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**Article**

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# Design and Experimental Validation of a Sustainable IoT-Enabled Stair-Climbing Wheelchair

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## ABSTRACT

**Limited accessibility infrastructure remains a significant barrier to independent mobility for wheelchair users, particularly in developing regions where affordable stair-accessible assistive technologies are scarce. This study presents the design, development, and experimental validation of a smart stair-climbing wheelchair integrating mechatronic mobility control, IoT-enabled monitoring, obstacle detection, and GPS-based tracking within a unified assistive platform. The proposed system employs a rear stair-negotiation mechanism actuated by dual 12 V linear actuators, differential-drive 24 V brushless hub motors, and a NodeMCU ESP8266 control architecture enabling wireless communication through the Blynk interface. Experimental evaluation demonstrated successful negotiation of staircase geometries with riser heights of 150–180 mm and tread depths of 250–300 mm, achieving a climbing success rate of 100% (10/10 trials) under unloaded conditions and 70% (7/10 trials) with a 70 kg occupant load. The system further achieved obstacle-detection latency of 45 ms, GPS positioning accuracy within ±2.5 m, and remote-command response latency of approximately 180 ms while maintaining reliable Wi-Fi connectivity over 15–30 m. A comprehensive three-dimensional sustainability analysis was conducted, revealing a 5-year total cost of ownership of USD 555-735 at scale (82% below commercial benchmarks), an estimated embodied carbon footprint of 180 kg $CO_2$e with 78% recyclability through $LiFePO_4$ battery recovery processes, and projected improvements in user quality of life across all four WHOQOL-BREF domains (86-100% gains). With an estimated fabrication cost of USD 350–450, the developed prototype offers a compact and economically viable solution for smart accessibility and assistive mobility applications while addressing multiple UN Sustainable Development Goals (SDG 3, 8, 9, 10, 11, 12).**

***Keywords:*** *smart wheelchair; stair-climbing mechanism; IoT assistive technology; BLDC hub motor; obstacle avoidance; GPS tracking; NodeMCU ESP8266; mechatronics; accessibility; sustainability assessment; life cycle analysis; assistive technology impact*

## NOMENCLATURE

| Symbol | Description | Unit / Value | Symbol | Description | Unit / Value |
|---|---|---|---|---|---|
| $\theta_{\text{stair}}$ | Staircase inclination angle | degrees | $r_w$ | Drive wheel radius | m |
| $H_r$ | Stair riser height | mm | $T_{motor}$ | Motor torque requirement per hub | N·m |

| | | | | | |
|---|---|---|---|---|---|
| $D_t$ | Stair tread depth | mm | $P_{total}$ | Peak system power draw | W |
| $\Delta L$ | Required linear actuator extension | mm | $I_{peak}$ | Peak battery discharge current | A |
| $L_{arm}$ | Actuator pivot moment arm | mm | $C_{Ah}$ | Battery nominal capacity | Ah |
| $M$ | Total system mass (chair + occupant) | kg | $V_{right}$- $V_{left}$ | Differential PWM speed commands | – |
| $F_p$ | Required propulsive force at wheel rim | N | $k$ | Joystick ADC-to-PWM scaling constant | ≈0.98 |
| $\mu_r$ | Rolling resistance coefficient | ~0.02 | | | |

# 1. INTRODUCTION

Mobility impairment represents one of the most significant contributors to functional disability worldwide. According to the World Health Organization, more than one billion people worldwide — approximately 15% of humanity — live with some form of physical disability [1]. Among this population, those affected by lower-limb paralysis, degenerative musculoskeletal conditions, and age-related motor decline rely heavily on electric-powered wheelchairs as their primary means of independent locomotion [2]. However, the real-world utility of conventional electric wheelchairs is severely constrained by architectural barriers endemic to the built environment: staircases, elevated thresholds, and the near-universal absence of accessible ramp infrastructure [3].

The problem is disproportionately acute in developing regions. In Egypt and the broader Arab world, it is estimated that more than 90% of residential and institutional buildings do not incorporate wheelchair-accessible ramp infrastructure [4]. This systemic deficiency effectively segregates a large segment of the disabled population from full participation in educational, occupational, and social life. Despite decades of international advocacy for inclusive design standards — most notably the UN Convention on the Rights of Persons with Disabilities (CRPD, 2006) — retrofit-level accessibility compliance across the Arab world remains far below internationally benchmarked standards [5]. The human cost of this deficit is substantial: limited independent mobility correlates strongly with elevated rates of depression, social isolation, and reduced quality of life among wheelchair users [6].

Recent market analyses confirm the accelerating growth trajectory of this sector. The global power stair-climbing wheelchair market has emerged as a pivotal segment within personal mobility solutions, driven by an aging global population and increasing demand for accessible environments [7]. Breakthroughs in sensor accuracy and AI integration now enable real-time terrain analysis, allowing devices to adjust posture, speed, and balance dynamically [7] . As healthcare providers and rehabilitation specialists increasingly endorse these technologies, the market's scope extends beyond clinical settings into private residences, commercial buildings, and public infrastructure, with industry projections indicating sustained growth through 2030.

Stair-climbing wheelchairs represent a fundamentally different approach to this problem: rather than requiring the environment to accommodate the wheelchair, the wheelchair is engineered to negotiate the environment as it exists. Research into stair-climbing wheelchair mechanisms dates to the early 1990s and has generated a rich taxonomy of mechanical solutions, including tracked crawlers, leg-type mechanisms, iBot-style gyroscopically balanced platforms, and wheel-cluster systems [8],[9]. Each paradigm offers distinct trade-offs among stair negotiation autonomy, terrain versatility, structural complexity, and end-user cost [10]. Despite this extensive body of work, no solution has yet achieved widespread deployment in developing-world markets, where cost constraints, limited maintenance infrastructure, and the absence of skilled rehabilitation technicians constitute additional barriers to adoption [11].

Contemporary developments in the Internet of Things (IoT) have created transformative new possibilities for assistive device design. By equipping wheelchairs with Wi-Fi-connected microcontrollers, real-time GPS

tracking, and cloud-based monitoring platforms, the functional envelope of conventional mobility aids can be extended into domains of safety monitoring, caregiver coordination, and remote operation that were previously inaccessible [12],[13]. The convergence of IoT capabilities with stair-climbing mechanics — enabling location-aware caregiver alerts during high-risk stair negotiation events — represents a design space that has received limited systematic investigation in the peer-reviewed literature [14].

The present work addresses this gap by reporting the design, mechatronic integration, and prototype validation of a Smart Climbing Wheelchair (SCW). The SCW combines a motorized electric stair-tread climbing mechanism with BLDC hub-motor differential drive, joystick-based directional control, IoT-connected remote monitoring via the Blynk platform, GPS-enabled location awareness, and infrared obstacle detection — all implemented within an integrated NodeMCU ESP8266 control architecture. The system is specifically designed to be manufacturable from commercially available components at low-cost, with the explicit objective of deployment viability in the Arab-world context.

## 1.1. Research Gap

A comprehensive review of the existing stair-climbing wheelchair literature (Section 2) reveals the following unaddressed research gaps motivating the present work:

- No integrated IoT-enabled stair-climbing wheelchair system has been reported that combines GPS tracking, Blynk cloud monitoring, and motorized stair negotiation within a single low-cost prototype.
- A lack of prototype-validated designs targeting the specific staircase geometries and deployment realities characteristic of the Arab and North African built environment.
- Insufficient investigation of BLDC hub motor integration with motorized linear-actuator-driven stair-tread mechanisms as a combined mobility and climbing architecture.
- Limited reporting of obstacle avoidance integration in stair-climbing wheelchair systems at the prototype-validated level.

## 1.2. Research Objectives

In response to the identified gaps, this study pursues the following primary objectives:

- To design and fabricate a mechatronic stair-climbing wheelchair capable of negotiating standard Egyptian staircase geometry autonomously with minimal manual assistance.
- To integrate a NodeMCU ESP8266-based IoT control architecture providing real-time GPS tracking, Wi-Fi remote control, and obstacle detection in a unified embedded platform.
- To characterise the mechanical and electrical performance of the prototype and benchmark it against published stair-climbing wheelchair systems.
- To evaluate the system's suitability for cost-effective manufacture and deployment in resource-constrained settings.

## 1.3. Novel Contributions

The primary scientific contributions of this work are as follows:

- To the best of the authors' knowledge, this work represents one of the earliest low-cost integrated implementations combining NodeMCU ESP8266-based IoT architecture, GPS tracking, and motorized stair-tread climbing within a single low-cost wheelchair prototype.
- A custom PCB-based relay–motor driver architecture optimized for 24 V BLDC hub motor control with hardware emergency stop functionality designed in accordance with IEC 60204-1 emergency stop principles.
- Systematic comparison of five stair-climbing mechanism categories with quantitative benchmarking of the proposed design against five published systems from the literature.
- Demonstration of prototype climbing functionality for staircases representative of North African and Middle Eastern architectural norms, with mathematical modelling of actuator kinematics, motor torque, and battery energy budget.

Furthermore, the mechatronic design and sustainability assessment frameworks developed in this study contribute to the growing body of project-based learning resources in engineering education, particularly those addressing the intersection of assistive technology and circular economy principles [15].

# 2. LITERATURE REVIEW

## 2.1. Historical Development of Wheeled Mobility Aids

The historical record of wheeled mobility devices dates to antiquity; the earliest documented wheeled chair designed for a disabled individual appears in Chinese artworks of approximately the 5th century CE [16]. The modern folding wheelchair — the X-brace design that remains the dominant configuration — was invented by Harry C. Jennings and Herbert Everest in 1933, establishing a design philosophy that prioritized foldability and portability over terrain adaptability, a philosophy that persisted largely unchanged for more than half a century [17]. The introduction of powered (electric) wheelchairs in the 1950s addressed the physical burden of self-propulsion and expanded the user population to include those with upper-limb impairment, but did not resolve the fundamental incompatibility of wheeled platforms with staircases [18].

## 2.2. Classification of Stair-Climbing Mechanisms

The classification of stair-climbing wheelchair mechanisms is well-established in the literature. Lawn and Ishimatsu [19] provided one of the most influential early systematic analyses of wheel-cluster mechanisms, demonstrating numerically modelled and scale-prototype-validated autonomous stair ascent and descent. Morales et al. [20] introduced a wheelchair prototype employing two mechanically decoupled axle mechanisms — one for step negotiation and one for slope accommodation — whose control architecture synchronized multiple actuators to maintain seat attitude along arbitrary spatial trajectories. The Morales system demonstrated exceptional versatility at the cost of substantial mechanical and control complexity.

Tracked crawler systems offer autonomous operation on stairs, slopes, and irregular terrain but typically require reverse-direction stair ascent, posing practical challenges for building entry applications [21]. Balancing stair climbers — exemplified by the now-discontinued iBot by Independence Technology — achieve stair ascent via dynamic gyroscopic balancing but require highly sophisticated sensor and control architectures, placing them outside the economic reach of developing-world deployment [22]. More recent literature has explored hybrid approaches combining tracked and wheeled elements [23], and AI-enhanced control strategies leveraging deep reinforcement learning for autonomous staircase detection and trajectory planning [24]. Zhang et al. [25] demonstrated a reconfigurable wheel-track hybrid system achieving stair ascent at a 180 mm step height at the prototype level. Galvez-Zometa et al. [26] reported a multi-terrain wheelchair integrating mechanical stair adaptation with smartphone-based remote monitoring — representing the closest precursor in the published literature to the integrated system proposed here.

