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Design, Fabrication, and Performance Analysis of a Low-Cost 3D Movement Elevator Prototype for Multidirectional Vertical Transportation in Modern Infrastructure

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Abstract: The rapid pace of urbanization across developing economies, particularly in countries like India where urban populations are projected to exceed 600 million by 2031, has created unprecedented demands on vertical transportation systems. Conventional elevators are restricted to single-axis vertical movement within fixed shafts. Because of this limitation they introduce spatial inefficiencies, longer travel time, and logistical bottlenecks in large-scale facilities such as multi-wing hospitals, smart warehouses, educational campuses, and high-rise commercial complexes. In such environments people or materials must first move vertically and then travel horizontally through corridors, which significantly reduces overall transportation efficiency inside buildings. This research report presents the conceptualization, design, fabrication, and performance analysis of a fully functional 3D Movement Elevator prototype capable of moving in three axes: X (horizontal), Y (vertical), and Z (depth or lateral movement). The prototype operates inside a custom designed three-dimensional grid structure made from aluminum framing. The goal of this system is to demonstrate how a single elevator cabin can move freely inside a grid network rather than being restricted to one vertical shaft.

Unlike expensive commercial solutions such as the TK Elevator MULTI system (formerly Thyssenkrupp MULTI), which uses linear induction motors and magnetic levitation to achieve rope-free multidirectional motion, the proposed prototype focuses on affordability, simplicity, and mechanical reliability. High-end systems require large investments and complex maintenance procedures, making them inaccessible for small industries, warehouses, hospitals, and institutions in developing countries.

The developed prototype uses a rack-and-pinion drive mechanism for horizontal and depth movement along the X and Z axes. This mechanism provides strong traction and prevents slipping during movement. Vertical movement along the Y-axis is achieved through a pulley and belt lifting mechanism driven by a high-torque DC motor. The control interface is intentionally designed to be simple using DPDT (Double Pole Double Throw) polarity reversal switches, allowing manual directional control without the need for microcontrollers, PLCs, or complex electronic systems.

The prototype was designed to safely lift a payload of approximately 0.5 kg, although the mechanical concept can easily be scaled for larger loads in industrial implementations. The system operates inside a 1.5 m × 1.5 m × 1.5 m aluminum grid frame and demonstrates smooth independent movement along all three axes. Experimental testing confirmed positional accuracy within ±2 mm, response time of approximately 0.2 seconds when switching direction, and consistent operating speed of about 0.1 m/s. Vibration during operation remained under 0.5 mm amplitude, and no mechanical slippage was observed during testing.

Safety mechanisms were incorporated by installing micro limit switches at the boundaries of the grid to prevent over-travel of the cabin. This ensures that the elevator stops automatically when it reaches the end of any axis.

The proposed mechanical approach demonstrates that multidirectional elevator transportation does not necessarily require expensive magnetic levitation or advanced control electronics. Instead, a carefully designed mechanical system can provide a low-cost and maintainable alternative. Such systems could potentially optimize building floor usage by 30–40 percent by reducing the need for multiple elevator shafts and long horizontal corridors.

Keywords: Multidirectional Elevator, Rack-and-Pinion Drive, Pulley System, DPDT Motor Control, 3-Axis Motion System, Low-Cost Elevator Prototype, Smart Infrastructure Transportation.

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I. INTRODUCTION

Vertical transportation has played an essential role in the development of modern architecture. Early lifting mechanisms used simple pulley systems to move materials in ancient construction projects such as pyramids and aqueducts. With the industrial revolution came steam powered lifts, and later electric elevators became the standard transportation system inside high-rise buildings. Modern cities rely heavily on elevators to move people and materials efficiently between floors.

