material properties were adopted from the SolidWorks material library, with the following values: Young's modulus of 6.62×10^{10} N/m², Poisson's ratio of 0.27, tensile strength of 1.52×10^8 N/m², compressive strength of 5.72×10^8 N/m², and density of 7200 kg/m³. The mechanical simulation in this study used grey cast iron as the assumed material for the wheelchair frame due to its well-documented mechanical properties, including high compressive strength, good vibration damping, and structural stability under static loading. However, it should be noted that this material selection was used as a modelling assumption for simulation purposes and does not necessarily represent the exact material used in the physical prototype.

The simulation aimed to evaluate structural behaviour under standardised loading conditions and to estimate safety factors within a controlled analytical framework. Therefore, the use of grey cast iron provides a conservative, stable reference for assessing stress distribution, deformation, and safety margins. Future studies should incorporate material characterisation based on the actual prototype frame to improve the accuracy and applicability of simulation results.

This simulation uses fixed geometry at several points to simulate realistic operational conditions. A

standard load of 500 N is placed on a single surface to indicate the user's weight. The mechanical simulation applied a standardised load of 500 N to represent a conservative partial loading condition on the wheelchair frame. This value corresponds to a distributed load scenario and does not represent the user's full body weight. In practical trials, the system was additionally tested with users weighing up to 80 kg to validate real-world performance. The mechanical simulation applied a 500 N load to simulate a partial loading condition acting on the wheelchair frame. This value corresponds to approximately 50 kg of mass under the influence of gravity and was selected to simulate a conservative distributed load rather than the user's full body weight. In practical use, the average user weight may reach 80 kg (≈ 784 N); however, the load applied to the frame is not concentrated at a single point but distributed across multiple structural components, including the seat, frame joints, and support elements. Therefore, the 500 N load represents a realistic partial load condition that captures the effective stress acting on the structure's critical regions. This approach is commonly used in mechanical simulations to evaluate structural performance under simplified yet representative loading conditions.

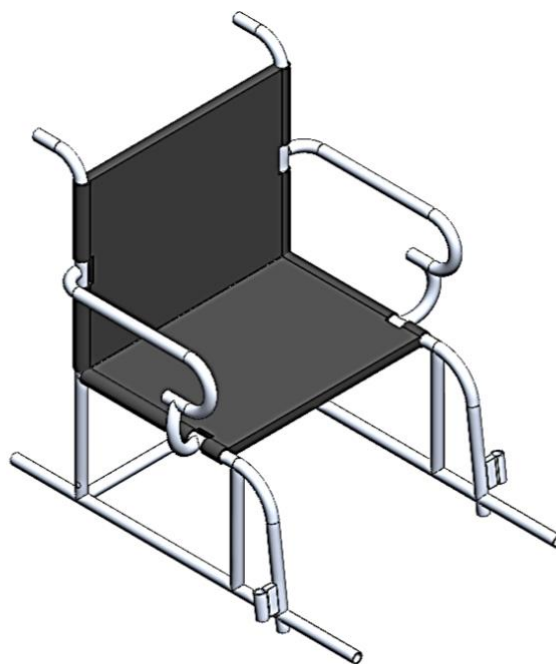


Figure 9. 3D Modelling of a wheelchair

The resulting safety factor of 7.47 indicates that the structure remains well within safe operational limits, even when considering higher real-world loading scenarios. This justification ensures consistency between simulation assumptions and actual usage conditions. The results of the loading test showed a total reaction of 500 N and a reaction moment of 2.76 Nm, indicating structural stability under the applied load. The Wheelchair Cushion is shown in Figure 10.

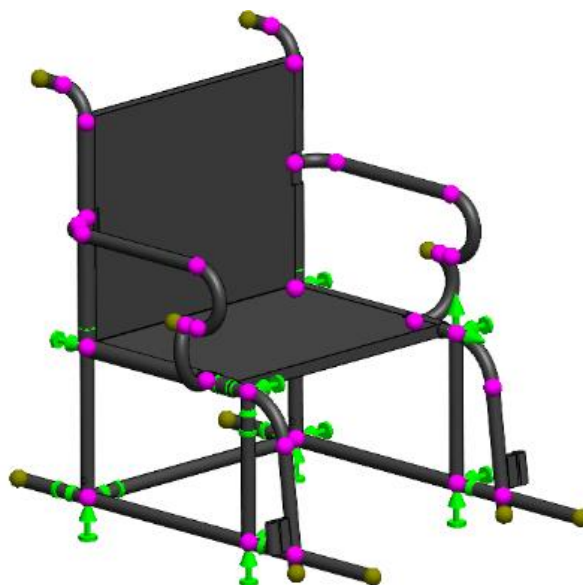


Figure 10. Wheelchair cushioning

The wheelchair load application is shown in Figure 11.