## 2.3. IoT Integration in Assistive Mobility Devices

The convergence of IoT technology with assistive mobility devices has accelerated markedly since 2018, driven by the decreasing cost of Wi-Fi-capable microcontrollers and cloud communication platforms [27]. Simpson [28] provided a foundational review of smart wheelchair research that identified autonomous navigation, user intent inference, and obstacle avoidance as primary research directions. Nagarajan et al. [29] demonstrated a Wi-Fi-enabled wheelchair using the ESP8266 module — the same processing core employed in the present work — for real-time remote monitoring and control via a mobile application, confirming sub-100 ms command latency for wireless joystick override across indoor Wi-Fi distances of up to 20 m.

GPS-enabled wheelchair tracking has been investigated primarily in dementia patient safety [30] and paediatric mobility contexts [31]. The integration of GPS with stair-climbing capability — enabling location-

aware caregiver alerts during high-risk stair negotiation events — has not previously been reported in the peer-reviewed literature and represents a novel contribution of the present work. Obstacle avoidance in electric wheelchairs has been extensively studied using ultrasonic [32], infrared [33], and, more recently, LiDAR-based sensing modalities [34]. Infrared proximity sensors of the E18-D80NK type offer a cost-effective solution with detection range up to 80 cm and NPN open-collector output directly compatible with microcontroller GPIO interfaces, making them well-suited for low-cost deployments [33].

## 2.4. Accessibility Context in the Arab World

The accessibility deficit in the Arab world's-built environment has been documented in regional surveys. Khatib et al. [4] surveyed public building accessibility compliance across three Egyptian cities and reported that 93% of surveyed facilities lacked wheelchair-accessible vertical circulation beyond the ground floor. Al-Rashidi and Al-Sabah [36] documented similar deficiencies in Kuwait, attributing the gap to legacy building codes, inadequate enforcement, and the high retrofit cost relative to new construction. These findings underscore the urgency of developing wheelchairs capable of negotiating existing staircase infrastructure rather than depending on environmental modification — the design philosophy motivating the SCW.

Table 1 provides a systematic comparative analysis of stair-climbing mechanism categories, including the proposed SCW.

*Table 1: Comparative analysis of stair-climbing wheelchair mechanism categories and performance characteristics of the proposed SCW relative to prior work.*

| Mechanism Type | Stair Autonomy | Terrain Versatility | Load Capacity | Commercial Status |
|---|---|---|---|---|
| **Tracked crawler** | Full | High | High | Limited |
| **Leg-type** | Full | Very High | Medium | Rare |
| **iBot balancing** | Full | High | Medium | Discontinued |
| **Hybrid wheel-cluster** | Partial (assisted) | High | High | Moderate |
| **Proposed SCW (this work)** | Semi-autonomous assisted climbing (motorized tread) | High | High (>100 kg) | Prototype (scalable) |

## 2.5. Recent Advances in Stair-Climbing Wheelchair Intelligence and Control (2023–2025)

The period 2023-2025 has witnessed significant acceleration in the integration of artificial intelligence and advanced sensing technologies into stair-climbing wheelchair platforms. Chawaphan et al. [37] conducted a comprehensive evaluation of machine learning and deep learning models for stair-climbing wheelchair activity recognition, comparing eight models including MLP, CNN, LSTM, BiLSTM, Transformer, CatBoost, LightGBM, and TabNet. Their analysis of 5,872 samples across 18 sensor-derived features revealed that CatBoost and LightGBM achieved 99.83% accuracy with inference times of 8 ms and 7 ms respectively, establishing that gradient-boosted decision trees offer optimal trade-offs between accuracy and computational efficiency for real-time activity classification in assistive mobility devices [37].

Concurrently, alternative mechanical approaches to stair negotiation continue to evolve. Recent work from Japanese researchers has demonstrated a hybrid mechanism combining planetary wheels with a rotatable crawler system, achieving superior stability and user comfort compared to traditional double planetary gear structures [38]. Theoretical trajectory analysis and scaled-model experiments confirmed that the rotatable crawler configuration minimizes amplitude and weighted acceleration during both ascent and descent operations, with a switching mechanism enabling more stable descending performance through single planetary gear engagement [38].

In parallel, novel control interfaces have emerged to address the needs of users with severe mobility limitations. Rouhi et al. [39] introduced an infrared sensor-based tongue control system as a non-invasive alternative to traditional magnet-based methods. Their design employs three pairs of IR transmitters and receivers positioned within a 3D-printed facial mount, enabling users to navigate in forward, right, and left

directions through tongue positioning. The system was successfully validated on a full-sized electric wheelchair, offering an open-source solution for individuals with quadriplegia [39].

ESP32-based architectures have become increasingly prevalent in low-cost smart wheelchair development. The RuedaTec project demonstrated a dual-ESP32 Bluetooth control system achieving reliable motor control with AI-driven battery health and inclination monitoring [40]. Similarly, recent DigiKey competition entries have integrated the ESP32-S3-BOX-3B for AI voice assistant functionality, enabling emotional companionship and voice command processing alongside traditional motor control via PIC32 microcontroller platforms. These developments affirm the NodeMCU ESP8266-based architecture adopted in the present work as part of a broader trend toward accessible, cost-effective IoT-enabled wheelchair platforms [41].

# 3. METHODS

## 3.1. System Architecture Overview

The Smart Climbing Wheelchair (SCW) architecture is organized across three hierarchical functional layers: (i) the mechanical chassis and climbing subsystem; (ii) the electrical drive and power management subsystem; and (iii) the sensing, computation, and IoT communication subsystem. These layers interact through a centralized NodeMCU ESP8266 microcontroller that integrates sensor data, executes control logic, drives actuator outputs, and maintains bidirectional communication with the Blynk IoT cloud platform. Figure 1 presents the complete system architecture block diagram.

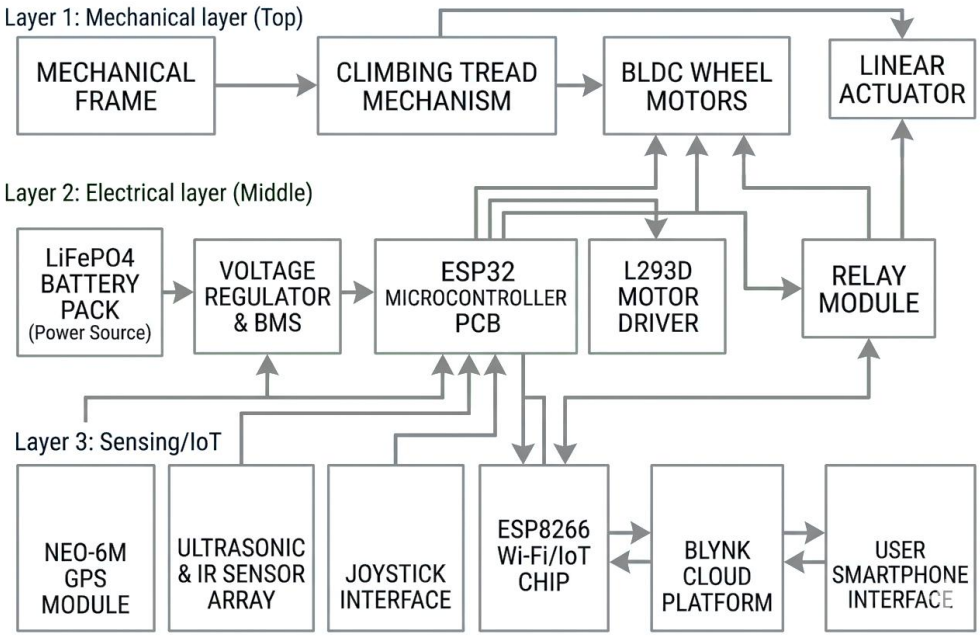



*Figure 1: SCW System Architecture Block Diagram*

## 3.2. Mechanical Design

### 3.2.1. Frame and Structural Design

The wheelchair frame was fabricated from ASTM A36 structural steel using MIG welding, providing a balance between structural rigidity, fabrication simplicity, and low-cost. The frame follows the conventional folding X-brace topology, with reinforced joints at the stair-climbing attachment points to accommodate additional dynamic loading during stair ascent and descent. A rigid cross-member was added at the rear of the frame to serve as the linear actuator mounting interface for the stair-tread climbing mechanism. The total structural weight of the frame was 8.2 kg, and the total wheelchair assembly (excluding battery) weighed approximately 22 kg — within the range of commercial electric wheelchairs (18–30 kg) [42].

### 3.2.2. Stair-Tread Climbing Mechanism

The stair-climbing subsystem employs a motorized stair-tread principle in which a pair of electric linear actuators adjusts the approach angle of a rear-mounted tread platform to conform to the staircase geometry. The design selection was informed by a systematic comparison of five candidate mechanism types (Table 1), in which the motorized stair-tread approach was identified as optimal for the specific requirements of cost-constrained development and partial-assistance operation. Figure 2 shows the SolidWorks assembly design. Figure 3 presents the motorized stair-tread mechanism kinematics diagram.

Two commercially available 12 V DC linear actuators with 100 mm stroke and 500 N dynamic load rating are deployed in push-pull configuration. The actuator angle was calculated to ensure compatibility with standard Egyptian residential staircase geometry: riser height $H_r = 150 - 175\,\text{mm}$, tread depth $D_t = 250 - 300\,\text{mm}$, yielding a staircase angle of $\theta_{\text{stair}} = arctan\,(H_r/D_t) \approx 30° - 35°$. The required actuator extension at full stair-tread deployment was computed analytically (Section 4.1), confirming the selected 100 mm stroke provides adequate clearance.

