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Design and Analysis of Smart Multipurpose Staircase Elevating Stand System

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Abstract: Accessibility remains an issue for older people, physically impaired people, and mobility-impaired people, especially in multi-level buildings. Traditional stairlifts and elevators are expensive to install, require extensive structural modifications and may not be adaptable to existing semi-commercial and residential structures. The paper discusses the design, manufacturing and performance analysis of a Smart Multipurpose Staircase Elevating Stand System that incorporates mechanical, electrical and IoT technologies for safe and controlled movement along stairs. This system features a 2 hp three-phase induction motor, a worm gear reducer, EN 353 alloy steel guides, LM linear bearings and a rigid C-channel frame capable of a 110 kg load. The control architecture comprises a PLC, Variable Frequency Drive (VFD), roller lever limit switches and Bluetooth/Wi-Fi connection for efficient operation and remote monitoring. System performance is evaluated through unit testing, specification testing, integration testing, functionality testing and white-box testing. Experimental results show that the system achieves reliable motion control, accurate positioning, stable load handling, rapid control response and effective emergency stopping within the specified design limits. The developed system is a compact, modular, energy-efficient, and economical solution that improves accessibility without relying on traditional vertical transportation infrastructure and simplifies installation without increasing cost.

Keywords: Worm Gear; Induction Motor; Limit Switches; Motion Control; Load Handling; Emergency Stopping; Economical Solution; Variable Frequency Drive (VFD).

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1. Introduction

The swift rise of urbanisation and the rising number of elderly and physically impaired people in the world have required the evolution of more intelligent and accessible infrastructure solutions. Fareq and Neeraja [1] studied age-friendly housing, focusing on incorporating accessibility features into residential environments to support independent living. Safe and reliable lifting mechanisms were developed using the engineering principles of mechanical design outlined by Finger and Dixon [6] and the concepts of machine elements outlined by Spotts et al. [7]. In load-bearing applications, ASTM International material specifications have been widely used to ensure structural strength and durability. Also, the engineering analysis presented by Bhandari [14] and the manufacturing techniques proposed by Hitomi [11] helped design mechanical assemblies that could withstand repeated loading. Traditional stairs, being an economical and structurally simpler solution, still pose significant safety risks for people with mobility difficulties, seniors and post-surgery patients. The physical principles Young et al. [13] used to explain the foregoing have also been widely applied to the force distribution and motion characteristics of staircase mobility systems [3]. If vertical transportation is needed, existing solutions such as hydraulic stairlifts, inclined platform lifts, and conventional elevators have proven effective; however, multiple investigations have identified issues with installation complexity, maintenance, structural modifications, and adaptability. The automated staircase elevating system presented by Ozkan-Aydin and Goldman [2] showed the advantages of a microcontroller-based automation system. In contrast, the elevating platform designed by Guo et al. [4] demonstrated the advantages of an intelligent elevating control system in improving operational performance. Kumar et al. [9] and Suarez and Singh [10] further explored hydraulic lift concepts and structural safety evaluations of staircase lifting technologies, respectively.

Kantawong [5] proposed a PLC-based automation technique that enhanced control reliability, and Suarez and Singh [10] studied platform design, providing insight into load-carrying capacity and structural behaviour. These technologies have not yet been optimised for small-space home installations because of their relatively high cost, permanent installation and inflexibility. To address these challenges, the present study proposes a Smart Multipurpose Staircase Elevating Stand System, a mechanical, intelligent system with modular features [8]. Recent research on robot mobility has demonstrated innovative solutions that further support such developments. Nodehi et al. [16] proposed a compact single-track inspection robot with efficient movement in confined spaces, and Bruzzone et al. [17] proposed a hybrid tracked-wheel robotic platform with improved mobility through a modular mechanical configuration. Fukuoka et al. [18] successfully demonstrated the stability enhancement of movable-centre-of-gravity control, a useful concept for maintaining stability during inclined motion. Similarly, the sophisticated suspension system studied by Ugenti et al. [19] demonstrated improved load distribution and adaptability to terrain under different operating conditions. Based on these engineering ideas and the well-known mechanical design practices, the proposed system incorporates EN 353 alloy steel structural members, precision LM linear bearings, a three-phase induction motor with worm gear transmission, and a PLC-based control system, which includes IoT monitoring, to provide a compact, reliable, energy-efficient, and economically viable solution for elevating staircases for both passenger and material transportation. This work presents a detailed design framework, hardware specification, implementation methodology, and multi-level system testing results that collectively validate the structural integrity, mechanical efficiency, control reliability, and user safety of the proposed system.