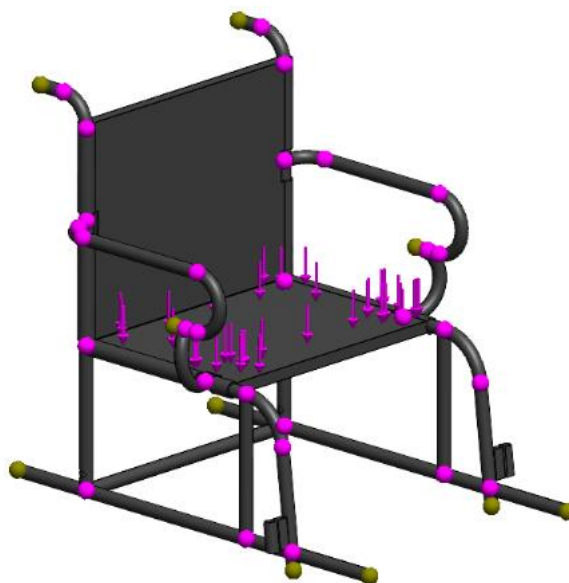


Figure 11. Applying weight to a wheelchair

4.4. Simulation Results

The simulation results show that the wheelchair design can withstand the load safely, as follows. Maximum voltage (von Mises): 13.65 MPa, well below the limit of the material's strength.

The simulation results indicate a maximum strain value of 0.00021, which remains well within the elastic limit of the selected material (Grey Cast Iron). This low strain value confirms that the structural deformation under the applied loading condition is minimal and does not approach the material's yield threshold. Therefore, the wheelchair frame is expected to maintain its structural integrity without permanent deformation during normal operational use.

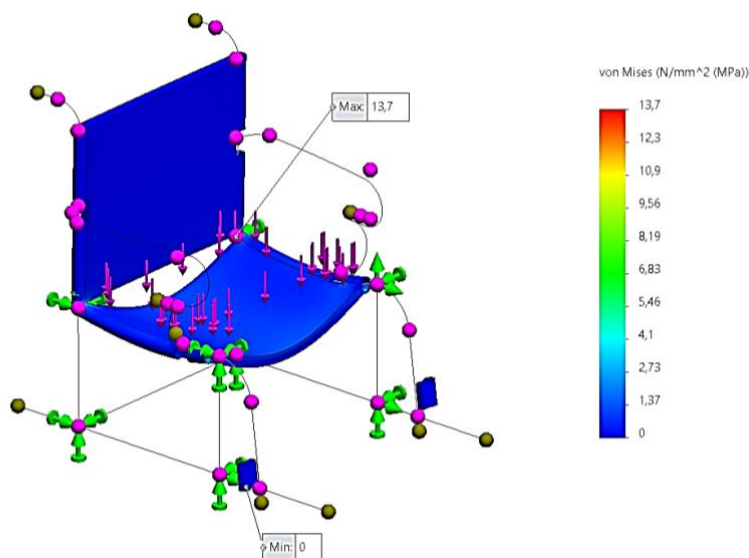


Figure 12. Simulation results in the form of voltage values

Maximum displacement: 0.0429 mm, indicating minimal deformation.