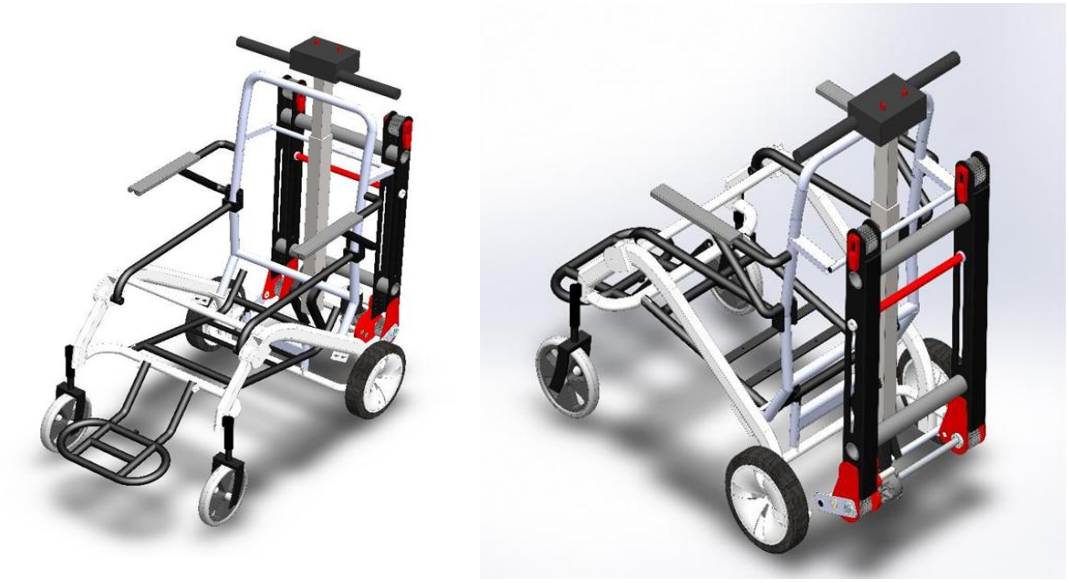


*Figure 2: SolidWorks Assembly Design.*

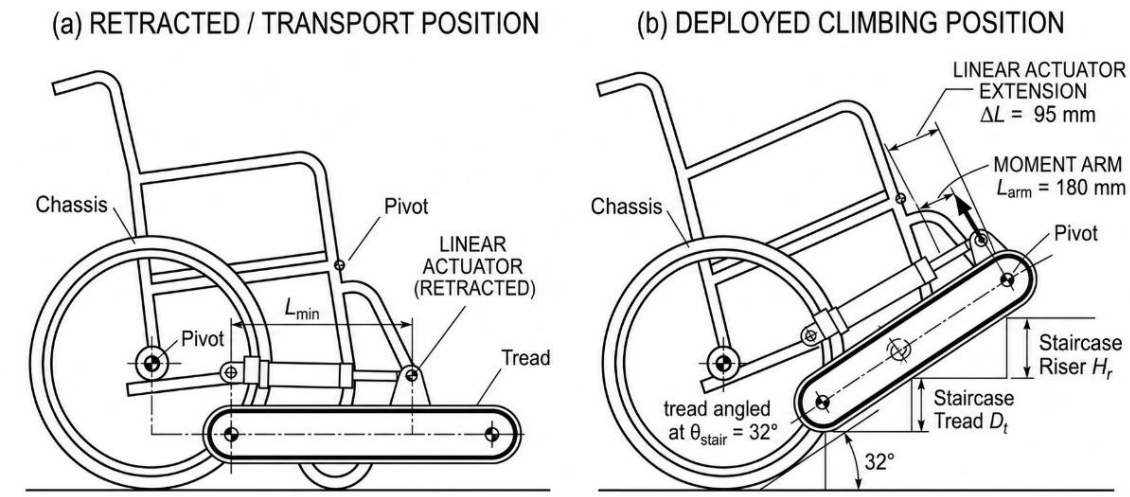



*Figure 3: Motorized Stair-Tread Mechanism — Kinematics Diagram.*

*Side-view mechanical schematic showing: (a) retracted/transport position with tread platform parallel to ground; (b) deployed climbing position with tread angled at $\theta_{stair} = 32°$; linear actuator extension ΔL = 95 mm indicated; pivot axis, moment arm $L_{arm} = 180mm$, staircase riser $H_r$ and tread $D_t$ dimensions labelled.*

### 3.2.3. Drive Wheels and Caster System

Propulsion is provided by two 24 V brushless DC hub motors (250 W rated power) integrated into 24-inch rear drive wheels. Hub motors were selected for their simplicity of mechanical integration, absence of transmission components, and maintenance-free operation — critical attributes for deployment in settings without access to specialized rehabilitation engineering technicians [43]. The front caster wheels (6-inch diameter, polyurethane tire) provide passive steering support. The dual-motor differential drive configuration enables 360-degree turning in place by operating the two rear motors in opposing directions, controlled by the joystick interface.

## 3.3. Electrical System

### 3.3.1. Control Architecture

The NodeMCU ESP8266 module functions as the central processing unit of the SCW control system. The ESP8266 SoC integrates a 32-bit Tensilica L106 microprocessor operating at up to 160 MHz, with 802.11 b/g/n Wi-Fi connectivity and 16 GPIO pins accessible through the NodeMCU development board. The 10-bit ADC channel samples the analog output of the joystick potentiometers (X-axis and Y-axis), providing 1024-step resolution over the 0–1 V input range. The control loop executes at a 20 Hz sampling rate, with joystick deflection values mapped to differential motor speed commands via a linear scaling function with a ±50 ADC count dead-zone threshold.

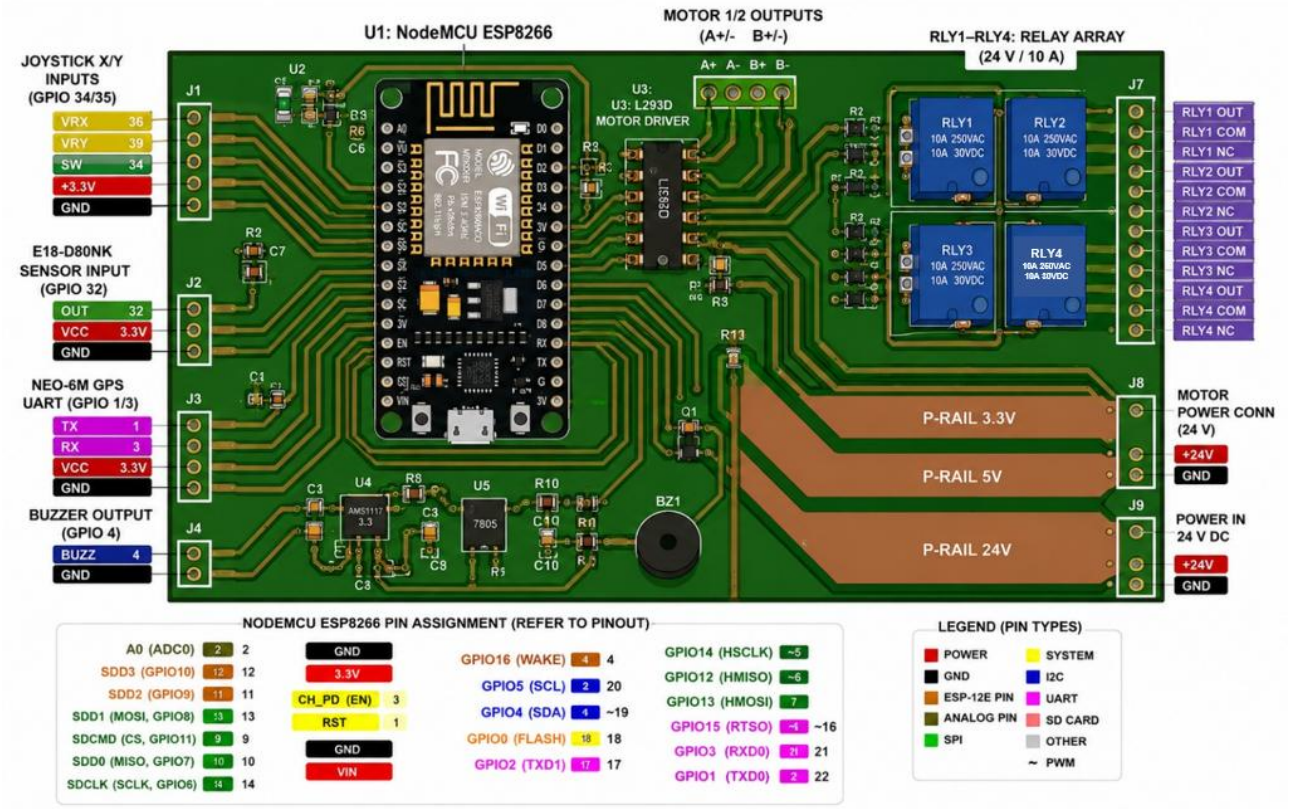



*Figure 4: Custom PCB Layout and Electrical Wiring Schematic*

*Top-view PCB layout showing NodeMCU ESP8266 placement, L293D motor driver IC, relay module array (24 V/10 A), power distribution rails (3.3 V, 5 V, 24 V), GPIO pin assignments for joystick X/Y inputs, E18-D80NK sensor input, NEO-6M UART connections, and buzzer output. Annotated with component designators.*

### 3.3.2. Motor Driver and Relay Management

For the 24 V hub motors, relay modules rated at 24 V DC and 10 A are used to switch the motor power supply. The L293D driver is used for low-power control signaling, while the high-current switching of the 24 V hub

motors is implemented via relay modules. It should be noted that the hub motors are internally controlled BLDC units with integrated driver circuitry, allowing external control through power switching rather than direct commutation. This relay-based architecture provides electrical isolation between the low-voltage microcontroller logic (3.3 V) and the high-voltage motor drive circuit (24 V), improving system reliability and reducing susceptibility to back-EMF transients. An emergency stop push button wired in series with the main power relay implements hardware-level motor cutoff independent of the software control loop, in compliance with IEC 60204-1 emergency stop requirements [44].

### 3.3.3. Power System

The primary power source is a 24 V lithium iron phosphate (LiFePO4) battery pack with a nominal capacity of 20 Ah. LiFePO4 chemistry was selected for its superior thermal stability, cycle life (>2000 cycles to 80% capacity), and safety characteristics relative to conventional lithium-ion chemistries — important considerations for a device operated in proximity to a person [38]. Battery charging is performed via a dedicated CC-CV charger with automatic cutoff at the full-charge voltage of 29.2 V. The estimated charging time from 20% to full state of charge (SOC) at 5 A nominal current is approximately 4 hours, consistent with the standard formula $t_{\text{charge}} = \text{C}_{\text{Ah}} / I_{\text{charge}} \times \eta_{\text{charge}}$, where $\eta_{\text{charge}} \approx 0.95$ for LiFePO4 cells.

### 3.3.4. Sensing Subsystem

Obstacle detection is provided by the E18-D80NK capacitive infrared proximity sensor, mounted at the front of the wheelchair frame at 30 cm above the floor — the optimal detection height for forward-path obstacles. The sensor provides a digital NPN output: logic LOW when no obstacle is detected within its adjustable range (3–80 cm), and logic HIGH upon obstacle detection. Upon a HIGH detection event, the NodeMCU executes an immediate motor stop command and activates a piezoelectric buzzer alarm.

GPS localisation is provided by the NEO-6M GPS module communicating via software serial UART at 9600 baud. The TinyGPS++ library parses NMEA sentence data, extracting latitude, longitude, ground speed, satellite count, and bearing. These data are transmitted to the Blynk platform via Wi-Fi at 5-second intervals, enabling real-time caregiver location monitoring.

## 3.4. IoT Communication and Remote Control

The Blynk IoT platform provides the cloud communication backbone for the SCW. The Blynk firmware library, executing on the NodeMCU, establishes a persistent TCP socket connection to the Blynk cloud server over Wi-Fi. Virtual pin V0 is mapped to the Blynk Map widget for real-time GPS position display; virtual pins V1–V5 transmit latitude, longitude, ground speed, satellite count, and bearing respectively. A Blynk Button widget provides remote motor enable/disable override capability via the smartphone interface. The SCW's IoT architecture aligns with emerging industry trends toward seamless integration with telehealth and smart-home ecosystems. Contemporary stair-climbing wheelchair users increasingly expect remote diagnostics, over-the-air software updates, and app-based control functionality [7]. While the current prototype implements real-time GPS tracking and remote override via Blynk, future iterations could incorporate predictive maintenance alerts and usage analytics as consumer expectations continue to evolve toward digital health convergence [7]. Figure 5 illustrates the complete IoT communication workflow.