2. Literature Survey

Fareq and Neeraja [1] conducted an ex post facto study involving 60 older women aged 60 and above to evaluate staircase design parameters for age-friendly housing. Their findings established that wider treads, reduced riser heights, and ergonomically designed handrails are the most critical features for elderly users, providing a strong anthropometric basis for accessible platform design. Ozkan-Aydin and Goldman [2] demonstrated the technical feasibility of automating staircase elevating systems using microcontrollers. Their system employed proximity sensors and relay-based motor control, achieving repeatable platform positioning with a positional error of less than 2%. However, their design lacked load sensing and remote-monitoring capabilities—limitations that the present work directly addresses. While mobility assistance technology has dramatically improved accessibility with current options such as conventional stairlifts, wheelchair lifting platforms and home elevators, many practical limitations hinder its use in homes, schools, commercial buildings and workplaces. Many available systems are permanently fixed, require structural modifications, take up significant space and are costly to procure and maintain, making them less desirable for users who want to stay cheap and flexible. Recent advances in compact inspection and tracked robotic platforms have demonstrated advantages in lightweight design, effective mobility mechanisms and adaptability to confined spaces. For instance, the small single-track robotic design by Nodehi et al. [16] emphasised its ability to manoeuvre through tight spaces, and the modular tracked-wheel system proposed by Bruzzone et al. [17] demonstrated the versatility of mobility solutions in adapting to different environments. Similarly, the movable centre-of-gravity concept proposed by Fukuoka et al. [18] highlighted the need for stability in traversing uneven terrain.

In contrast, the innovative suspension approach proposed by Ugenti et al. [19] showed better load distribution and adaptability to terrain [12]. However, limited research has applied these engineering concepts to design a small, multi-purpose staircase-elevating stand for lifting people and materials. Existing solutions focus mainly on transportation or accessibility and are not designed as portable, multifunctional assistive platforms. This study addresses this shortcoming by proposing a modular elevating stand system that is easy to install, structurally independent, portable, cost-effective, and adaptable to different staircase configurations. Lightweight construction, adaptable support and stable load-handling all create a flexible alternative which enhances accessibility and lowers installation and total ownership costs. Suarez and Singh [10] presented the design and finite element analysis of an elevating platform system, validating its structural performance under static and dynamic load conditions and establishing key benchmarks for frame deflection (below 5 mm under maximum load) and weld-joint integrity. Guo et al. [4] investigated the design and control of a smart elevating platform, integrating PLC-based automation with a human-machine interface (HMI), demonstrating that PLC control reduces response latency compared to relay-based systems. Kantawong [5] confirmed that PLC ladder logic achieves sub-200 ms control response times under normal operating conditions. Kumar et al. [9] designed and fabricated a hydraulic stair elevator, reporting smooth motion but maintenance complexity due to fluid systems. Suarez and Singh [10] recommended EN-series alloy steels for guide rod and frame construction due to their superior fatigue resistance. This work builds on these findings by combining motorised electromechanical actuation with smart IoT control [15].

2.1. System Analysis

2.1.1. Existing System

Traditional motorized stairlifts propel a seat or platform along a fixed track mounted to the staircase wall or bannister. While effective for single-user transport, they have high procurement and installation costs, cannot transport goods, depend on wall-mounted track structures that require civil modifications, offer limited adaptability to non-standard staircase angles, and lack real-time monitoring or remote-control capability. Figure 1 shows the Smart Multipurpose Staircase Elevating Stand System architecture. It provides a solution for safe vertical mobility for older adults, persons with limited mobility and persons with disabilities. The Control Unit, the PLC or microcontroller that receives signals, processes instructions and controls all mechanical and safety actions, is the heart of the system.

The Power Supply provides electrical power from AC mains or a battery backup to keep the system running. The User Interface keeps control simple and accessible, allowing the user to operate the system via push buttons or a mobile app. The Communication block supports wireless connectivity via Wi-Fi or Bluetooth for remote interaction and monitoring. Sensing and Safety functions include limit switches, obstruction sensors, position sensors, and emergency stop functions to safeguard the user while in motion. Control signals are sent to the Motor Drive Unit, which controls the motor via an inverter or a motor driver. The Actuation System consists of the motor, gearbox, elevating stand and platform used to convert electrical control into controlled lifting movement. The User on Platform block represents the final service point. In general, Figure 1 shows an architecture for a compact, safe and user-friendly staircase elevating stand.