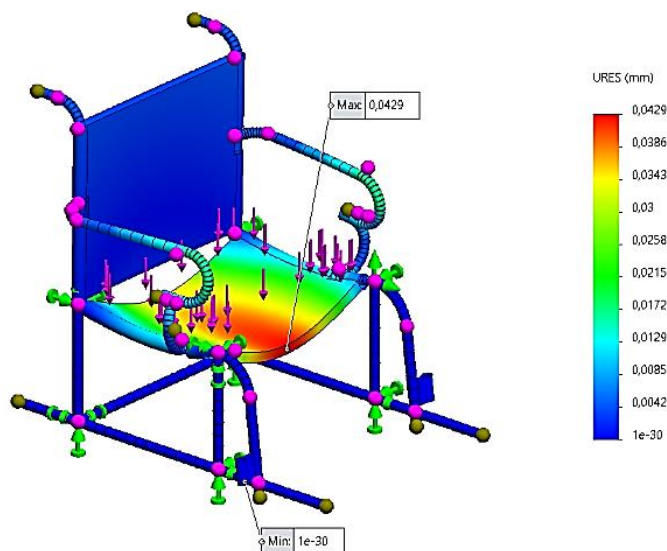


Figure 13. Simulation results in the form of displacement values

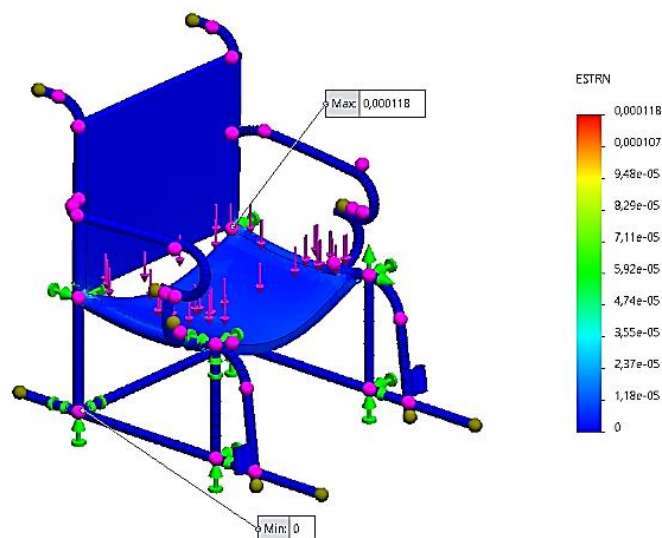


Figure 14. Simulation results in the form of strain values

Maximum safety factor: 7.47, which indicates the design is structurally safe for everyday use.

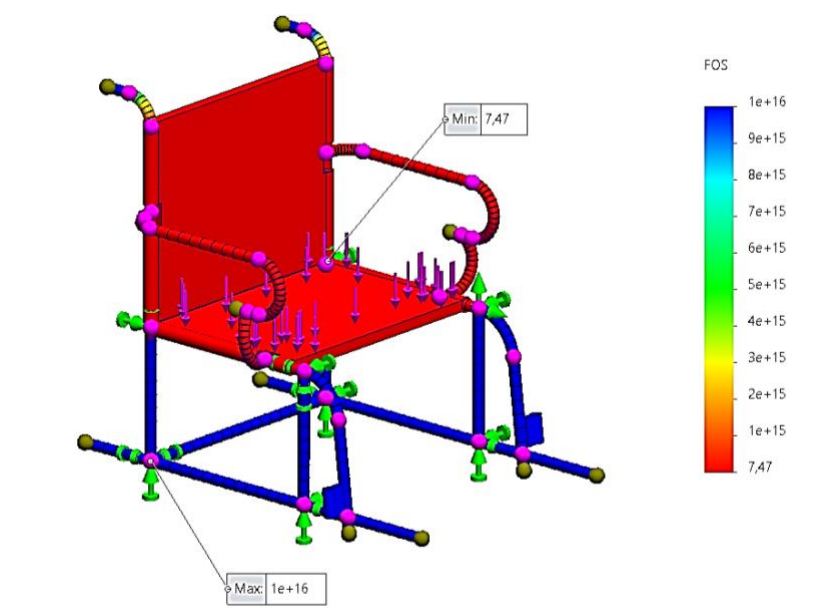


Figure 15. Simulation results in the form of safety factor values

4.5. Expert Validation Results

The feasibility test in this study includes aspects of efficiency, durability, aesthetics, precision, and safety. The advanced features of this smart wheelchair, such as sensor-based automated navigation, obstacle detection, and smartphone-based control, are designed to help students with disabilities better access learning materials and move more easily and independently in a hybrid classroom environment. Based on the results of the feasibility test conducted by 5 experts in their fields, which were reviewed from 5 indicators, namely the essence of the tool, the durability of the tool, aesthetics, precision value, and safety. Thus, the feasibility test results for the development of smart wheelchair assistants to be integrated into hybrid classes for students with disabilities were obtained. The results of the feasibility test are shown in Table 2.

Table 2. Validation results of each indicator

Validator	Indicator					Average Validation Results	Category
	Tool Efficiency	Tool Durability	Aesthetic	Precision Values	Safety		
1	100%	100%	100%	100%	100%	100%	Highly Feasible
2	100%	88%	92%	92%	92%	93%	Highly Feasible
3	100%	100%	100%	100%	100%	100%	Highly Feasible
4	75%	75%	75%	67%	58%	70%	Feasible
5	81%	75%	92%	75%	75%	80%	Highly Feasible