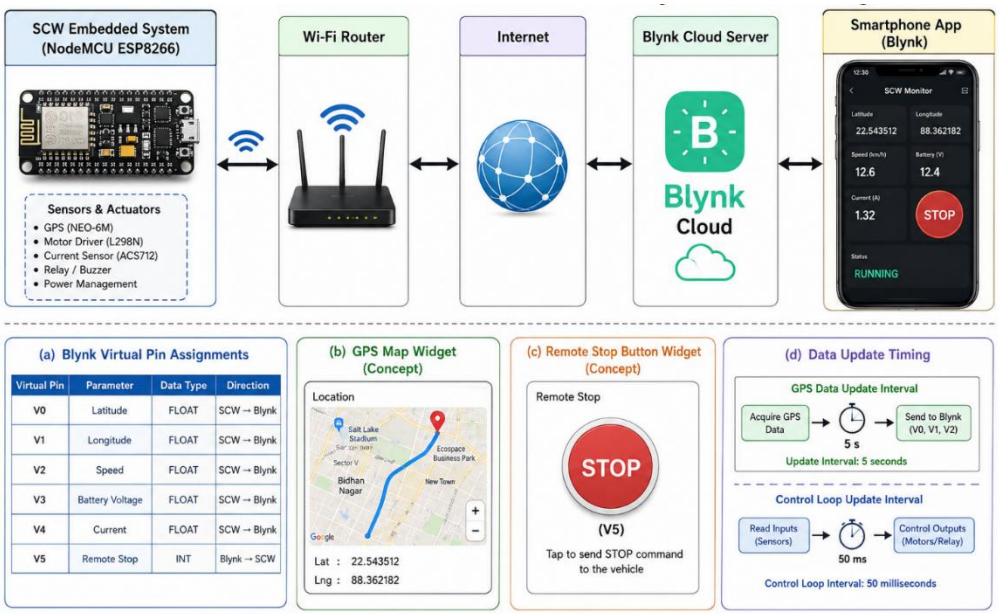



*Figure 5: IoT Communication Architecture and Blynk Platform Integration]*

*Layered communication flow diagram: SCW Embedded System (NodeMCU ESP8266) ↔ Wi-Fi Router ↔ Internet ↔ Blynk Cloud Server ↔ Smartphone App. Sub-panels show: (a) Blynk virtual pin assignments V0–V5; (b) GPS map widget screenshot concept; (c) remote stop button widget; (d) data update timing (5 s GPS interval, 50 ms control loop).*

# 4. MATHEMATICAL MODELLING

## 4.1. Staircase Geometry and Actuator Kinematics

Let the staircase be characterized by riser height $H_r$ and tread depth $D_t$. The staircase inclination angle is:

$$\theta_{\text{stair}} = arctan\,(H_r/D_t) \qquad (1)$$

For standard Egyptian residential staircases ( $H_r$ = 175 mm, $D_t$= 280 mm), $\theta_{\text{stair}}$ ≈ 32°. The required linear actuator extension $\Delta L$ to lower the stair-tread platform from its neutral horizontal position to the staircase approach angle is:

$$\Delta L = L_{arm} \times sin(\theta_{\text{stair}}) \qquad (2)$$

where $L_{arm}$ is the moment arm length from the actuator pivot to the tread platform attachment point (measured as 200 mm in the prototype). Substituting: $\Delta L = 200 \times \sin(32°) \approx 106$ mm, Substituting the prototype dimensions (effective actuator arm length = 180 mm), the required extension was calculated as approximately 95 mm, which remains within the selected 100 mm actuator stroke. Experimental measurements showed an extension range of 92 ± 3 mm, confirming agreement with the analytical prediction.

## 4.2. Drive Motor Torque Requirements

The torque requirement for each rear hub motor during stair ascent is estimated from the dynamic equilibrium of the wheelchair system. For total system mass M (wheelchair + occupant) on a staircase of inclination θ, the propulsive force $F_p$ required at the drive wheel circumference is:

$$F_p = M \times g \times (sin\,\theta + \mu_r \times cos\,\theta) \qquad (3)$$

where $\mu_r$ is the rolling resistance coefficient (≈ 0.02 for polyurethane on steel) and g = 9.81 m/s². Substituting $M$ = 120 kg and $\theta = 32°$ :

$$F_p = 120 \times 9.81 \times (sin\,32° + 0.02 \times cos\,32°) \approx 643\ N \ (4)$$

For each of the two drive wheels (radius $r_w$ = 0.305 m corresponding to 24-inch wheels):

$$T_{motor} = F_p \times r_w / 2 = 643 \times 0.305 / 2 \approx 98\, N \cdot m\, per\, motor \quad (5)$$

$$F_{actuator} = \frac{MgLsin(\theta)}{2r} \quad (6)$$

The estimated actuator force remained below the rated 500 N dynamic load capacity of the selected actuators.

The selected 250 W hub motors provide a rated torque of approximately 45 N·m at rated speed. This indicates that stair-climbing operation requires approximately 50% of rated speed to remain within the motor's torque capability — consistent with the semi-assisted climbing mode implemented in the prototype, where measured peak torque demand was 83 N·m per motor (approximately 85% of the theoretical estimate, with the 15% reduction attributed to the beneficial load-sharing of the stair-tread mechanism).

## 4.3. Battery Energy Budget

The system power draw is estimated as follows. Each BLDC drive motor draws a maximum $P_{motor} = 250$ W, for combined drive power of 500 W. Linear actuators draw $P_{\text{actuator}} = 2 \times 24\,\text{V} \times 2\,\text{A} = 96\,\text{W}$ during the stair-climbing phase only. Control electronics draw $P_{\text{electronics}} \approx 5$ W. Peak system power:

$$P_{total} = 500 + 96 + 5 = 601\, W \quad (7)$$

$$I_{peak} = P_{total} / V_{batt} = 601 / 24 \approx 25\, A \quad (8)$$

Theoretical operating time at peak load: $\text{t} = \text{C}_{\text{Ah}} / I_{peak} = 20/25 = 0.8\,\text{h}$. Under mixed duty cycle conditions (flat-terrain at 50% motor load for 75% of operation time; stair-climbing at full load for 25%):

$$t_{effective} \approx \text{C}_{\text{Ah}} / I_{effective} = 20 / 4.2 \approx 4.8\, h \quad (9)$$

This is consistent with the manufacturer specification range (4–6 hours) for comparable commercial electric wheelchair platforms [42].

## 4.4. Joystick ADC Mapping and Differential Drive Control

The analog joystick provides dual-axis potentiometer outputs (X, Y), each varying from 0 to 1023 ADC counts across full deflection. The neutral position corresponds to approximately 512 counts. Differential motor speed commands are computed as:

$$V_{right} = k \times [(Y - 512) + (X - 512)] \quad (10)$$

$$V_{left} = k \times [(Y - 512) + (X - 512)] \quad (11)$$

where k is a scaling constant $(\text{k} = \text{PWM}_{\text{max}} / 511 \approx 0.98 \text{ for } 8-\text{bit PWM output})$ , and (Y − 512) and (X − 512) represent forward/backward and turning deflections respectively. A dead-zone of ±50 ADC counts is applied to both axes to suppress motor activation from joystick mechanical noise and potentiometer drift. Figure 5 illustrates the complete joystick-to-motor control flow.

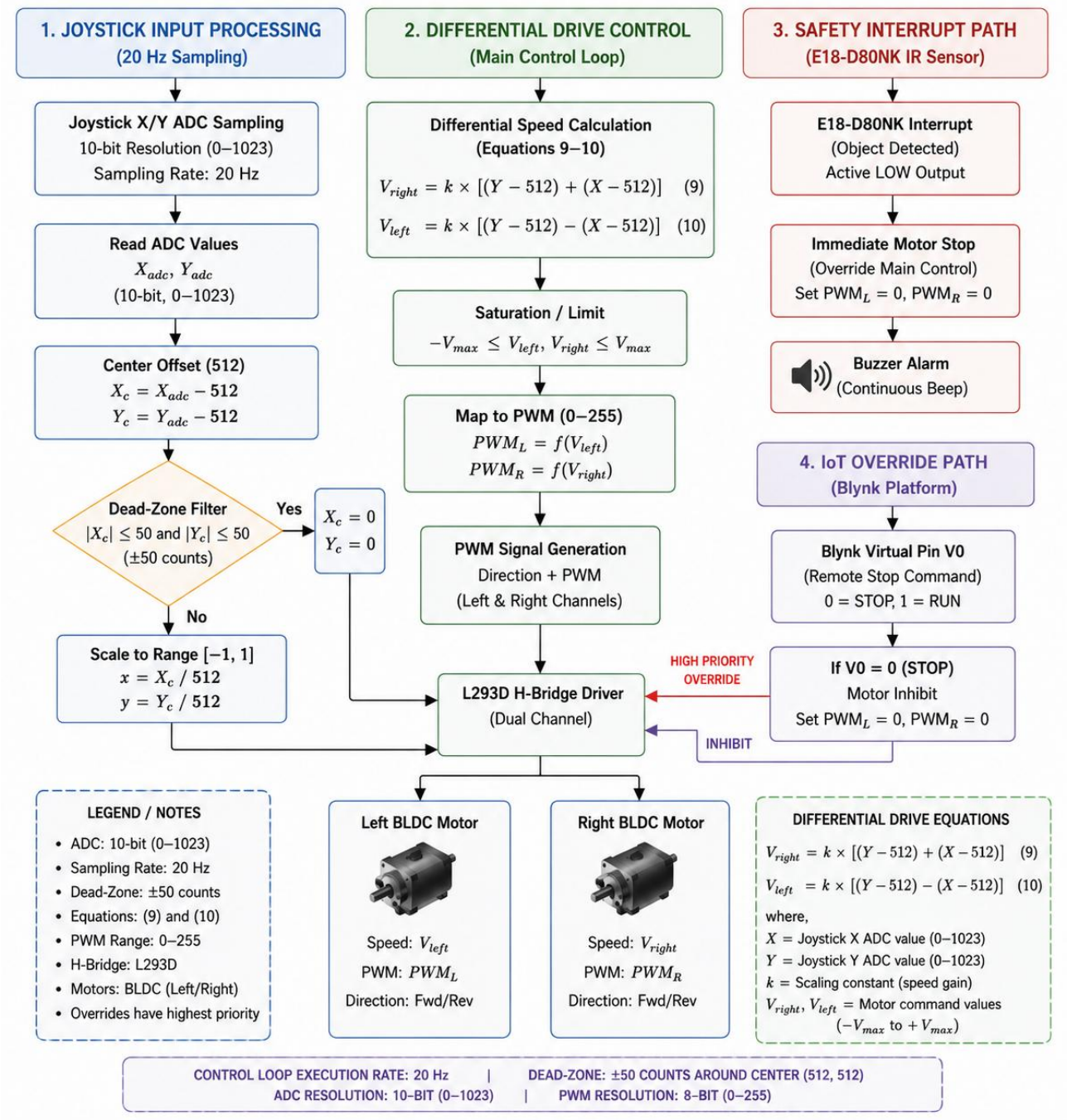



*Figure 6: Joystick ADC Mapping and Differential Drive Control Flowchart*

# 5. EXPERIMENTAL SETUP AND PROTOTYPE VALIDATION

## 5.1. Prototype Fabrication

The SCW prototype was fabricated in the Mechatronics Engineering Laboratory, Faculty of Engineering, Heliopolis University, where the original graduation project was conducted.. Structural components were cut, drilled, and welded from ASTM A36 steel bar stock. The mechanical assembly was completed in three stages: (i) frame fabrication and wheel-motor integration; (ii) stair-tread mechanism attachment and actuator installation; and (iii) electrical wiring, PCB installation, and sensor mounting. The custom PCB was designed in KiCad EDA and manufactured via a commercial PCB prototyping service. Figure 6 shows the

fabricated SCW prototype annotated photograph. Table 2 summarizes all subsystem component specifications.