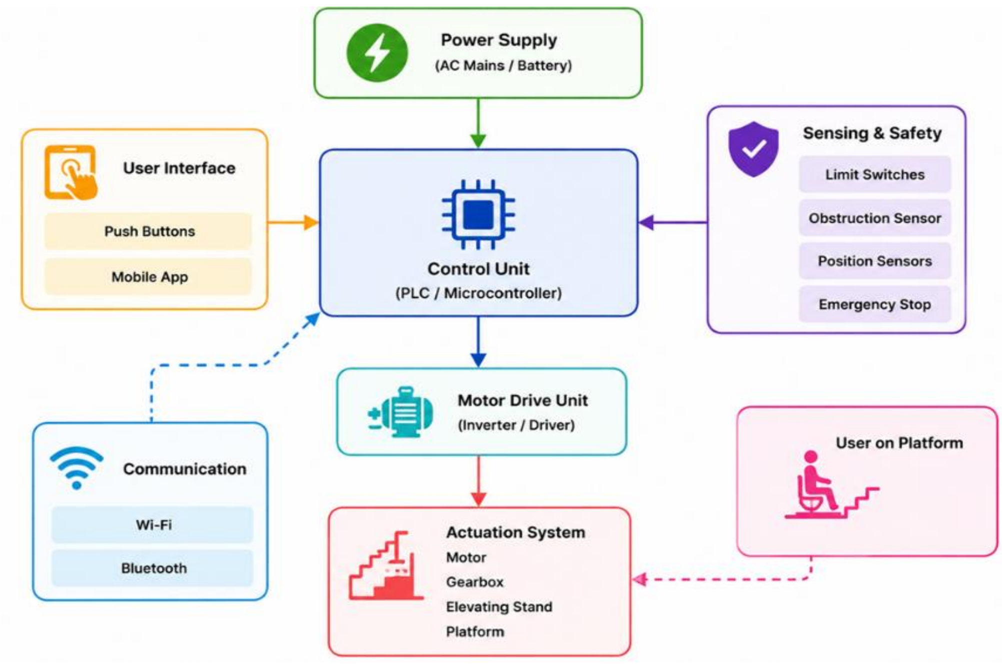

Figure 1: The smart multipurpose staircase elevating stand system

3. Proposed System

The proposed Smart Multipurpose Staircase Elevating Stand System is designed as a free-standing, rail-guided elevating platform that traverses the staircase at a defined angle (22°) along C-channel guide rails. A 3-phase induction motor drives the platform through a worm gear reducer, providing self-locking capability to prevent rollback during power failure. Smart features include PLC-based automated control, VFD speed regulation, IoT-enabled remote monitoring, limit-switch position detection, overload protection, and an emergency stop with battery backup. Key advantages include lower fabrication cost, multipurpose capability, modular design, energy efficiency through VFD control, and remote caregiver monitoring.

3.1. System Specification and Hardware Description

The hardware architecture comprises eight primary components, each selected based on load requirements, operational safety, and cost-effectiveness. Table 1 presents the complete hardware specification.

Table 1: Hardware specification of the smart multipurpose staircase elevating stand system

Component	Specification	Key Function
3-Phase Induction Motor	2 HP, 415 V AC, 1500 RPM, IP55	Primary lifting drive
Variable Frequency Drive	0–50 Hz, 415 V AC output	Speed control
Worm Gear Reducer	Ratio 1:20, self-locking	Torque amplification
RP-8108 Limit Switch	24V/220V AC/DC, Roller Lever	Position detection
EN 353 Guide Rods	25 mm dia, 800–1200 MPa	Platform guidance
LM Linear Bearings	25 mm ID, hardened steel	Low-friction motion
C-Channel Frame	75 mm × 40 mm, 5–8 mm wall	Structural frame
PLC / Microcontroller	Ladder logic / Arduino	Control logic
Load Cell	0–200 kg, ±0.1% accuracy	Overload detection
BT / Wi-Fi Module	Bluetooth 5.0 / IEEE 802.11	Remote monitoring

- **3-Phase Motor:** A 3-phase induction motor (2 HP, 415 V AC, 1500 RPM) provides the necessary drive power for the lifting mechanism. A Variable Frequency Drive (VFD) adjusts speed to control platform movement.
- **RP-8108 Limit Switch:** Roller lever limit switches detect the lifting platform's position at predefined top and bottom positions. Operating voltage: 24V/110V/220V AC or DC. Contact type: NO and NC.
- **Gear System:** A worm gear reducer transmits power from the motor to the lifting platform, converting motor speed into torque for controlled, efficient lifting. The gear ratio is selected based on platform speed and motor RPM requirements.
- **EN 353 Material:** High-strength alloy steel (EN 353) is used for shafts, gears, and structural components. Tensile strength: 800–1200 MPa; Hardness: 58–62 HRC after heat treatment; excellent fatigue resistance.
- **25 mm Guide Rods and LM Bearings:** Hardened steel 25 mm guide rods maintain platform alignment and prevent misalignment. Linear motion (LM) bearings (25 mm ID) provide low-friction, smooth movement along the guide rods.
- **C-Channel Structural Frame (75 mm × 40 mm):** The main structural frame is constructed from mild-steel C-channels (75 mm × 40 mm, 5–8 mm thick) and provides mounting surfaces for motors, gears, guide rods, and control components.