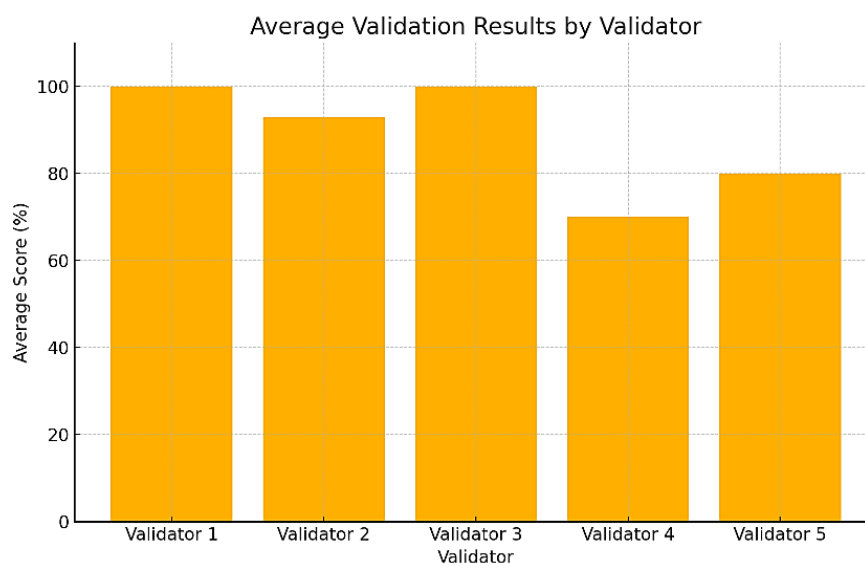


Figure 16. Average validation result by validator

Based on the validation results from five experts across five main aspects: tool efficiency, tool durability, aesthetic, precision values, and safety, the developed product is generally classified as highly feasible for use. Validators 1 and 3 awarded a perfect score of 100% across all indicators, indicating that the product performs excellently in terms of efficiency, durability, visual design, functional accuracy, and user safety. Validator 2 also provided a very high average score of 93%, although slight reductions were observed in the aspects of durability, aesthetics, precision, and safety; nevertheless, the product remained within the Highly Feasible category. In contrast, Validator 4 assigned an average score of 70%, categorised as Feasible, suggesting that while the product is sufficiently acceptable for use, several improvements are necessary, particularly in precision (67%) and safety (58%) to enhance reliability and user protection. Validator 5 reported an average score of 80%, categorised as Highly Feasible, indicating that the product meets the required feasibility standards, although further refinement is still possible in durability and safety. Based on the validation results presented in Table 2, the product falls within the "Highly Feasible" and "Feasible" categories, supporting its application in the learning process while incorporating the recommended improvements from the validators.

4.6. Performance Testing Results

Figure 17 shows a standard manual wheelchair in its original condition before any modification or integration of an automatic control system. This wheelchair is still in its conventional form and has not yet been equipped with electronic components, sensors, motors, or remote-control features. It represents the initial baseline condition before the development and installation of the automatic wheelchair system.

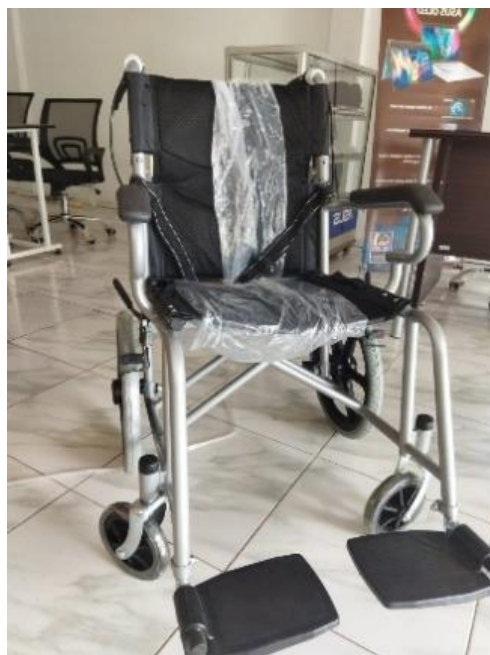


Figure 17. Normal wheelchair without a smart module

Figure 18 illustrates a series of performance tests conducted on the automatic wheelchair prototype to evaluate its control system, mobility, and load-bearing capability. The testing was carried out in an outdoor environment under various operating conditions. The results demonstrate that the system functions properly and responds reliably to control commands. The wheelchair can be operated remotely via a wireless remote control, with stable, consistent performance. Furthermore, the tests were conducted under two conditions, namely with load (user seated on the wheelchair) and without load. In both conditions, the wheelchair maintained stable motion, accurate directional control, and reliable motor response, indicating that the automatic wheelchair system performs effectively and is suitable for practical use. Smart Wheelchair devices integrated into hybrid classes are urgently needed. This device can help people with physical disabilities be more flexible in learning in a Hybrid classroom environment and help control other assistive devices specifically designed for people with disabilities. The trial results show that this smart wheelchair performs well in the classroom. Although there was a problem with the motion system of one wheel during initial testing, after evaluation and repair, the system performs effectively. Subsequent tests: The wheelchair can avoid obstacles and change paths in response to changes in the classroom layout through a sensor-based automatic navigation system. Observational results from repeated trials indicate stable movement, responsive directional control, and effective obstacle avoidance under classroom conditions. These findings are based on controlled trial observations rather than large-scale statistical evaluation.

