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Autonomous Goods Transport: A Comprehensive Review of Stair- Climbing Robot Technologies

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Abstract : The development of stair-climbing robots for goods transport has gained significant attention due to their potential to revolutionize industries like logistics, construction, and healthcare. These robots, capable of autonomously navigating stairs and uneven terrains, offer efficient solutions for material handling in multi-level environments, reducing human labor and enhancing operational productivity. Key design categories include wheeled systems, which are faster but struggle with stairs, and legged robots, which provide better adaptability and stability for stair navigation. Hybrid designs that combine both wheels and legs, as well as modular robots that can be reconfigured for specific tasks, are also being explored to improve performance across different environments. Additionally, sensor technologies and artificial intelligence (AI) are integral to enabling autonomous navigation. Sensors like lidar, cameras, and force sensors help the robots detect obstacles, stairs, and variations in the terrain, while AI algorithms process this data for real-time navigation. Despite the progress made, challenges such as stability, energy efficiency, and safety remain. Ensuring balance while transporting goods on stairs, optimizing power usage for extended operational time, and maintaining safe interactions with humans and the environment are key obstacles. Future research will likely focus on overcoming these challenges, particularly through advancements in stability, energy management, and the integration of more sophisticated AI and sensor systems, ultimately improving the robot's performance in diverse, multi-level environments.

IndexTerms - Stair-Climbing Robots, Hybrid Designs, Artificial Intelligence (AI), Sensor Technologies, Energy Efficiency

I. INTRODUCTION

The increasing demand for automation in material handling across various industries, including logistics, construction, and healthcare, has led to the development of robots capable of navigating complex environments. One of the most significant challenges in these environments is the presence of stairs and uneven terrains, which are common in multi-level buildings and outdoor settings. Goods transport stair-climbing robots offer a promising solution by autonomously carrying materials up and down stairs, reducing the reliance on human labor and improving overall efficiency. These robots are particularly valuable in environments where traditional conveyance systems, such as elevators or ramps, are unavailable or impractical.

Stair-climbing robots have the potential to transform industries by enhancing safety, speed, and productivity in material transport. Their ability to navigate stairs autonomously can significantly reduce human effort and prevent injury associated with manual handling of heavy or bulky loads. Additionally, these robots can be deployed in a wide range of environments, from warehouses and factories to hospitals and construction sites, providing versatile solutions for diverse operational needs. The development of stair-climbing robots has seen significant progress over the past few decades, driven by advancements in robotics, artificial intelligence (AI), sensor technologies, and materials science. Researchers have explored various design approaches, including wheeled, legged, and hybrid systems, to achieve efficient and stable stair navigation. Furthermore, the integration of AI algorithms and sophisticated sensor systems enables robots to autonomously detect stairs, obstacles, and other environmental factors, improving their ability to navigate complex terrains.

Despite these advancements, several challenges remain in the development of goods transport stair-climbing robots. These include ensuring stability during load transport, optimizing energy efficiency for longer operation times, and addressing safety

concerns when interacting with humans and other machinery. This literature review aims to provide a comprehensive overview of the current research in this field, discussing the various design strategies, technological innovations, challenges, and future prospects for goods transport stair-climbing robots.

II. LITERATURE SURVEY

3.1 SungJun Park, Sahoon Ahn, JeongPil Shin, Hanbom Kim, Jeongmo Yang, YoungHwan Kim, Kyeongtae Lim, and TaeWon Seo [1], This paper presents the WAVE robot, which is designed to be a last-mile delivery robot capable of climbing stairs and traversing flat ground. The authors employ a four-bar linkage mechanism that allows WAVE to climb stairs in a stable and efficient manner. The robot's body and legs rotate in parallel as the cranks of the four-bar linkage rotate, allowing for smooth stair climbing. The design features a right-angled groove at the bottom of the robot, which fits the shape of the stairs, ensuring stability during ascent and descent. Additionally, in-wheel motors are attached to the robot's bottom to allow for movement on flat surfaces. The paper provides a detailed mechanical analysis to determine the required motor torque and friction coefficient for effective stair climbing. The experimental results confirm that WAVE can traverse stairs of varying sizes, demonstrating its practical utility in real-world delivery scenarios. The authors also emphasize the robot's ability to maintain balance and stability while moving across different terrains, marking a significant achievement in the development of delivery robots with stair-climbing capabilities.