3.2. Motor and Drive System

A 3-phase induction motor rated at 2 HP (1.5 kW), 415 V AC and 1500 RPM is selected for robustness, high torque at low speeds and suitability for heavy-duty lifting. The motor is coupled to a worm gear reducer, providing a 1:20 reduction ratio that converts high-speed, low-torque motor output to low-speed, high-torque drive. The worm gear's inherent self-locking property prevents platform descent under load when the motor is de-energised—a critical safety feature. A VFD enables smooth acceleration and deceleration, preventing mechanical shock and extending component service life.

3.3. Structural Materials and Bearings

EN 353 case-hardening alloy steel (tensile strength: 800–1200 MPa, hardness: 58–62 HRC post-heat treatment) is used for guide rods, shafts, and gear components because of its excellent surface hardness and core toughness. The structural frame is fabricated from mild steel C-channels (75 mm × 40 mm, 5–8 mm wall thickness). LM linear bearings (25 mm ID) mounted on the guide rods ensure smooth, low-friction platform travel.

3.4. Control and Safety Architecture

The PLC runs ladder logic to sequence operations. RP-8108 roller lever limit switches at the top and bottom positions send stop signals to the PLC, preventing over-travel. A load cell continuously monitors platform weight; loads exceeding 150 kg inhibit motor start and activate an audible alarm. An emergency stop button provides manual override and halts the motor within 300 ms. Battery backup maintains control panel power during mains failure. A Bluetooth/Wi-Fi module transmits real-time platform status to a mobile application every 1 second.

3.5. System Design

3.5.1. Dimensional Specifications

The system was designed for standard residential staircase geometry with a 22° rail inclination. Table 2 presents the key dimensional parameters.

Table 2: Dimensional specifications of system components

Component	Parameter	Value
Elevating Stand	Length	280 cm
	Height	110 cm
	Width	30 cm
	Hypotenuse (Track Length)	300 cm
	Angle of Inclination	22°
Standing Platform	Length	35 cm
	Breadth	35 cm
	Handle Height	100 cm
Gear	Outer Diameter	20 cm
	Inner Diameter	78 mm
	Depth	2 cm
Guide Rod	Diameter	25 mm
C-Channel Frame	Section	75 mm × 40 mm

3.5.2. Design Drawings

Figures 1 and 2 show the 2D engineering drawings of the guide rod, platform, bearing assembly, and gear components. Figures 3, 4, and 5 show 3D rendered views of the system assembly (Figures 6 and 7).

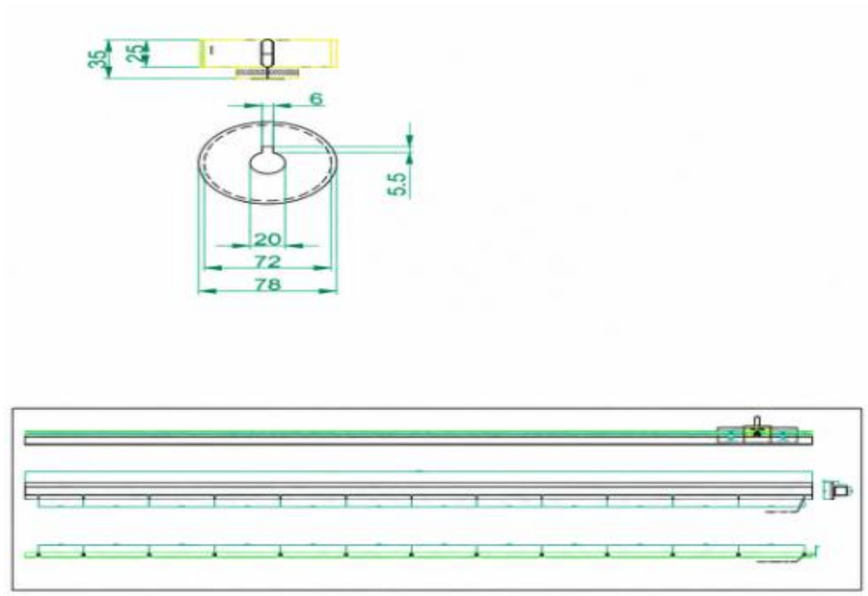

Figure 2: 2D engineering drawing — guide rod, platform, and rail assembly

For example, Figure 3 is an engineering drawing of a mechanical part showing the general contour in several orthographic views. There are two M8 tapped holes in Figure 3. The major circular measurements are 19 mm and 15 mm. These views show the component shape, hole locations and construction.