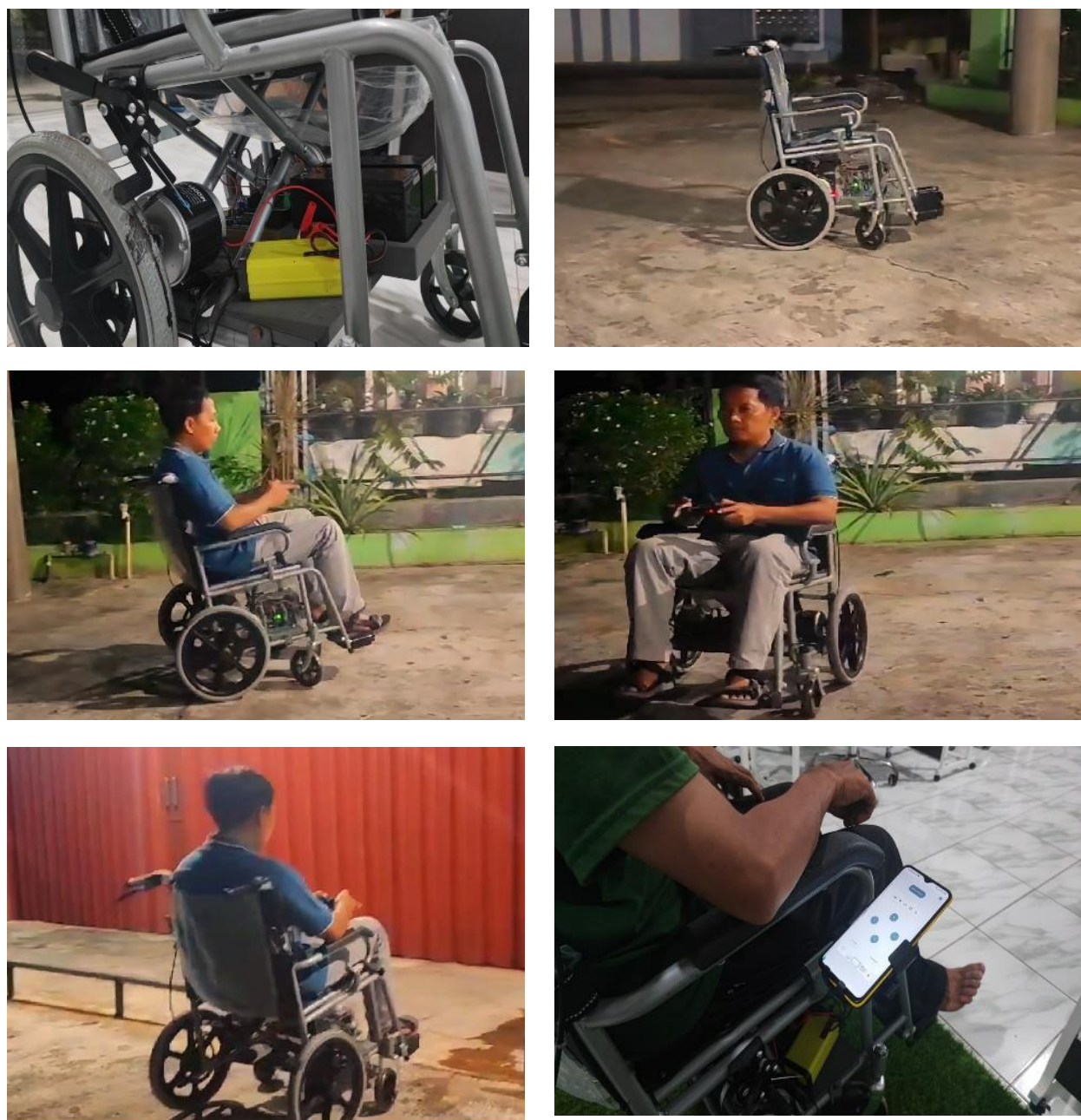


Figure 18. Picture of the test results

The results of the feasibility test on the tool efficiency indicator based on the assessment of 5 experts obtained the percentage results of each validator, namely three validators with an assessment result of 100% with the category of Highly Feasible, one validator gave an assessment of 75% with the feasible category and one validator gave an assessment result of 81% with the category of Highly Feasible. The results of the validator assessment on the tool efficiency indicator indicated that the smart wheelchair assistive technology developed can improve the mobility of students with disabilities during learning in hybrid classes, and that the developed smart wheelchair navigation system functions well. In addition, the tools developed are easy for students with disabilities to use.

Based on the results of the feasibility test in Table 2, two expert validators provide 100% assessments in the Highly Feasible category, one validator provides an 88% assessment in the Highly Feasible category, and two validators provide 75% assessments in the feasible category. Based on the expert assessment of the tool's durability indicator, the developed tool shows resistance to impact or shock, and the power system (battery) on this smart wheelchair can withstand daily use. This smart wheelchair is equipped with a variety of advanced features that consistently show performance on various types of floor surfaces.