3.2 Geono Kim, Hoon Chung, and Baek-Kyu Cho [2], This paper introduces MOBINN, a mobile balancing robot designed to overcome the challenge of climbing stairs in both indoor and outdoor environments. Unlike traditional robots, MOBINN utilizes a novel flexible wheel mechanism that adapts to the shape of the stairs, reducing the torque required for climbing. The flexible wheels allow the robot to climb stairs without the need for an additional degree of freedom, making it a simpler and more efficient solution. Furthermore, the robot's head structure is designed to maintain the horizontal orientation of the delivery package, preventing damage during ascent. The paper outlines the implementation of a linear quadratic regulator (LQR)-based motion controller, which ensures smooth and stable stair climbing. Experimental validation confirms that the flexible wheels significantly reduce the required torque and improve the robot's stability while climbing stairs. This design offers an innovative solution to the growing demand for stair-climbing robots in delivery services, showcasing the potential for improving the mobility and efficiency of robots in urban environments.

3.3 Teng Ma, Jiale Zhu, Kuangen Zhang, Wentao Xiao, Haiyuan Liu, Yuquan Leng, Haoyong Yu, and Chenglong Fu [3], The focus of this paper is to understand the dynamics of stair climbing through the estimation of leg stiffness and the subdivision of the stair climbing gait phase. Leg stiffness plays a significant role in locomotion and impacts the robot's ability to effectively navigate stairs. The authors propose a method to estimate the changes in leg stiffness during stair ascent and descent by analyzing the relationship between the ground reaction force and the leg length during the stance phase. Using a force-length curve, the study identifies various segments of the leg stiffness curve and correlates them with the center-of-mass (CoM) work rate. The results of this research offer insights into the biomechanics of stair climbing, which can guide the development of better biomimetic control strategies for wearable robots or exoskeletons. This approach allows for a more nuanced understanding of how the body adjusts during complex movements like stair climbing, providing valuable information for future robotics designs focused on human-like mobility.

3.4 Chuanqi Zheng, Siddharth Sane, Kangneoung Lee, Vishnu Kalyanram, and Kiju Lee [4], This paper introduces α-WaLTR, an adaptive wheel-and-leg transformable robot that is designed for versatile multiterrain locomotion. The robot features four passively transformable wheels, each consisting of a central gear and multiple leg segments with embedded spring suspension. This unique design allows the robot to adapt to various terrains, obstacles, and stairs while maintaining the simplicity and control principles of traditional wheeled robots. The paper discusses the multiobjective design optimization process used to determine the robot's chassis dimensions and center of gravity, which ensures stability while navigating obstacles. The integration of spring suspension helps to reduce vibrations, making the robot more efficient when transitioning between legged and wheeled modes. Experimental results validate that α-WaLTR can autonomously detect and climb stairs, demonstrating its capability to traverse diverse environments. This adaptive design represents a significant advancement in the development of robots that can navigate both rough terrains and urban infrastructures, offering a promising solution for real-world applications.

3.5 Yuan Wei, Kiju Lee [5], This paper introduces the CLAW mechanism, a novel wheel-leg system designed to improve the stair and obstacle climbing abilities of mobile robots. CLAW integrates cycloidal legs with traditional wheels, utilizing a passive bar mechanism that allows the legs to extend and retract with the wheel's rotation. This system enables the robot to generate cycloidal trajectories as it moves, significantly enhancing its ability to climb obstacles without the need for additional actuators. The authors demonstrate the effectiveness of the CLAW mechanism through experimental tests with CLAWbot, a robot equipped with this system. The results show that CLAWbot is capable of climbing obstacles up to 2.6 times the wheel radius and can traverse a variety of terrains, including concrete, grass, ramps, and rocky surfaces. The CLAWbot also exhibits smooth and efficient turning and climbing behavior. This innovative approach offers a simple yet powerful solution to improve robot mobility, making it more versatile in complex environments. The paper showcases how passive mechanical design can be leveraged to solve challenging mobility problems in robotics.

3.6 Tongxin Cui, Wenhui Wang, Zheng Zhu, Jing Wu, and Zhenzhong Jia [6], This paper proposes a stair-climbing robot equipped with a passive star-wheel configuration, which allows it to ascend stairs without the complexity of active control systems. The robot's four-star-wheels are designed to climb stairs by exploiting the shape and geometry of the star-wheel, providing stability and preventing slippage. The paper discusses the torque consumption required for stair climbing and provides a statics-based analysis to validate the robot's performance. The authors perform simulations to quantify the robot's ability to climb stairs under various load conditions. They also build a prototype to physically test the robot, and the experimental results confirm the robot's capability to climb standard indoor stairs at a speed of 0.7 seconds per step. The robot also shows adaptability to different stair sizes, offering a practical solution for environments with stairs of varying dimensions. This research presents a novel approach to stair climbing in robots, focusing on simplicity and stability without the need for complex control mechanisms.