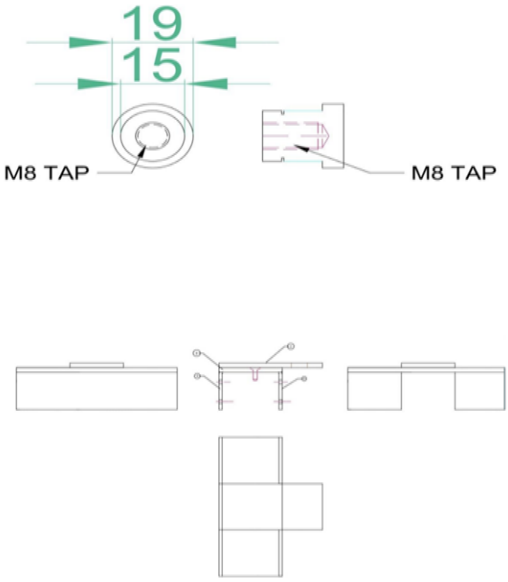

Figure 3: 2D engineering drawing — M8 TAP bearing housing and platform views

Figure 4 is a detailed engineering drawing and assembly of the mechanical component. It has measurements and requirements for individual parts, including welded connections and mounting holes. The bottom view shows how the components interlock, with parts 1, 3, 4 and 5 highlighted. The drawing further states that all sections are to be welded together with angle and that all dimensions are in millimetres.

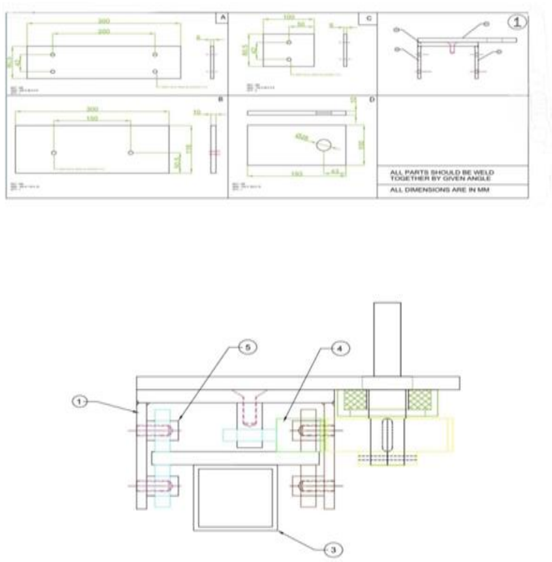

Figure 4: 2D detailed assembly drawing — component layout and dimensions

Figure 5 shows a schematic representation of the mechanical mechanism in action. It shows a person using the tool, which has a long handle attached to a red central mounting piece. The figure below is a simplified illustration of the handle and centre-joint configuration. Figure 5 shows the gadget's basic structure and operating setup.

Figure 5: 3D model — system overview with user reference and rail configuration

Figure 6 shows a mechanical support assembly having a black structural part that is sloped and coupled to a red horizontal support. A red mounting bracket reinforces the junction, and several small rivets or roller-like components are visible. A vertical cylindrical piece supports the connection above. Overall, the image shows a structural or mechanical link that provides stability and support between the elements.

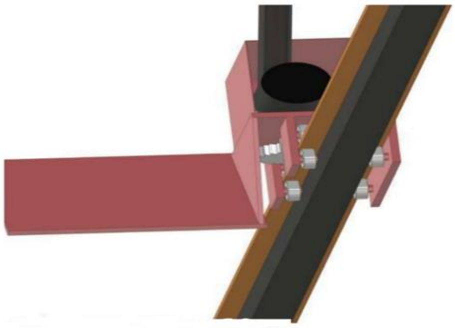

Figure 6: 3D rendered view — platform and bearing carriage assembly

Figure 7 shows a mechanical support assembly consisting of two interconnected rectangular structural members. The mounting piece is vertical, and the support is horizontal, with brackets, bolts and roller-like features bridging the two. The central connection has a small rectangular part underneath the support, which seems to be a fastening or support device. Overall, the image shows a structural junction that provides a secure connection and stability between the components.