In the aesthetic indicators, the results of the feasibility test are based on Table 2. Two experts gave an aesthetic percentage assessment of 100% with a very decent category; two experts also gave a review of 92% with a Highly Feasible category; and one validator gave a review of 75% with a feasible category. Based on the study's results, experts stated that the developed smart wheelchair tool has an easily recognisable appearance as an educational aid. The layout of the buttons and controls on this wheelchair is well-designed, making it easier for users to operate. In addition, the smart chair's design pays close attention to user needs.

In the precision value indicator, the validator stated that the smart chair developed has a navigation system that precisely determines the path and adapts to changes in the room or terrain. Two experts gave 100% assessments with a Highly Feasible category; one expert gave a 92% assessment with a Highly Feasible category; one expert gave a 67% assessment with a feasible category; and one expert gave a 75% assessment with a feasible category. In addition, based on the results of safety indicators, they are tested by simulations in various indoor and outdoor environments. This Smart Wheelchair can be moved via Bluetooth from a smartphone or a joystick. In detecting dangers, the system demonstrates stable performance with low response latency and consistent navigation accuracy under controlled testing conditions. This is also seen based on the results of the feasibility test in Table 2, where two experts give a 100% percentage assessment of safety indicators with a Highly Feasible category, 1 expert gives a percentage assessment of 92% with a Highly Feasible category, and one expert gives a percentage of 58% with a feasible category. And one expert gave a 75% rating in the feasible category.

Early trial results show that smart wheelchair assistant technology is highly promising for navigation, compatibility with hybrid classroom environments, and compatibility with hybrid classroom layouts and digital learning activities. This technology can improve the accessibility and involvement of students with disabilities in hybrid classrooms. The proposed system incorporates several advanced features designed to

support adaptive mobility in hybrid learning environments.

4.7. Feature Validation and Scope Clarification

The current prototype implementation focuses on validated features, including sensor-based navigation, ultrasonic obstacle detection, Bluetooth-based manual control, GPS-assisted positioning, and auto-parking functionality. These features were tested through functional trials, demonstrating stable navigation performance, responsive control, and reliable obstacle avoidance. Several advanced features mentioned in earlier sections, including accident detection, automatic braking systems, and full integration with hybrid learning software, have not yet been fully implemented or experimentally validated within this study. Therefore, these features should be considered as part of future development rather than confirmed system capabilities. Future work will focus on integrating advanced safety mechanisms, such as real-time hazard detection, adaptive braking systems, and intelligent terrain recognition, as well as improving interoperability with digital learning platforms. These enhancements are expected to strengthen further the system's role in supporting accessibility and safety in hybrid learning environments.



Figure 19. Simulation of controlling Internet of Things (IoT) devices with a Smart Wheelchair

The feasibility of the proposed smart wheelchair is strongly supported by expert validation results, which indicate high scores across efficiency, durability, aesthetics, precision, and safety. These findings demonstrate that the system is technically reliable and structurally safe for daily use in hybrid classroom environments. From a usability perspective, the integration of joystick control, smartphone-based operation via Bluetooth, GPS tracking, and auto-parking features enables users to operate the wheelchair independently with minimal training. The intuitive control system allows students with disabilities to navigate dynamic classroom layouts, adjust speed and direction easily, and interact more actively with

learning activities. However, several challenges must also be considered. From a cost perspective, the use of sensors, GPS modules, microcontrollers, and motor drivers may increase initial production costs, potentially limiting large-scale implementation, particularly in institutions with restricted budgets. In addition, classroom conditions such as narrow aisles, uneven floor surfaces, limited wireless connectivity, and frequent layout changes may affect navigation performance and require further system calibration. Therefore, future development should focus on optimising hardware efficiency, reducing production costs, enhancing system robustness across various classroom conditions, and improving compatibility with existing digital learning infrastructures to ensure scalable, sustainable implementation.

4.8. Comparison with Previous Studies

Comparative Analysis with Previous Studies: The findings of this study align with previous research on smart wheelchair technologies that emphasise sensor-based navigation and assistive mobility. However, unlike earlier systems developed primarily for healthcare or outdoor contexts, the prototype in this study demonstrates effective navigation in hybrid classroom environments. This distinction marks a shift from general assistive mobility to educational accessibility, addressing a gap noted by [12] and Zhou [14]. Compared with AI-assisted wheelchairs or IoT-based mobility devices in previous studies, the proposed system offers stronger classroom adaptability through its combination of ultrasonic sensors, infrared line detection, and Bluetooth manual override. These features enable precise navigation through narrow classroom pathways and flexible seating arrangements, capabilities that existing studies did not explicitly address.

Novelty and Contribution to Hybrid Learning Accessibility: This study contributes a novel integration of smart mobility technology within hybrid learning environments. The prototype is designed not only for movement but also to support independent access to digital learning tools, classroom interactions, and physical participation. This focus on hybrid-learning accessibility differentiates the system from previous smart wheelchair designs, which seldom consider classroom dynamics or digital learning requirements. The strong expert validation scores and high navigation accuracy suggest that the prototype is functionally feasible for educational use. The system's ability to maintain stable movement, avoid obstacles, and respond quickly to manual commands indicates its readiness for real-world hybrid learning environments. These results reinforce the effectiveness of the adaptive sensor configuration and highlight the practical value of integrating assistive mobility with instructional accessibility.