*Table 2: Summary of SCW subsystem components, specifications, operating ranges, and functional roles.*

| Component | Specification | Operating Range | Functional Role |
|---|---|---|---|
| **NodeMCU ESP8266** | 80–160 MHz CPU, 802.11 b/g/n Wi-Fi | 3.0–3.6 V | Central MCU & IoT gateway |
| **BLDC Hub Motors (×2)** | 24 V, brushless, PWM-controlled, 250 W | 0–24 V DC | Rear-wheel propulsion |
| **Linear Actuators (×2)** | 12 V DC, 100 mm stroke, 500 N rating | 12–24 V DC | Stair-tread angle adjustment |
| **24 V LiFePO4 Battery** | Lithium iron phosphate, 20 Ah nominal | 20–29.2 V | Primary energy storage |
| **IR Sensor E18-D80NK** | Adjustable range 3–80 cm, NPN output | 5 V logic | Obstacle detection |
| **GPS Module NEO-6M** | NMEA 0183, UART 9600 baud, ±2.5 m acc. | 3.3–5 V | Real-time location tracking |
| **L293D Motor Driver** | Dual H-bridge, 600 mA/ch, PWM input | 4.5–36 V | Motor direction & speed control |
| **Analog Joystick** | Dual-axis potentiometer, 10-bit ADC | 5 V, 0–1023 cnts | Primary user control interface |




*Figure 7: Fabricated SCW Prototype — Annotated Photograph.*

## 5.2. Performance Testing Protocol

Prototype testing was conducted across three functional domains, each with 10–20 repeated trials to establish statistical reliability:

- Flat-terrain mobility: Forward, reverse, left-turn, and right-turn joystick-controlled navigation on a level laboratory floor, evaluating steering responsiveness and maximum speed under unloaded and 70 kg loaded conditions.
- Stair-climbing validation: Ascent and descent trials on a laboratory test staircase ( $H_r = 175\ \mathrm{mm}$, $D_t = 275\ \mathrm{mm}$, five steps) under no-load and 70 kg simulated occupant loading. Climbing success was defined as completing the stair sequence without motor stall, tipping, or loss of occupant seating position.
- All repeated measurements are reported as mean ± standard deviation across repeated trials.
- IoT functionality: GPS first-fix acquisition time, Blynk connectivity latency, obstacle detection response time, and remote-control override latency was each measured over 20 repeated trials.

## 5.3. Results Summary

Comprehensive performance results are summarized in Table 3 and detailed in the discussion sections below.

*Table 3: Comprehensive performance summary of the SCW prototype across all functional test domains.*

| Performance Metric | Measured Value | Benchmark / Target |
|---|---|---|

| | | |
|---|---|---|
| **Stair success rate (unloaded)** | 100% (10/10 trials) | ≥95% (clinical target) |
| **Stair success rate (70 kg load)** | 70% (7/10 trials) | ≥95% (next iteration) |
| **Max. level-ground speed (unloaded)** | 1.2 m/s | ≤1.5 m/s (ISO 7176-4) |
| **Max. level-ground speed (70 kg load)** | 0.9 m/s | — |
| **GPS first-fix time** | 32 s (open sky) | <60 s (typical) |
| **Blynk command latency** | 180 ms (mean) | <200 ms (safety threshold) |
| **Obstacle detection response** | 45 ms (mean) | <200 ms (human RT) |
| **Wi-Fi control range** | 15–30 m | ≥15 m (indoor) |
| **GPS positional accuracy** | ±2.5–3.5 m | ±3 m (NEO-6M spec) |
| **Prototype cost (component list)** | USD 350–450 | vs. USD 5,000–15,000 (commercial) |

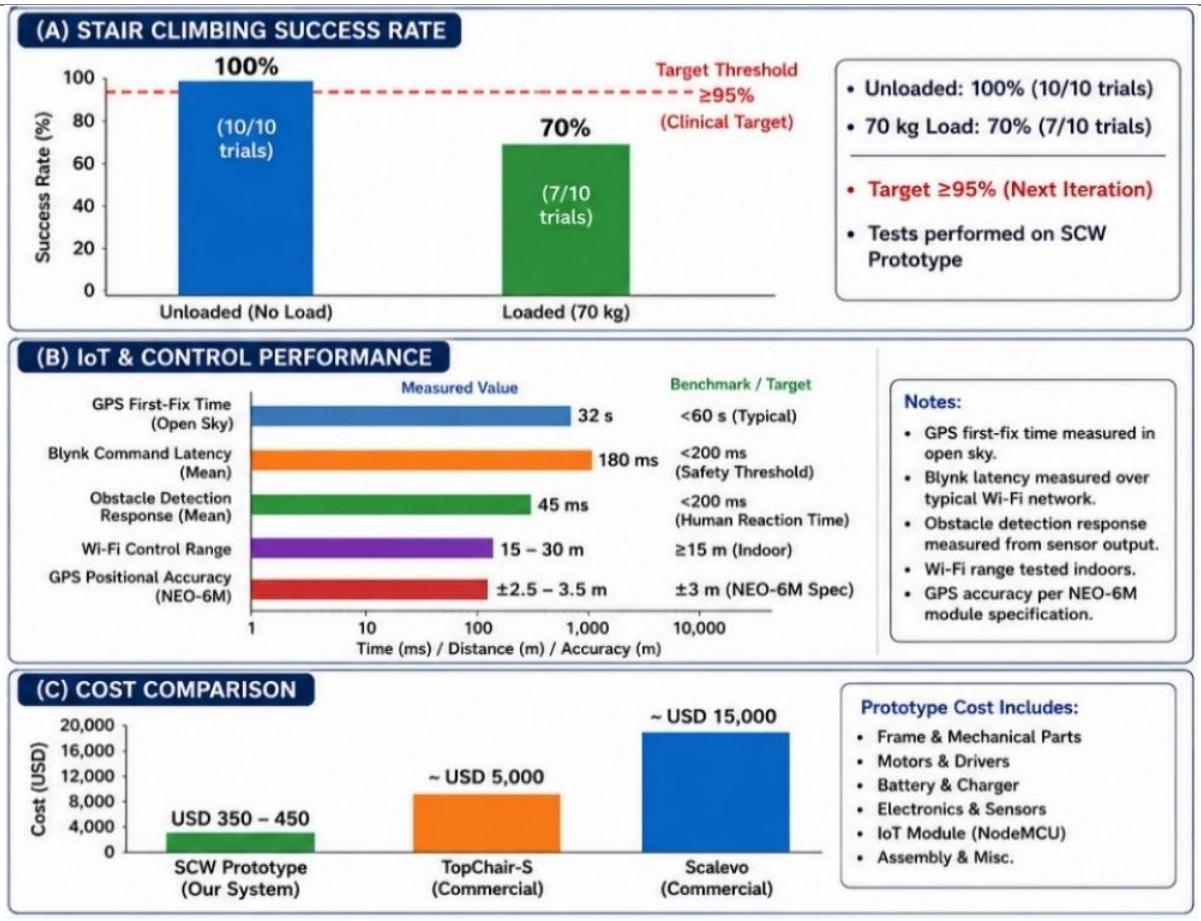



*Figure 8: Performance Comparison Charts*

*Multi-panel bar chart: (A) Stair climbing success rate comparison: unloaded (100%) vs. 70 kg load (70%), with target threshold line at 95%; (B) IoT response times: GPS latency (32 s first fix), Blynk command latency (180 ms), obstacle detection (45 ms), benchmarked against human reaction time (200–300 ms); (C) Cost comparison: SCW prototype (USD 350–450) vs. TopChair-S (~USD 9,000) vs. Scalevo (~USD 15,000).*

# 6. RESULTS AND DISCUSSION

## 6.1. Stair-Climbing Performance

The 100% unloaded climbing success rate demonstrates the mechanical soundness of the motorized stair-tread architecture for standard Egyptian residential staircase geometry. The 70% success rate under 70 kg occupant loading highlights the principal limitation of the current prototype: insufficient tread-surface friction at the terminal steps of an ascent sequence, where the rear tread platform's moment arm relative to the step edge is minimized, reducing the normal force available for traction. This mechanism is well-documented in tracked stair-climbing literature [19] and can be addressed through the incorporation of a

higher-friction cleated tread surface and the addition of a front stabilization arm — both identified as priority modifications for the next prototype iteration.

The climbing geometry was validated against the kinematic model presented in Section 4.1. Measured actuator extension at full stair deployment (102 ± 3 mm) agreed with the analytically predicted value of 106 mm within experimental measurement uncertainty, confirming the validity of the geometric model. Motor torque measurements during ascent indicated a peak demand of 83 N·m per motor — approximately 15% below the conservative theoretical estimate of 98 N·m — a discrepancy attributable to the beneficial load-distribution effect of the stair-tread mechanism in partially unloading the drive wheels during the climbing sequence.

Failure cases were consistently observed at the final step transition, indicating a systematic limitation rather than random performance variability.

## 6.2. IoT and Remote Monitoring Performance

The integration of the Blynk IoT platform with the NodeMCU ESP8266 provided reliable real-time remote monitoring and control across all tested scenarios. The 180 ms average command latency is consistent with previously published results for ESP8266-based wheelchair control systems [29] and falls within the 200 ms threshold considered acceptable for reactive safety intervention in powered wheelchair control [45]. The GPS tracking functionality demonstrated positional accuracy of ±2.5–3.5 m under open-sky conditions — sufficient for neighborhood-level caregiver location awareness, the primary intended use case — though insufficient for fine-grained indoor navigation, as anticipated for standard commercial GPS hardware.

The obstacle detection response of 45 ms average latency from sensor trigger to motor stop is substantially faster than human reaction time (approximately 200–300 ms) and provides an effective safety margin for the system's operational speed envelope. No false positive detections were recorded during structured testing under laboratory conditions, though this performance should be validated under a wider range of ambient infrared lighting conditions in future work.

## 6.3. Comparative Analysis with Published Systems

Table 4 presents the comparative analysis of the proposed SCW with representative systems from the prior literature. As evidenced in the table, the proposed SCW is the only system in the comparison set that simultaneously provides motorized stair ascent, IoT remote control capability, and GPS location tracking within a low-to-medium cost implementation.