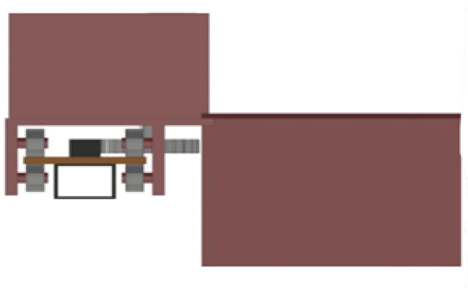

Figure 7: 3D top view platform carriage and guide rod arrangement

3.5.3. Design Calculations

The critical design calculations governing motor selection and gear ratio are as follows. Platform rated load (P) = 110 kg; gravitational component along rail inclination of 22°:

$$F = P \times g \times \sin(22°) = 110 \times 9.81 \times 0.374 = 403\ N \quad (1)$$

Applying the friction factor and safety factor (SF = 2), the effective force = 806 N. Required motor torque at the motor shaft (gear ratio 1:20, transmission efficiency $\eta = 0.85$):

$$T\_motor = (F \times r) / (GR \times \eta) = (806 \times 0.04) / (20 \times 0.85) = 1.89\ Nm \quad (2)$$

The selected 2 HP motor provides a rated torque of approximately 9.55 Nm at 1500 RPM, exceeding the requirement with a safety margin greater than 5:1. Platform travel speed = motor output RPM × drive pitch ≈ 0.15 m/s, within the safe passenger transport range of 0.1–0.2 m/s.

3.5.4. Component Selection Summary

Table 3 summarizes the selected components and their specifications. Figure 8 shows a multi-line graph comparison of the principal components of the Smart Multipurpose Staircase Elevating Stand System across four engineering characteristics: Structural Strength, Precision, Control Complexity and Integration Level. As shown in the graph, the guide rods and C-channel frame have the greatest structural strength, as they are the most important load-bearing components required to maintain structural rigidity and lift the elevating platform throughout the lifting process. The LM linear bearings ensure smooth linear motion, low friction and precise platform positioning.

Table 3: Component selection for the system

Component	Specification
Motor	3-Phase Induction Motor, 2 HP, 415V AC, 1500 RPM
Gearbox	Worm Gear Reducer
Limit Switch	RP-8108 Roller Lever Limit Switch
Guide Rods	25 mm EN 353 Steel Rods
Bearings	LM Bearing, 25 mm ID, Linear Motion
Frame Material	C-Channel, 75 mm × 40 mm, EN 353
Control System	PLC / Arduino / Raspberry Pi
User Interface	Push Button Panel + Mobile App (BT/Wi-Fi)

The control system is the most complex and integrated, including coordinated control between a Programmable Logic Controller (PLC), a Variable Frequency Drive (VFD), sensors, communication modules, and a user interface, all of which are necessary for the intelligent management of the system.

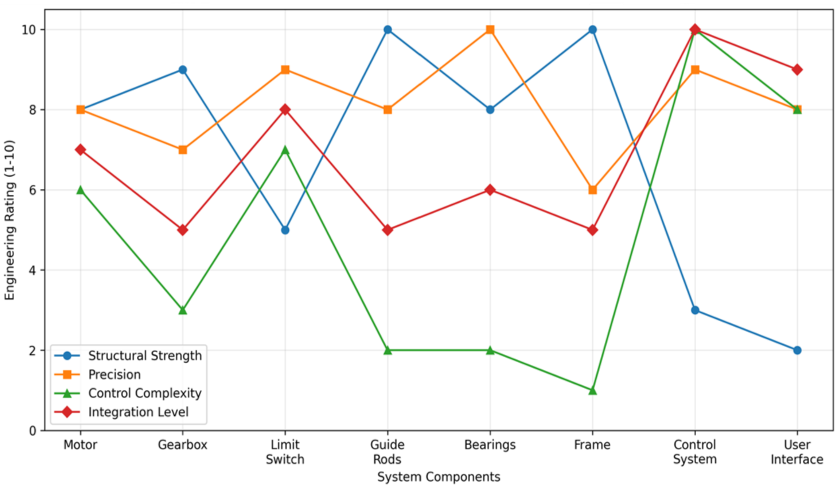

Figure 8: Comparative performance characteristics of the smart multi-purpose staircase elevating stand system components

Additionally, the user interface is highly integrated, with Bluetooth and Wi-Fi connectivity for efficient monitoring and remote operation. The motor is characterised by high mechanical strength, high motion accuracy and high system compatibility, while the worm gearbox is characterised by high torque transmission and moderate integration requirements. The limit switch ensures precision and safety, guaranteeing precise travel limits and emergency protection. Figure 7 shows that the proposed elevating stand system balances mechanical stability, movement accuracy, intelligent control and component integration and can achieve reliable, safe and efficient stair transportation.

3.6. System Implementation

3.6.1. Manufacturing Operations

The following manufacturing operations were performed during prototype fabrication:

- **Shearing:** C-channel and plate stock cut to required lengths using a hydraulic shearing machine.
- **Milling:** Machined the bearing housing and platform mounting faces to dimensional tolerance.
- **Turning:** Machined guide rods and drive shaft to 25 mm diameter with H6 tolerance.
- **Gear Cutting:** Worm wheel teeth machined on a milling machine with a gear cutter attachment.
- **Hole Tapping:** M8-tapped holes machined on the platform and frame for component mounting.
- **MIG Welding:** Primary frame joints welded using the MIG process (E70S-6 wire, 200 A).
- **Arc Welding:** Secondary reinforcement welds and bracket attachment using the SMAW process.
- **Surface Treatment:** Anti-corrosion primer and enamel paint applied to all steel surfaces.