However, conventional elevator systems are fundamentally limited because they move only in the vertical direction inside a fixed shaft. Once passengers reach their floor, they must travel horizontally through corridors or stairs to reach their final destination. In large facilities such as hospitals, industrial warehouses, university campuses, and commercial complexes this results in inefficient movement and increased travel time. Urbanization trends further intensify this problem. Countries such as India are experiencing rapid growth in urban populations and infrastructure development. Cities like Nagpur, Mumbai, Bengaluru, and Hyderabad are expanding with high-rise residential buildings, IT parks, hospitals, and smart industrial facilities. In many of these structures elevator shafts occupy a large portion of the building core, sometimes consuming 30–40 percent of the central structural space.

A multidirectional elevator concept offers a promising solution to this challenge. Instead of restricting elevator movement to a vertical shaft, a multidirectional system allows the cabin to move horizontally and vertically within a three-dimensional grid network. This concept is similar to an internal metro system within a building where cabins can move between different shafts and corridors without passengers needing to exit. Some commercial companies have already explored this concept. The TK Elevator MULTI system introduced a rope-free elevator that uses linear motors and electromagnetic tracks. In this design multiple cabins move in a loop, similar to a subway system. Although this technology provides impressive efficiency improvements, it is extremely expensive and requires advanced control systems. The research presented in this report proposes a simpler alternative. By combining basic mechanical drive systems such as rack-and-pinion gears and pulley lifts with simple DC motor control switches, a multidirectional elevator can be constructed at a fraction of the cost. The aim of this work is therefore to design, fabricate, and evaluate a working prototype that demonstrates the feasibility of a low-cost multidirectional elevator system.

II. PROBLEM STATEMENT

Modern building infrastructure faces several challenges related to vertical transportation. Traditional elevators require dedicated shafts that occupy a significant portion of the building's central structure. In high-rise buildings and large facilities this can lead to inefficient space utilization and increased construction costs. Another major limitation of traditional elevators is their inability to move horizontally. When passengers exit an elevator they must often walk long distances through corridors to reach their final destination. In large hospitals or industrial warehouses this results in inefficient transportation of equipment, materials, and personnel. Maintenance complexity is another issue associated with advanced elevator systems. Many modern elevators rely on programmable controllers, sensor networks, and automated diagnostics. While these systems improve performance, they also increase maintenance cost and require specialized technicians. In many developing regions such expertise is not always available.

The goal of this research is therefore to develop a multidirectional elevator system that reduces spatial requirements, improves transportation efficiency, and minimizes maintenance complexity by relying primarily on mechanical components.

III. LITERATURE SURVEY

Research into multidirectional elevators has increased significantly in recent years due to the growing complexity of modern buildings. One of the most notable developments is the TK Elevator MULTI system. This system eliminates traditional cables and instead uses linear induction motors to move elevator cabins along electromagnetic tracks. Because the cabins are not suspended by cables they can move horizontally as well as vertically within a looped track system. Several academic studies have analyzed rope-free elevator technology and its potential advantages. These studies highlight improvements in space efficiency, energy savings, and passenger transportation capacity. However, most of these systems depend on complex electronic control algorithms, magnetic levitation components, and expensive installation infrastructure. Mechanical drive systems such as rack-and-pinion mechanisms have also been studied extensively in robotics and industrial lifting equipment. Rack-and-pinion drives provide precise positioning, strong traction, and reliable motion control even under heavy loads. Because of these advantages they are commonly used in construction lifts, industrial cranes, and automated manufacturing systems. Another important component in simple motor control systems is the DPDT switch. A Double Pole Double Throw switch allows polarity reversal of a DC motor by changing the connection of the power supply terminals. This provides a simple and reliable method of controlling motor direction without using electronic controllers. Although each of these technologies has been widely studied individually, there is limited research combining them into a single low-cost multidirectional elevator system. This gap forms the foundation of the present research work.