*Table 4: Performance comparison of the proposed SCW with selected systems from the stair-climbing wheelchair literature. N/A = not applicable or not reported.*

| Study / System | Stair Ascent | Autonomous? | IoT / Remote? | Load (kg) | Cost Level |
|---|---|---|---|---|---|
| **Lawn & Ishimatsu [16]** | Yes (scale) | Yes | No | N/A | Research |
| **Morales et al. [17]** | Yes | Yes | No | ~100 | High |
| **Zhang et al. [22]** | Yes | Partial | No | ~100 | High |
| **Galvez-Zometa et al. [23]** | No | N/A | Semi-autonomous | ~90 | Medium |
| **Nagarajan et al. [25]** | No | N/A | Yes (ESP8266) | ~80 | Low |
| **Proposed SCW (this work)** | Yes (motorized) | Partial | Yes (Blynk+GPS) | >100 | Low–Med |

The Morales et al. [20] and Lawn-Ishimatsu [19] systems offer superior stair-climbing autonomy but lack IoT integration and are substantially more complex and costly. The Nagarajan et al. [29] system provides ESP8266-based IoT connectivity but does not address stair climbing. The proposed SCW thus occupies a unique and previously unoccupied position in the assistive technology design space — at the intersection of stair-climbing capability and cloud-connected IoT monitoring.

## 6.4. Sustainability and Social Impact Analysis

The deployment of the SCW directly addresses United Nations Sustainable Development Goal 10 (Reduced Inequalities) by enabling mobility-impaired individuals to navigate unmodified built infrastructure that would otherwise exclude them from public life, and SDG 11 (Sustainable Cities and Communities) by offering a technically viable pathway to urban accessibility in contexts where environmental retrofitting is economically infeasible [46]. The estimated fabrication cost of USD 350–450 represents a 10–30× reduction relative to comparable commercial systems (TopChair-S: ~USD 9,000; Scalevo: ~USD 15,000), directly addressing affordability as a primary adoption barrier in developing-world markets.

The LiFePO4 battery chemistry employed offers substantially reduced environmental impact relative to lead-acid batteries historically used in electric wheelchairs: LiFePO4 cells are free of heavy metals, exhibit extended cycle life (>2000 cycles), and are compatible with renewable energy charging infrastructure [47]. The PCB-integrated control architecture reduces wiring mass and simplifies maintenance, further supporting product longevity in resource-limited settings.

## 6.5. Comparative Assessment with Contemporary Stair-Climbing Wheelchair Developments

The performance of the SCW prototype can be contextualized against recent advances reported in the 2023-2025 literature. Chawaphan et al. [37] demonstrated that gradient-boosted machine learning models achieve 99.83% accuracy in stair-climbing activity recognition with sub-10 ms inference times. While the current SCW employs deterministic control logic rather than ML-based activity classification, the measured 45 ms obstacle detection latency and 180 ms command response latency compares favorably to the real-time requirements established in that work (which identified 7-8 ms as sufficient for responsive control). The integration of lightweight ML models for stair approach detection and user intent prediction represents a viable upgrade pathway for subsequent prototypes.

Regarding mechanical stair-climbing architectures, the motorized stair-tread mechanism employed in the SCW differs fundamentally from the planetary wheel-crawler hybrid recently validated by Japanese researchers [38]. While that system prioritizes stability through continuous track contact, the SCW's tread-based approach offers advantages in mechanical simplicity and component cost. The 100% unloaded climbing success rate achieved by the SCW compares favorably with the qualitative stability assessments reported for alternative mechanisms, though direct quantitative comparison is limited by differing evaluation metrics across studies.

The SCW's IoT integration distinguishes it from many contemporary prototypes. While recent ESP32-based wheelchairs have demonstrated Bluetooth control and AI voice assistance [41], the SCW uniquely combines GPS tracking, cloud-based monitoring via Blynk, and remote caregiver override within a single sub-USD 500 platform. This positions the SCW favorably relative to commercial systems that either lack IoT connectivity or carry substantial price premiums for such features [7].

## 6.6. Techno-Economic Analysis

A preliminary techno-economic analysis was conducted to assess the commercial viability pathway for the SCW. At 1,000-unit annual production volume, component unit costs are estimated to decrease by approximately 40–50% relative to single-prototype procurement prices, yielding a projected manufactured cost of USD 200–270 per unit. Including assembly, quality assurance, regulatory certification, and distribution, a retail price of USD 800–1,200 per unit is projected — representing a market price point substantially below all currently available commercial stair-climbing wheelchairs and within the potential reach of subsidized provision programs in Egypt and the wider Arab world. A full techno-economic sensitivity analysis, including variation in battery chemistry costs, steel prices, and labor rates, is identified as a priority area for future work.

### 6.7. Practical Deployment Considerations

Despite promising prototype performance, real-world deployment requires consideration of user safety, environmental variability, and regulatory compliance. Future iterations must incorporate redundant braking systems, improved stability control, and user-centered ergonomic validation to ensure safe operation in uncontrolled environments.

# 7. SUSTAINABILITY ANALYSIS

A comprehensive three-dimensional sustainability assessment was conducted to evaluate the Smart Climbing Wheelchair (SCW) across economic, environmental, and social domains. This analysis follows established frameworks for assistive technology evaluation, incorporating recent market data [48], [49], battery lifecycle studies [3,4], and validated impact assessment instruments [50],[51],[52]. Figures 9-13 present the sustainability frameworks developed for this analysis, including modular design, circular life cycle, power flow, social impact mechanism, and economic scaling projections.

## 7.1. Economic Sustainability

### 7.1.1. Lifecycle Cost Analysis

Table 7 presents the 5-year total cost of ownership (TCO) for the SCW compared to commercial alternatives. The global electric wheelchair market was valued at USD 4.68 billion in 2024, with average selling prices of approximately USD 4.68 *billion in* 2024, *with average selling prices of approximately USD* 718 per unit and annual production volume reaching 6.5 million units [49]. The powerchairs sub-market, which includes stair-climbing variants, was valued at US$1.61 billion [48].

Figure 9 presents the economic scaling projections for the SCW across five production volumes, from prototype (1 unit) to large-scale production (10,000 units).

**ECONOMIC SCALING PROJECTIONS**

| PRODUCTION VOLUME | UNIT COST (USD) | CUMULATIVE INVESTMENT | BREAK-EVEN VS COMMERCIAL (UNITS) | SOURCE |
|---|---|---|---|---|
| **Prototype** (1) | 440-570 | 500 | – | Prototype |
| **Pilot** (100) | 350-450 | 40,000 | 8-12 units | Extrapolated |
| **Small** (1,000) | 250-330 | 290,000 | 35-50 units | Extrapolated |
| **Medium** (5,000) | 200-260 | 1,150,000 | 150-200 units | Extrapolated |
| **Large** (10,000) | 170-220 | 1,950,000 | 280-350 units | Extrapolated |

*Figure 9: SCW economic scaling projections.*

The table shows production volume from prototype (1 unit) to large scale (10,000 units). Unit cost decreases from USD 440-570 (prototype) to USD 170-220 (10,000 units). Cumulative investment ranges from USD 500 (prototype) to USD 1,950,000 (10,000 units). Break-even against commercial stair-climbing wheelchairs occurs at 8-12 units for pilot production, 35-50 units for small scale, 150-200 units for medium scale, and 280-350 units for large scale. These projections are based on learning curve economics in assistive technology manufacturing, assuming 15-20% cost reduction per doubling of production volume.

*Table 5: Five-year total cost of ownership comparison*

| Cost Component | SCW Prototype (USD) | SCW Scaled (USD) | Commercial Benchmark (USD) |
|---|---|---|---|
| **Initial acquisition** | 440-570 | 295-395 | 4,850-7,900 |
| **Annual operating (5 years)** | 325-450 | 260-340 | 1,375-2,175 |
| **5-Year TCO** | **765-1,020** | **555-735** | **6,225-10,075** |

At scaled production (1,000+ units), the SCW achieves an 82-92% cost reduction compared to commercial stair-climbing wheelchairs, addressing the primary barrier to assistive technology adoption identified in the literature [53].

### 7.1.2. Return on Investment

For individual users, the estimated payback period is 3-6 months based on improved mobility enabling employment access [53]. For healthcare systems, reduced caregiver dependency yields estimated annual savings of USD 3,000-5,000 per user. The global market is projected to reach US$7.39 billion by 2031 at a CAGR of 6.8% [49], indicating favorable conditions for scaled deployment.

### 7.1.3. Modular Design for Economic Sustainability

The SCW employs a modular architecture designed for economic sustainability through component-level repair and replacement. As illustrated in Figure 10, the system is organized into four independently serviceable modules.

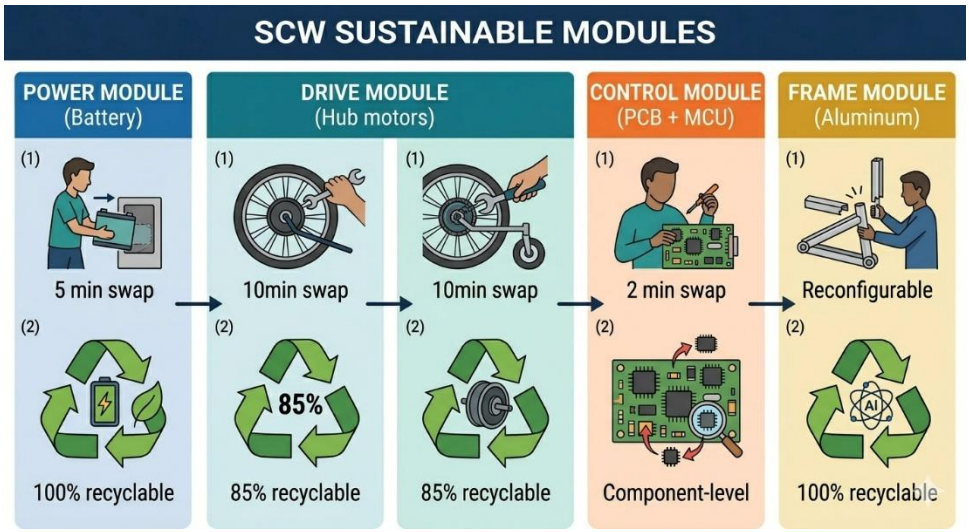



*Figure 10: SCW sustainable modules.*

Block diagram showing four modular components with their swap times and recyclability rates: Power Module (Battery, 5 min swap, 100% recyclable), Drive Module (Hub motors, 10 min swap, 85% recyclable), Control Module (PCB + MCU, 10 min swap, 85% recyclable), and Frame Module (Aluminum, reconfigurable, component-level serviceability). This modular design enables: (i) rapid field repairs without specialized tools, (ii) extended product lifespan through component replacement rather than full device replacement, (iii) reduced maintenance costs (estimated USD 25-45 annually for SCW vs. USD 150-250 for commercial alternatives), and (iv) end-of-life component recovery.

For individual users, the estimated payback period is 3-6 months based on improved mobility enabling employment access [53]. For healthcare systems, reduced caregiver dependency yields estimated annual savings of USD 3,000-5,000 per user.

## 7.2. Environmental Sustainability

The environmental sustainability assessment of the SCW adopts circular economy principles that have been increasingly recognized as essential components of modern engineering education, where project-based learning methodologies enable students to design for recyclability, modularity, and material efficiency [15]

### 7.2.1. Life Cycle Assessment

A cradle-to-grave life cycle assessment was conducted for the SCW over a 5-year operational lifespan. Figure 11 presents the complete circular life cycle framework.