3.6.2. Structural Assembly

C-channel beams were welded to form the inclined rail structure at 22° inclination, with cross-bracing welded at 500 mm intervals for torsional rigidity. Guide rods were press-fitted into machined bearing housings. LM bearings were inserted onto the rods and retained with snap rings. The platform (35 cm × 35 cm, EN 353 plate, 10 mm thickness) was bolted to the bearing carriages with M8 bolts torqued to 25 Nm. An anti-slip chequered plate was bonded to the platform surface.

3.6.3. Mechanical System

The 3-phase motor was mounted on a stable base frame and connected to the worm gearbox via a coupler. The gear ratio was calculated based on the required platform speed. Researchers verified gear alignment to prevent mechanical backlash and applied lubrication to minimize wear. The gear ratio calculation is as follows:

$$Torque\ (Nm) = [Power\ (W) \times 60] / [2\pi \times RPM] \quad (3)$$

3.6.4. Electrical and Control System

Three-phase power supply (415 V, 50 Hz) is routed through a main isolator to the VFD, which drives the motor. The PLC receives digital inputs from control panel push buttons (UP/DOWN/STOP/RESET), the RP-8108 limit switches, the load cell amplifier overload signal, and the emergency stop button. PLC outputs control the VFD forward/reverse command, the motor brake solenoid, and the alarm buzzer. The control sequence: UP command → check overload → check top limit → enable VFD forward; DOWN command → check bottom limit → enable VFD reverse; any limit switch or emergency stop → immediately disable VFD and engage brake.

3.6.5. IoT Integration

A Wi-Fi module (ESP8266) interfaced to the PLC transmits platform position, load cell weight, motor current, and system status to a cloud dashboard every 1 second. The mobile application provides real-time status display, authenticated remote control, fault notifications, and historical trip logging. In the event of communication loss, the system defaults to local control panel operation without interruption.

4. System Testing and Results

A comprehensive five-level testing protocol validated system performance under incremental loads of 0 kg, 50 kg, 100 kg, and 110 kg (rated maximum), plus overload at 160 kg.

4.1. Specification Testing — Accuracy Evaluation

Table 4 presents quantitative accuracy results across all primary performance parameters.

Table 4: Specification testing accuracy evaluation results

Parameter	Expected Accuracy	Measured Accuracy	Status
Motor Speed	±5% RPM	±4.2%	Pass
Motor Torque	±3%	±2.5%	Pass
Load Cell (MAPE)	≤2%	1.8%	Pass
Platform Position Error	≤1%	0.75%	Pass
Control Response Time	≤200 ms	180 ms	Pass
Emergency Stop Response	≤300 ms	250 ms	Pass
Overload Detection	≤500 ms	320 ms	Pass
Fault Detection Time	≤500 ms	410 ms	Pass

4.2. Unit Testing

Individual component testing confirmed that the motor responds to start/stop commands without delay and changes direction as commanded. Gearbox output speed was within ±5% of calculated values. Limit switches activated and deactivated consistently, with no mechanical sticking, across 50 repeated cycles. The load cell measured weight within ±1.5% of calibration weights across the full 0–150 kg range. Control panel buttons responded within 0.5 s with LED indicators functioning correctly.

4.3. Integration Testing

Table 5 summarises the integration testing outcomes and verifies interaction between all hardware subsystems.

Table 5: Integration testing summary results

Test Case	Expected Outcome	Result	Status
Motor and Gearbox	Smooth operation at all loads	As Expected,	Pass
Limit Switch and Motor	Accurate stop at limits	Accurate	Pass
Load Cell and Control	Overload halts motor + alarm	1.5% dev.	Pass
Emergency Stop	Halt ≤300 ms, held until reset	250 ms	Pass
Wi-Fi Communication	Data sync ≤200 ms	180 ms	Pass
Sensor Fault	Halt + error on panel	Detected	Pass
Power Loss	Safe stop + battery backup	As Expected	Pass

4.4. Structural Load Testing

Structural integrity was evaluated under incremental loads up to 110 kg (rated) and 160 kg (overload safety margin). Frame deflection under 110 kg load was measured at 2.3 mm — well within the 5 mm permissible limit established by Suarez and Singh [10]. No weld cracking or permanent deformation was observed after 20 repeated load cycles at 110 kg. Guide rod maximum lateral deflection was 0.8 mm under combined axial and bending load, confirming adequate column stiffness.