The study demonstrates that integrating automated navigation with adaptive sensor systems significantly improves classroom accessibility for students with disabilities. The prototype enables independent mobility during hybrid learning activities, reducing reliance on assistance and enhancing participation in both digital and physical learning interactions. This supports inclusive education policies and expands opportunities for equal engagement in smart-classroom environments.

4.9. Limitations and Future Work

Several limitations were identified during system development and testing. First, the prototype was tested mainly in controlled classroom environments, limiting generalisation to larger or more complex spaces. Second, the ultrasonic sensors exhibited reduced accuracy at very close distances (<20 cm). Third, indoor GPS functionality was limited, restricting full utilisation of outdoor-to-indoor navigation.

Future development should focus on enhancing navigation intelligence through AI-based path prediction, integrating LiDAR sensors for improved indoor mapping, and utilising advanced motor drivers for smoother directional control. Additional work is also recommended to expand interoperability with smart-classroom systems, including IoT-enabled attendance tracking, automated desk alignment, and assistance notifications. Broader testing across diverse classroom layouts and involving actual student users will strengthen the prototype's applicability.

5. Conclusion

This study developed a smart wheelchair equipped with automated navigation, sensor-based obstacle detection, and Bluetooth-controlled manual override to enhance accessibility for students with disabilities in hybrid learning environments. The ADDIE-based development process enabled systematic design, testing, and refinement of the prototype. Expert validation results and performance tests confirmed that the system operates efficiently, safely, and reliably within classroom settings. The prototype supports independent mobility, improves classroom participation, and bridges the accessibility gap in hybrid learning. Its successful navigation performance and structural stability demonstrate its potential as a practical assistive technology solution for inclusive education, particularly in smart-classroom ecosystems that integrate digital and physical learning activities. Future work should focus on enhancing indoor navigation precision, expanding IoT interoperability, and conducting larger-scale user trials involving students with disabilities to validate long-term usability and educational impact. These improvements will

strengthen the system's role in promoting accessible, equitable, and technology-supported learning environments.

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References

- [1] J. Singh, K. Steele, and L. Singh, "Combining the best of online and face-to-face learning: Hybrid and blended learning approach for COVID-19, post vaccine, & post-pandemic world," *Journal of Educational Technology Systems*, vol. 50, no. 2, pp. 140-171, 2021, doi: <https://doi.org/10.1177/00472395211047865>.
- [2] G. Papaioannou, M.-G. Volakaki, S. Kokolakis, and D. Vouyioukas, "Learning spaces in higher education: a state-of-the-art review," *Trends in Higher Education*, vol. 2, no. 3, pp. 526-545, 2023, doi: <https://doi.org/10.3390/higheredu2030032>.
- [3] L. H. van der Woude *et al.*, "Rehabilitation: mobility, exercise & sports; a critical position stand on current and future research perspectives," *Disability and Rehabilitation*, vol. 43, no. 24, pp. 3476-3491, 2021, doi: <https://doi.org/10.1080/09638288.2020.1806365>.
- [4] E. Arcari, "Mini choice. Smart remote control for multisensorial and/or smart environments management," M.S. thesis, School of Design, Politecnico di Milano, Milan, Italy, 2019.
- [5] E. Karageorgou, S. Adam, S. Doukakis, and P. Vlamos, "Digital Accessibility for Students with Disabilities and Inclusive Learning in Education," in *International Genomics, Neuroscience, Therapeutics and Data Innovation Summit*: Springer, 2024, pp. 417-424. https://doi.org/10.1007/978-3-032-03402-1_44
- [6] B. Meskhi, S. Ponomareva, and E. Ugnich, "E-learning in higher inclusive education: needs, opportunities and limitations," *International Journal of Educational Management*, vol. 33, no. 3, pp. 424-437, 2019, doi: <https://doi.org/10.1108/IJEM-09-2018-0282>.
- [7] Y. Riady, M. Arisanty, E. Kuswanti, S. Sukatmi, M. F. Karim, and M. Ajmal, "The role of open and distance education in digital ecosystem transformation: A qualitative study on enhancing educational accessibility," *IJOEM Indonesian Journal of E-learning and Multimedia*, vol. 4, no. 2, pp. 81-89, 2025, doi: <https://doi.org/10.58723/ijoem.v4i2.386>.
- [8] V. Fitranita, E. Risdianto, and M. Ardina, "Feasibility Test of Moocs Platform Development for Interactive Adaptive Digital Modules for Hybrid Classes Implementation in Providing Easy Access for Students with Disabilities," *JENTIK: Jurnal Pendidikan Teknologi Informasi Dan Komunikasi*, vol. 3, no. 2, pp. 45-49, 2024, doi: <https://doi.org/10.58723/jentik.v3i2.329>.
- [9] S. U. Khadilkar and N. Wagdarikar, "Android phone controlled voice, gesture and touch screen operated smart wheelchair," in *2015 International Conference on Pervasive Computing (ICPC)*, 2015: IEEE, pp. 1-4, doi: <https://doi.org/10.1109/ICPC.2015.7388888>.