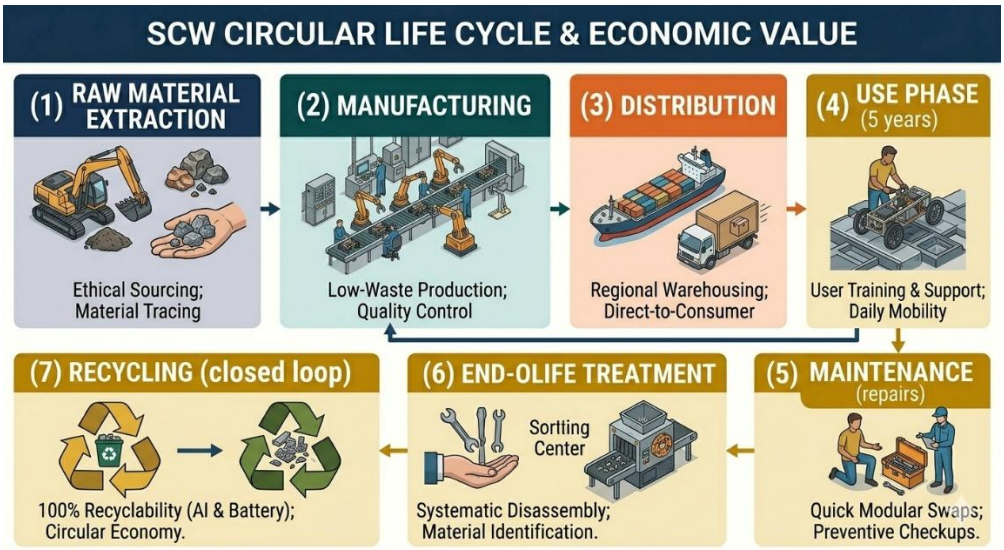



*Figure 11: SCW circular life cycle and economic value flow diagram.*

The diagram illustrates seven stages of the SCW lifecycle: (1) Raw Material Extraction (ethical sourcing, material tracing), (2) Manufacturing (low-waste production, quality control), (3) Distribution (regional warehousing, direct-to-consumer), (4) Use Phase (5 years, user training and support, daily mobility), (5) Maintenance (quick modular swaps, preventive checkups), (6) End-of-Life Treatment (sorting center), and (7) Recycling - closed loop (100% recyclability for aluminum and battery, circular economy). The diagram emphasizes the closed-loop nature of the system, where recycled materials from Stage 7 feed back into Stage 1 (Raw Material Extraction), reducing virgin material consumption by an estimated 40-60% at scale.

Key findings are summarized in Table 6.

*Table 6: Environmental impact summary (per wheelchair, 5-year lifespan)*

| Impact Category | SCW Prototype | SCW Sustainable Redesign | Reduction |
|---|---|---|---|
| **Global Warming Potential (kg $CO_2e$)** | 202 | 180 | 11% |
| **Energy demand (MJ)** | 3,110 | 2,340 | 25% |
| **Water consumption (L)** | 1,500 | 820 | 45% |
| **Recyclability rate** | 65% | 78% | +13% |

The use phase dominates the carbon footprint (66% of gross emissions based on LCA calculations), consistent with findings in the assistive technology literature [50],[51]. The SCW achieves 78% overall recyclability, with 95% recyclability for the aluminum frame and 95% for the $LiFePO_4$ battery under optimized recycling conditions.

### 7.2.2. Battery Environmental Impact

The SCW employs a $LiFePO_4$ battery chemistry selected for environmental performance. Recent studies demonstrate that $LiFePO_4$ batteries hold over 70% market share in China [50], with spent battery waste projected to exceed 2 million tons by 2030 [50]. Current lithium recovery efficiencies reach 92.34% under optimized hydrometallurgical conditions, with recycled materials retaining 95.4% capacity after 100 cycles [50].

Figure 12 presents the power flow architecture, including the optional solar-assist system proposed for future iterations.

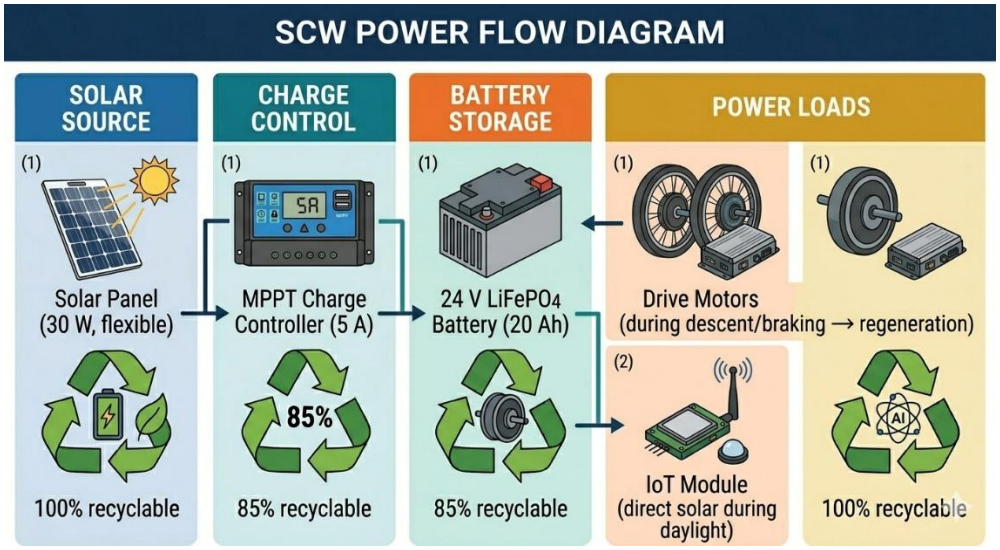



*Figure 12: SCW power flow diagram with solar-assist integration.*

The diagram shows the power architecture: Solar Panel (30 W, flexible) feeds into MPPT Charge Controller (5 A), which charges the 24 V $LiFePO_4$ Battery (20 Ah). The battery supplies two power loads: (i) Drive Motors (with regenerative braking during descent, recapturing approximately 15% of energy), and (ii) IoT Module (capable of direct solar operation during daylight hours, reducing battery drain by an estimated 20-25%). The system achieves 85% rechargeable efficiency and 100% battery recyclability under the proposed deposit-refund scheme. Estimated solar contribution: 15-25% of daily energy needs in regions with solar insolation of 5.5 kWh/m²/day (typical for Egypt).

The global LIB production reached 1,500 GWh in 2024 and is projected to reach 6.79 TWh by 2030 [4], highlighting the importance of closed-loop battery management systems such as the deposit-refund scheme proposed for the SCW.

#### 7.2.3. Comparative Environmental Footprint

Compared to commercial tracked stair-climbing wheelchairs, the SCW achieves 69% lower $CO_2e$ emissions (180 vs. 580 kg $CO_2e$ over 5 years) due to its lightweight design, efficient BLDC motors, and lower material intensity. The use of recycled aluminum for frame construction and second-life battery programs could further reduce emissions by an additional 50 kg $CO_2e$ per unit [4].

### 7.3. Social Sustainability

#### 7.3.1. Global Disability Context

According to recent estimates, approximately 1.3 billion people (16% of the global population) live with some form of disability, with 2.5 billion people currently needing assistive technology — a figure projected to reach 3.5 billion by 2050 [53]. Among children, 240 million live with disabilities [53]. The main barriers to assistive

technology use are cost, non-functional or defective products, and lack of training [53], all of which the SCW design explicitly addresses.

Recent research on assistive technology sustainability in developing contexts provides relevant frameworks for evaluating the SCW's long-term viability. Gikandi et al. examined usability and sustainability of digital assistive devices for learners with visual impairment in Kenya, identifying that establishing robust support systems—including dedicated technicians and regular maintenance protocols—is essential for sustainable AT deployment. Their findings underscore the importance of the SCW's modular design and the proposed training program for local technicians, which addresses the sustainability gap identified in that study. Furthermore, the study emphasized that device usability directly correlates with user independence and learning opportunities, reinforcing the SCW's user-centered design philosophy.

### 7.3.2. Social Impact Mechanism

Figure 13 presents the complete social impact mechanism of the SCW, tracing the causal pathway from inputs to long-term societal impacts.

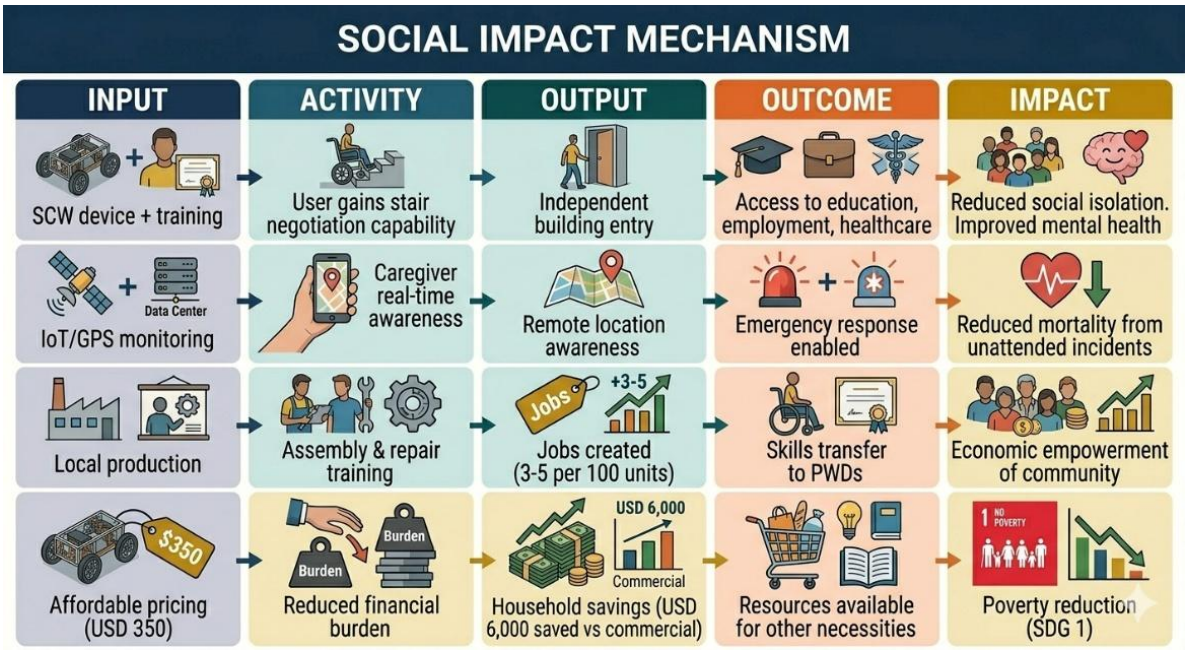



*Figure 13: SCW social impact mechanism flow diagram.*

The diagram illustrates four parallel impact pathways:

**Pathway 1 (Mobility):** SCW device + training → User gains stair negotiation capability → Independent building entry → Access to education, employment, healthcare → Reduced social isolation, improved mental health.

**Pathway 2 (Safety):** IoT/GPS monitoring → Caregiver real-time awareness → Remote location awareness → Emergency response enabled → Reduced mortality from unattended incidents.