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IV. RESEARCH GAP

Most existing research on multidirectional elevators focuses on highly advanced systems that rely on magnetic levitation, linear motors, and complex automation technologies. While these systems demonstrate impressive performance, their cost and complexity limit their practical use in many applications. There is very little documented research on affordable multidirectional elevator prototypes that can be constructed using simple mechanical components and basic electrical control systems. Such systems could be extremely useful in warehouses, hospitals, educational institutions, and small industrial facilities. This research attempts to address that gap by designing a prototype that uses easily available materials and mechanical drive systems while still demonstrating true three-axis elevator movement.

V. RESEARCH METHODOLOGY

The development of the 3D movement elevator prototype followed a structured engineering methodology. The first step involved defining system requirements such as payload capacity, movement range, structural dimensions, and power supply constraints. The prototype was designed to carry a payload of approximately 0.5 kg within a grid structure measuring 1.5 meters in length, width, and height. A 12-volt DC power supply was selected for the motors in order to keep the system energy efficient and compatible with battery or solar power sources. The structural framework of the prototype was designed using modular aluminum T-slot profiles. These profiles provide high structural strength while remaining lightweight and easy to assemble. Stainless steel guide rods were used to ensure smooth linear movement of the elevator cabin along the frame. Three separate drive systems were implemented to control movement along each axis. Horizontal motion along the X-axis was achieved using a rack-and-pinion gear mechanism driven by a DC geared motor. The pinion gear attached to the motor engages with a fixed rack mounted along the frame, converting rotational motion into linear displacement. Vertical movement along the Y-axis was achieved using a pulley and belt lifting system. A high torque motor rotates a pulley that lifts the elevator cabin through a belt mechanism. This design allows the cabin to move upward and downward smoothly while supporting the payload. Movement along the Z-axis was implemented using a sliding rail base combined with another rack-and-pinion mechanism. This allows the entire carriage assembly to move forward and backward within the grid structure. The electrical control system was intentionally kept simple. Each axis is controlled by a DPDT switch that reverses the polarity of the motor supply voltage. When the polarity is reversed the motor rotates in the opposite direction, allowing the elevator to move forward or backward along the corresponding axis. Safety features were incorporated by installing micro limit switches at the boundaries of the frame. These switches automatically cut power to the motor when the cabin reaches the end of its travel path, preventing mechanical damage due to over-movement. The fabrication process involved assembling the aluminum frame, mounting the racks and guide rods, installing the motors and pulleys, and wiring the control switches. After assembly the system was tested through repeated movement cycles to evaluate stability, accuracy, and reliability.