- <https://doi.org/10.1109/PERVASIVE.2015.7087119>.
- [10] A. M. Cook, J. M. Polgar, and P. Encarnação, *Assistive Technologies-E-Book: Assistive Technologies-E-Book*. Elsevier Health Sciences, 2019.
- [11] J. A. Vergara, Y. M. Ramirez, and J. E. Camargo, "A pervasive and ubiquitous mobile health application for tracking people with disabilities," in *2015 10th Computing Colombian Conference (10CCC)*, 2015: IEEE, pp. 206-213, doi: <https://doi.org/10.1109/ColumbianCC.2015.7333433>.
- [12] D. F. Hartopo, L. Hilfi, and M. N. Ardisasmita, "Development of Disability Inclusion Capacity Instrument for Community Cadres: Rasch Model Analysis," *Jurnal Ilmiah Pengabdian Masyarakat Bidang Kesehatan (Abdigermas)*, vol. 3, no. 2, pp. 82-96, 2025, doi: <https://doi.org/10.58723/abdigermas.v3i2.452>.
- [13] B. E. Dicianno *et al.*, "The voice of the consumer: a survey of veterans and other users of assistive technology," *Military Medicine*, vol. 183, no. 11-12, pp. e518-e525, 2018, doi: <https://doi.org/10.1093/milmed/usy033>.
- [14] B. Zhou, "Transforming translation education: A bibliometric analysis of artificial intelligence's role in fostering sustainable development," *International Journal of Learning, Teaching and Educational Research*, vol. 24, no. 3, pp. 166-190, 2025, doi: <https://doi.org/10.26803/ijlter.24.3.9>
- [15] E. Cano-Cruz, "Development of a Smart Lamp Device Using Project-Based Learning and the ADDIE Model for Teaching IoT to Software Engineering Students," *Computer Applications in Engineering Education*, vol. 34, no. 1, p. e70143, 2026, doi: <https://doi.org/10.1002/cae.70143>.
- [16] G. Bourhis and M. Sahnoun, "Assisted control mode for a smart wheelchair," in *2007 IEEE 10th International Conference on Rehabilitation Robotics*, 2007: IEEE, pp. 158-163, doi: <https://doi.org/10.1109/ICORR.2007.4428422>.
- [17] A. Nair, A. Bhatkar, B. Biju, A. Shetty, and M. Thomas, "Design and development of a smart wheelchair," in *2021 4th Biennial International Conference on Nascent Technologies in Engineering (ICNTE)*, 2021: IEEE, pp. 1-5, doi: <https://doi.org/10.1109/icnte51185.2021.9487650>.
- [18] G. Bourhis, O. Horn, O. Habert, and A. Pruski, "An autonomous vehicle for people with motor disabilities," *IEEE Robotics & Automation Magazine*, vol. 8, no. 1, pp. 20-28, 2001, doi: <https://doi.org/10.1109/100.924353>.
- [19] L. Ferrari, M. Berlingiero, F. Calabrese, and J. Reades, "Improving the accessibility of urban transportation networks for people with disabilities," *Transportation Research Part C: Emerging Technologies*, vol. 45, pp. 27-40, 2014, doi: <https://doi.org/10.1016/j.trc.2013.10.005>.
- [20] D. Harianto, H. S. Bintang, A. Ardiyanto, and V. L. D. Widyawan, "Development and Evaluation of an ESP32-based Temperature and Humidity Control Unit for Textile Storage", *International Journal of Engineering Continuity*, vol. 4, no. 1, pp. 1–19, 2024, doi: <https://doi.org/10.58291/ijec.v4i1.309>.
- [21] N. Wanluk, S. Visitsattapongse, A. Juhong, and C. Pintavirooj, "Smart wheelchair based on eye tracking," in *2016 9th Biomedical Engineering International Conference (BMEiCON)*, 2016: IEEE, pp. 1-4, doi: <https://doi.org/10.1109/BMEiCON.2016.7859594>.
- [22] T. I. Chowdhury, S. M. S. Ferdous, and J. Quarles, "VR disability simulation reduces implicit bias towards persons with disabilities," *IEEE Transactions on Visualization and Computer Graphics*, vol. 27, no. 6, pp. 3079-3090, 2019, doi: <https://doi.org/10.1109/TVCG.2019.2958332>.