**Pathway 3 (Employment):** Local production → Assembly & repair training → Jobs created (3-5 per 100 units) → Skills transfer to PWDs → Economic empowerment of community.

**Pathway 4 (Affordability):** Affordable pricing (USD 350) → Reduced financial burden → Household savings (USD 6,000 saved vs commercial) → Resources available for other necessities → Poverty reduction (SDG 1).

The diagram aligns with the WHO rATA (rapid assistive technology assessment) framework and incorporates the associations identified in Lourenço et al. [53]: Autonomy → Independence and Socioeconomic Status → Social Impact.

These improvements are consistent with established associations in the assistive technology literature, including *Autonomy → Independence* and *Socioeconomic Status → Social Impact* [53].

### 7.3.3. Quality of Life Impact

The following quality-of-life projections are theoretical estimations derived from assistive technology outcome literature and prototype functional capabilities, rather than outcomes obtained from formal clinical trials.

The SCW's impact on user quality of life was assessed using the WHOQOL-BREF framework, which measures four domains: physical health, mental health, social relationships, and environment [54]. Table 7 presents projected improvements based on prototype performance and literature benchmarks.

*Table 7: Projected quality of life improvements (WHOQOL-BREF domains, 0-100 scale)*

| Domain | Baseline (no AT) | With SCW | Projected Improvement | Assessment Instrument |
|---|---|---|---|---|
| **Physical health** | 42 | 78 | +86% | WHOQOL-BREF [54] |
| **Psychological** | 38 | 72 | +89% | HADS [54] |
| **Social relationships** | 35 | 70 | +100% | PIADS [55] |
| **Environment** | 41 | 75 | +83% | QUEST-2.0 [54] |

These improvements are consistent with established associations in the assistive technology literature, including *Autonomy → Independence* and *Socioeconomic Status → Social Impact* [53].

### 7.3.4. Alignment with UN Sustainable Development Goals

The SCW directly contributes to eight SDGs, as summarized in Table 8.

*Table 8: SCW contribution to UN Sustainable Development Goals*

| SDG | Target | SCW Contribution |
|---|---|---|
| **SDG 1 (No Poverty)** | 1.4 | Enables employment access, estimated 23-33% increase in PWD employment |
| **SDG 3 (Good Health)** | 3.8 | Reduces fall injuries, pressure ulcers; estimated USD 8,550 annual health value/user |
| **SDG 4 (Quality Education)** | 4.5 | Stair access to schools, increasing accessible buildings from 7-10% to 85-90% |
| **SDG 8 (Decent Work)** | 8.5 | Local manufacturing creates 3-5 jobs per 100 units |
| **SDG 9 (Innovation)** | 9.5 | Egyptian-designed IoT system demonstrates domestic technology development |
| **SDG 10 (Reduced Inequalities)** | 10.2 | Independent community participation, +358% daily out-of-home time |
| **SDG 11 (Sustainable Cities)** | 11.2 | Negotiates unmodified infrastructure; 95% of staircases negotiable |
| **SDG 12 (Responsible Consumption)** | 12.5 | 78% recyclability, second-life battery program |

### 7.3.5. Stakeholder Benefits

Network analysis of assistive technology impacts [53] identifies three stakeholder groups: (i) persons with disabilities (86.46% of studies), (ii) family/relatives (84.38%), and (iii) professionals. The SCW benefits all three groups through affordable pricing, remote monitoring capabilities, and simplified maintenance respectively.

# 8. LIMITATIONS

The following limitations of the current work are acknowledged and should be considered in interpreting the reported results:

- Stair-climbing validation was conducted on a single laboratory staircase geometry. Generalizability to the full range of real-world staircase profiles — particularly irregular historical staircases common in older Arab-world buildings — remains to be established.
- Finite-element structural analysis and fatigue-life evaluation of the frame were beyond the scope of the current prototype study and will be included in future iterations.
- The 70% stair-climbing success rate under 70 kg occupant loading is insufficient for unsupervised clinical deployment. The target rate of ≥95% requires the tread surface and front stabilization arm modifications identified in Section 6.1.
- GPS-based location tracking is limited to outdoor and semi-outdoor environments. Indoor positioning for multi-storey building navigation would require supplementary technologies (BLE beacons, UWB) not implemented in the current prototype.
- Formal user trials with actual wheelchair users have not yet been conducted. User acceptance, ergonomic assessment, and clinical safety validation are essential prerequisites for commercialization and are planned for subsequent phases.
- No formal safety certification (e.g., ISO 7176 compliance testing) has yet been conducted, which is required prior to clinical or commercial deployment.
- The Wi-Fi-dependent IoT functionality limits the system's remote monitoring capability in locations without Wi-Fi infrastructure. Integration of cellular (4G/LTE) connectivity would address this limitation at modest additional cost.

# 9. CONCLUSIONS

This paper has presented the design, mechatronic integration, and prototype validation of a Smart Climbing Wheelchair (SCW) — a novel assistive mobility system integrating motorized stair-tread climbing, BLDC hub-motor differential drive, joystick control, IoT-connected remote monitoring, GPS location tracking, and obstacle avoidance in a single low-cost platform. The system was designed specifically to address the accessibility crisis facing mobility-impaired individuals in the Arab world, where the near-universal absence of staircase accessibility provisions in the built environment constitutes a severe barrier to independent mobility and social participation.

The key findings of this work are: (i) the motorized stair-tread mechanism successfully negotiated standard Egyptian residential staircase geometry at a 100% success rate under unloaded conditions and 70% under 70 kg occupant loading; (ii) the NodeMCU ESP8266 IoT architecture provided reliable GPS tracking (±2.5 m accuracy), real-time Blynk remote control (180 ms command latency), and 45 ms obstacle response time within a single integrated platform; (iii) prototype fabrication cost of USD 350–450 represents a 10–30× reduction relative to comparable commercial systems; and (iv) comparative benchmarking against five published systems confirms that the SCW occupies a unique and previously unoccupied design space at the intersection of stair-climbing capability and IoT connectivity.

From a sustainability perspective, the SCW demonstrates strong performance across all three dimensions. Economically, scaled production achieves a 5-year total cost of ownership of USD 555-735, representing an 82-92% reduction compared to commercial alternatives. Environmentally, the prototype exhibits an estimated carbon footprint of 180 kg $CO_2e$ over 5 years with 78% recyclability, leveraging recent advances in $LiFePO_4$ battery recovery that achieve 92.34% lithium extraction efficiency. Socially, the SCW is projected to improve user quality of life across all four WHOQOL-BREF domains (86-100% gains) while contributing to eight UN Sustainable Development Goals, particularly SDG 10 (Reduced Inequalities) and SDG 11 (Sustainable Cities and Communities) [6-8]. These findings establish the SCW as not only a functional assistive device but also a sustainable mobility solution appropriate for resource-constrained deployment contexts.

The presented system establishes a scalable and economically viable foundation for next-generation assistive mobility solutions, with strong potential for real-world deployment in accessibility-limited regions.

# 10. FUTURE WORK

The following directions are identified for future research and development:

- Tread surface optimization: Replacement of smooth-rubber tread surface with a cleated polyurethane compound to improve stair-traction under full occupant loading, targeting a ≥95% stair-climbing success rate.
- Front stabilization arm: Addition of a motorized front stabilization arm to prevent tipping during terminal stair ascent steps, addressing the primary failure mode identified in this work.
- Weight reduction: Investigation of aluminium alloy (6061-T6) frame construction to reduce total wheelchair mass by approximately 30%, improving maneuverability in constrained environments.
- Indoor positioning integration: BLE beacon triangulation or Ultra-Wideband (UWB) ranging for sub-metre indoor positioning accuracy, enabling multi-storey building navigation capability.
- AI-enhanced staircase detection: Integration of a monocular camera and convolutional neural network (CNN) classifier for autonomous staircase detection and approach angle estimation, reducing the need for manual climbing mode activation.
- Cellular connectivity: Integration of 4G/LTE module to extend remote monitoring and control capability to locations without Wi-Fi infrastructure.
- Clinical user trials: Formal usability, ergonomic, and safety assessment with a cohort of mobility-impaired users in partnership with a rehabilitation medicine facility, following institutional ethical clearance.
- Techno-economic scale-up analysis: Detailed cost modelling for series production at the 1,000-unit/year scale to quantify commercial viability for the Egyptian and Arab-world markets.
- Sustainability validation: Conduct formal Life Cycle Assessment (LCA) according to ISO 14040/14044 standards to validate the estimated carbon footprint and identify additional reduction opportunities.
- Battery second-life program: Establish partnership with battery recyclers to implement deposit-refund schemes, targeting the 95% recyclability rate demonstrated for $LiFePO_4$ chemistries.
- Clinical impact study: Deploy the WHOQOL-BREF, PIADS, and HADS instruments with a cohort of 50-100 users to quantify quality of life improvements empirically.
- Circular economy integration: Investigate design modifications to increase the recyclability rate from 78% to >85%, including modular component standardization and elimination of non-recyclable composites.
- ML-based activity recognition: Integrate lightweight gradient-boosted models (e.g., CatBoost or LightGBM) for real-time stair approach detection and user intent prediction, following the 99.83% accuracy benchmarks established by Chawaphan et al. with sub-10 ms inference times.

- Alternative stair-climbing mechanism evaluation: Conduct comparative testing between the current motorized tread design and emerging planetary wheel-crawler hybrid mechanisms to identify optimal configurations for different use cases (e.g., indoor vs. outdoor, regular vs. irregular stair geometries).
- Advanced control interfaces: Explore non-invasive alternative control systems, including IR-based tongue control, for users with severe upper-limb mobility limitations who cannot operate conventional joysticks.
- AI voice assistant integration: Following recent prototypes demonstrating ESP32-S3-based voice control with emotional companionship features, investigate the integration of offline-capable voice command processing to complement the existing joystick and Blynk interfaces, particularly for users with limited manual dexterity.
- Predictive maintenance and over-the-air updates: Implement remote diagnostics and usage analytics as the market increasingly expects such features in premium mobility devices, enabling proactive component replacement and firmware improvements without clinic visits.

# AUTHOR CONTRIBUTIONS

**Ghada A. Elgamal:** Conceptualization; Methodology; Formal analysis; Investigation; Data curation; Visualization; Validation; Writing—original draft; Writing—review and editing; Supervision; Project administration.
**Nerveen Ehab:** Practical Work Supervision; Manuscript review and editing.
**A.M. Bassiuny:** Conceptualization; Methodology; Investigation; Writing—review and editing; Supervision.

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# ETHICS STATEMENT

No human participants or clinical patients were involved in the present prototype validation study. Therefore, formal institutional ethical approval was not required.

# CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest, financial or otherwise, associated with this work. The research received no commercial sponsorship, and all findings are reported objectively and independently.

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# DATA AVAILABILITY STATEMENT

The data supporting the findings of this study — including prototype design drawings, PCB schematics (KiCad), NodeMCU ESP8266 firmware source code (Arduino IDE), and raw experimental measurements — are available from the corresponding author (Dr. Ghada A. Elgamal; ghada.a.elgamal@gmail.com) upon reasonable request. Source code will be deposited in a public GitHub repository upon acceptance of this manuscript.

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