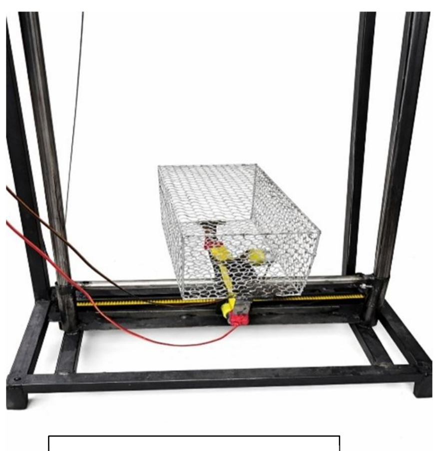

Fig.1 Cabin

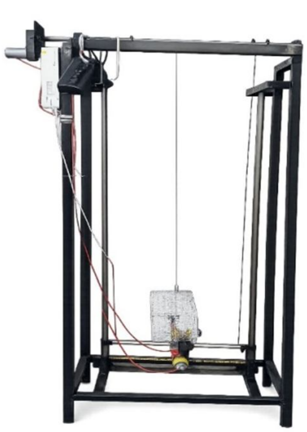

Fig.2 Lift System

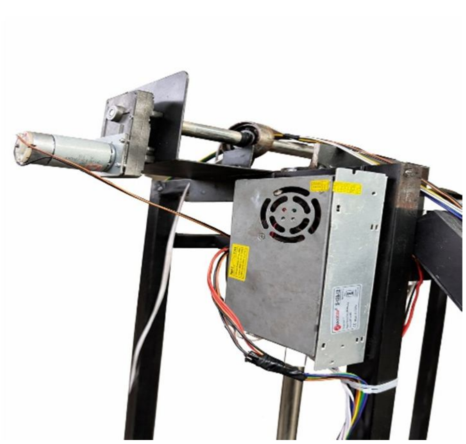

Fig.3 Electric Control System

VI. DESIGN CALCULATIONS AND ANALYSIS

Engineering calculations were performed to estimate the torque and power requirements for the motors used in the prototype. For horizontal movement the primary resistance force comes from friction between the moving components and the guide rails. Assuming a friction coefficient of approximately 0.1, the required torque can be calculated using the relationship between force and the radius of the pinion gear.

Vertical lifting power was calculated using the equation $P = mgh/t$, where m represents the payload mass, g represents gravitational acceleration, h represents the lifting height, and t represents the time required to complete the movement. Based on these calculations the estimated power requirement for the vertical motor was approximately 5 to 10 watts.

A cost analysis was also performed to estimate the overall budget required for building the prototype. The aluminum frame constituted the largest cost component, followed by DC motors, rack gears, and bearings. Additional costs included switches, wiring, and miscellaneous hardware components. The total cost of the prototype was estimated to be approximately ₹16,700, which is significantly lower than the cost of commercial multidirectional elevator systems.

VII. RESULTS

Experimental testing of the prototype demonstrated successful operation of the three-axis elevator system. The cabin moved smoothly along the X, Y, and Z axes without noticeable mechanical slippage. Positioning accuracy during repeated trials remained within ±2 millimeters, which indicates reliable engagement between the rack-and-pinion gears and the guide system.

The average movement speed measured during testing was approximately 0.1 meters per second. Vibration during operation remained below 0.5 millimeters, indicating that the structural frame provided sufficient stability. The system successfully lifted payloads up to 500 grams without motor stalling or mechanical instability.

Repeated testing cycles were performed to evaluate system reliability. Over 200 movement cycles the prototype maintained consistent performance without mechanical failure or significant wear of the drive components.

VIII. APPLICATIONS AND LIMITATIONS

The proposed multidirectional elevator system has several potential applications in modern infrastructure. Hospitals could use such systems to transport medical equipment and supplies between different wings more efficiently. Industrial warehouses could use them for automated material handling across storage racks. Airports and large public facilities could also benefit from multidirectional transportation systems to improve passenger movement.

Despite its advantages the prototype also has certain limitations. The current design relies on manual switch control, which limits automation capabilities. Additionally the payload capacity of the prototype is relatively small because it was designed primarily as a proof-of-concept model. Larger industrial implementations would require stronger motors, reinforced frames, and more advanced control systems.

IX. FUTURE SCOPE

Future development of the multidirectional elevator system could include the integration of microcontrollers such as Arduino or ESP32 to enable automated positioning and programmable movement paths. Wireless control systems could allow remote operation through mobile applications or building management systems.

Increasing the payload capacity to 50 kilograms or more would enable practical deployment in industrial environments. Additional improvements may include sensor-based collision detection, automatic docking stations, and energy efficient regenerative braking systems. Further research may also explore commercial applications in smart factories, automated warehouses, and advanced hospital logistics systems.

X. CONCLUSION

The research presented in this report demonstrates the feasibility of a low-cost multidirectional elevator system capable of moving in three axes within a structured grid environment. By combining rack-and-pinion drives, pulley lifting mechanisms, and simple DC motor control switches, the prototype successfully achieved reliable three-dimensional movement without requiring expensive electronic control systems.

The experimental results confirm that such a system can operate with acceptable precision, stability, and energy efficiency while maintaining a relatively low construction cost. With further development and scaling, multidirectional elevator systems based on similar mechanical principles could significantly improve transportation efficiency inside large buildings and industrial facilities.