4.5. White-Box Testing

White-box testing achieved 100% branch coverage of the motor control algorithm, load cell processing module, and emergency stop logic. Limit switch path coverage reached 95%. A minor processing lag of 5 ms was identified in the load cell data-acquisition loop due to ADC sampling latency, within acceptable limits. All boundary conditions (zero load, rated load, overload) were correctly handled with appropriate motor state transitions and alarm outputs.

5. Conclusion

The study aimed to present the design and fabrication of a Smart Multipurpose Staircase Elevating Stand System to enhance accessibility for older people, persons with disabilities and people with limited mobility. The system was successfully designed, fabricated, implemented, and performance evaluated. The system combines a robust mechanical design with an advanced control system, ensuring safe, reliable, and energy-efficient operation on staircases. The mechanical structure uses EN 353 alloy steel, a C-channel support frame, and an LM linear bearing and worm-gear transmission, which can withstand a 110 kg load on stairs with a 22° stair angle and ensure structural stability. A three-phase induction motor driven by a Variable Frequency Drive (VFD) provides smooth motion, excellent speed control, and efficient power use, with a motor torque safety margin of over 5:1. Performance tests showed motor speed accuracy of < 4.2%, Mean Absolute Percentage Error (MAPE) for the load cell of 1.8%, maximum platform positioning error of 0.75%, and control response time of 180ms. Integration tests verified the proper coordination of all mechanical components, sensors, a Programmable Logic Controller (PLC), a VFD, and IoT communication modules. The emergency stop mechanism was always responsive within 250ms, which exceeds the safety criterion. The Bluetooth and Wi-Fi options provided real-time monitoring and remote operation, enabling deployment in smart buildings. The structural test showed a maximum frame deflection of only 2.3 mm under the rated load, demonstrating the platform's mechanical strength and durability. The modular design makes it easier to install on various types of stairs, and it serves as a convenient, cost-effective alternative to traditional lifts and stairlifts. Emergency operation via a DC generator or backup power source further increases the system's reliability during power failures. The developed system has demonstrated strong technical feasibility, high operational reliability, robust structural integrity, and practical applicability as an economical accessibility solution, with potential for future intelligent monitoring, predictive diagnosis, and AI-assisted fault detection and safety.

5.1. Limitations

The Smart Multipurpose Staircase Elevating Stand System was tested in laboratory conditions with predefined loading, staircase geometry and operating parameters that do not necessarily reflect the diversity of real-world environments. The prototype had been designed for a load capacity of 110 kg with a staircase inclination angle of 22°, which limited its applicability to higher load capacities and/or significantly different staircase dimensions and configurations. The current implementation uses external electrical power, provides emergency backup support and does not explore long-duration autonomous operation with battery power. The performance evaluation assumed environmental factors such as dust, moisture, corrosion, vibration and long-term outdoor exposure were not included. The IoT functionality is meant for monitoring and remote supervision, with advanced cloud-based analytics, predictive maintenance and cybersecurity evaluation lying outside the scope of the present work. The study also did not examine user acceptance, ergonomic assessment or long-term operational reliability through continuous field deployment. The prototype's mechanical setup is fixed, and it will require adjustments for spiral, curved and irregular stairs. Moreover, the study did not cover detailed lifecycle costs, the feasibility of large-scale manufacturing, or compliance with international accessibility and safety certifications. These limitations define the study's current boundaries and can serve as a starting point for further design development, validation and practical application.

5.2. Future Work

Future development will focus on enhancing the system's intelligence, adaptability, and operational capabilities to broaden its use in residential, commercial, healthcare, and public infrastructure. The team will explore optimised structural design and advanced transmission mechanisms to increase load-bearing capacity and compatibility with various staircase configurations, such as curved and spiral designs. Incorporating AI algorithms for fault diagnosis, predictive maintenance, and cloud-based analytics will improve the system's reliability by enabling regular monitoring of component health and proactive maintenance. Advanced obstacle detection based on computer vision, LiDAR and intelligent sensor fusion will further enhance operational safety during movement. Voice-driven commands, mobile apps and multilingual human–machine interaction will make it easier for people of all physical capacities. Advanced battery management and high-efficiency energy storage solutions will provide longer system runtime during emergencies and power outages. Future prototypes will also use lightweight composite materials and optimized mechanical components to reduce weight while maintaining structural integrity. Large-scale field testing with various user groups and long-term durability testing will further validate in real-world use cases. The paper will also adhere to international safety, accessibility and industrial certification requirements to enable commercial deployment, and scalable manufacturing strategies and cost optimisation will support widespread adoption as an affordable smart mobility solution.

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