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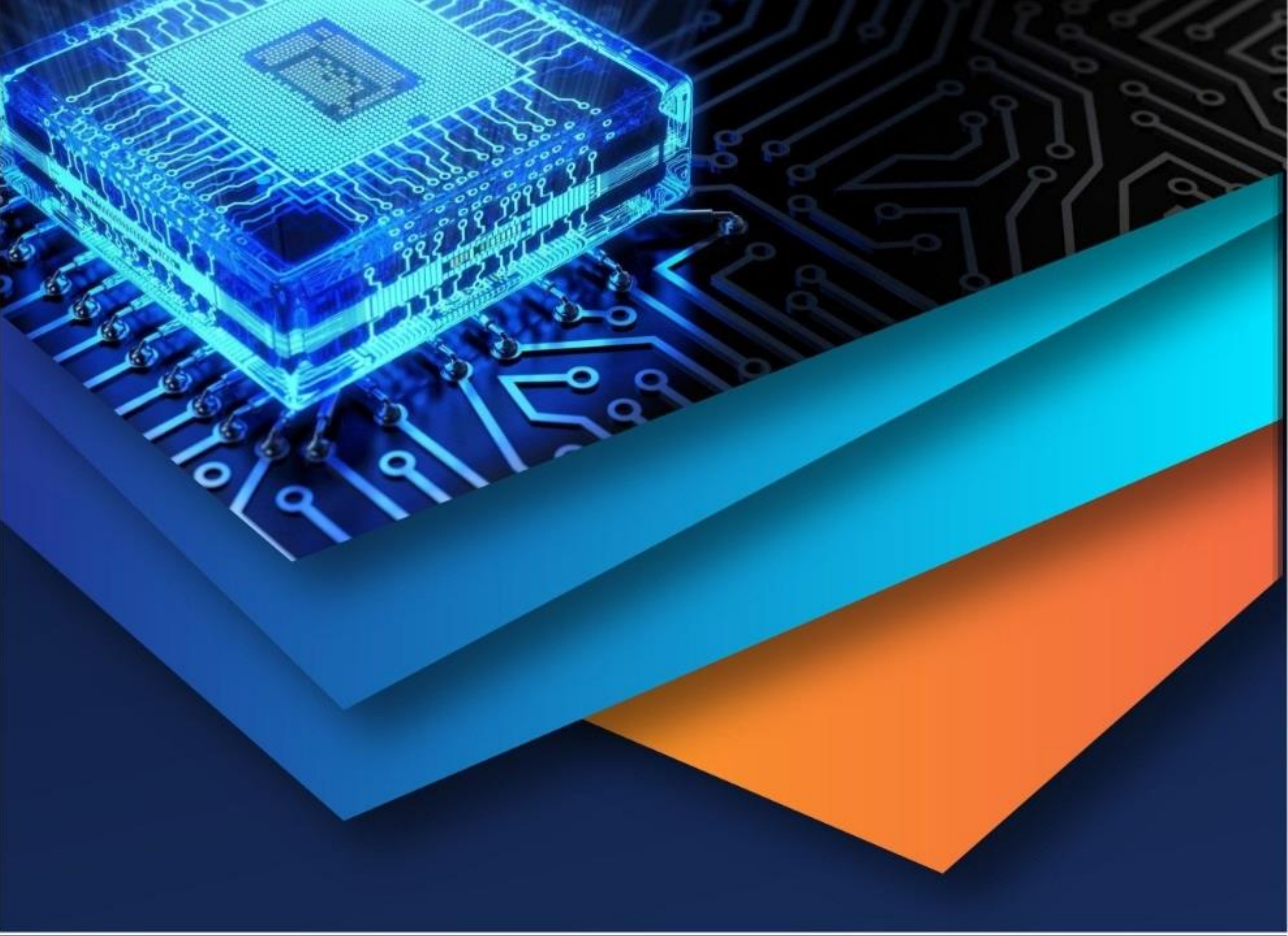

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