3.7 TaeWon Seo, Sijun Ryu, Jee Ho Won, Youngsoo Kim [7], In this comprehensive review, TaeWon Seo and his colleagues examine the diverse mechanisms and sensing technologies employed in the design of stair-climbing robots. The paper categorizes the various systems into four main types: legged, tracked, wheel-legged, and wheel-linkage, each offering distinct advantages and

challenges for navigating stairs. The authors emphasize that while considerable progress has been made in stair-climbing robotics, significant hurdles remain, particularly in developing a robot capable of climbing stairs quickly and reliably in various environments. They also highlight the importance of sensing methods in improving stability and mobility during stair traversal. The paper proposes useful criteria for evaluating the performance of stair-climbing robots, including factors such as stability, speed, adaptability, and the ability to handle various stair dimensions. In this comprehensive review, the authors examine various mechanisms and sensing technologies utilized in stair-climbing robots, categorizing them into four main types: legged, tracked, wheel-legged, and wheel-linkage. Each type offers distinct advantages and challenges for navigating stairs, with legged systems providing superior adaptability but requiring complex control. The paper highlights the significant progress made in the field, yet acknowledges that developing a robot that can climb stairs quickly and reliably in diverse environments remains a major challenge.

3.8 Youngsu Cho, Kwang Joon Kim, Jongwoo Park, Hyunuk Seo, Hyunmok Jung, Byungin Kim, Dong-il Park, Jeongdo Ahn, and Chanhun Park [8], In this paper, the authors propose a design for an electric wheelchair capable of climbing stairs, which is equipped with a tri-spoke wheel and supporting leg system. The main challenge in designing a stair-climbing wheelchair is ensuring stability and speed during the ascent, which the proposed design addresses by using a tri-wheel configuration along with a supporting leg. The paper provides a detailed mechanical analysis of the climbing mechanism, including the design parameters that ensure stability and the continuity of motion. The authors also include equations to describe the robot's climbing performance and collision dynamics during stair traversal. The experimental results validate that the wheelchair can ascend and descend stairs at a speed of 10 steps per minute, with a stable posture even under extreme conditions. The paper includes a detailed mechanical analysis of the climbing mechanism, offering equations to describe the robot's performance and collision dynamics.

III. Comparitative Analysis Of Literature Reviews

Table 3.1: Comparison Study of Papers

Paper Title	Authors	Comparative Study
WAVE: Last Mile Delivery Robotic Platform With Stair-Climbing Ability Via Four-Bar Linkage-Based Locomotion	SungJun Park, Sahoon Ahn, JeongPil Shin, Hanbom Kim, Jeongmo Yang, YoungHwan Kim, Kyeongtae Lim, and TaeWon Seo	This paper introduces a four-bar linkage mechanism to allow a robot to navigate stairs, ideal for last-mile delivery. Unlike other systems, it combines stair climbing with flat surface navigation using in-wheel motors. Its design is focused on stability and dynamic analysis for effective motor torque calculation.
MOBINN: Stair-Climbing Mobile Robot With Novel Flexible Wheels	Geono Kim, Hoon Chung, and Baek-Kyu Cho	MOBINN features flexible wheels that adapt to stairs, reducing the required torque and eliminating the need for additional degrees of freedom. Compared to other robots, it provides a simpler, more efficient solution with fewer moving parts, and includes a motion controller to stabilize climbing.

α-WaLTR: Adaptive Wheel-and-Leg Transformable Robot for Versatile Multiterrain Locomotion	Chuanqi Zheng, Siddharth Sane, Kangneoung Lee, Vishnu Kalyanram, and Kiju Lee	α-WaLTR introduces a transformable wheel-leg robot with spring suspension and passively adjustable wheels. It is more versatile than purely wheeled robots and can navigate both flat and rough terrains. This paper combines multiple terrain adaptability with autonomous control, highlighting its efficiency for real-world applications.
CLAW: Cycloidal Legs-Augmented Wheels for Stair and Obstacle Climbing in Mobile Robots	Yuan Wei, Kiju Lee	CLAW integrates cycloidal legs with wheels, allowing the robot to climb obstacles without extra actuators. This design preserves the simplicity of wheeled robots but significantly enhances climbing ability, distinguishing it from robots requiring complex mechanisms for stair climbing.
A Stair-Climbing Robot with Star-wheel Configuration	Tongxin Cui, Wenhui Wang, Zheng Zhu, Jing Wu, and Zhenzhong Jia	This paper presents a star-wheel configuration for stair climbing, which is passive and simple to implement compared to other active systems. The design is lightweight and adaptable, focusing on ease of control while providing stability during stair traversal.
Stair-Climbing Robots: A Review on Mechanism, Sensing, and Performance Evaluation	Youngsu Cho, Kwang Joon Kim, Jongwoo Park, Hyunuk Seo, Hyunmok Jung, Byungin Kim, Dong-il Park, Jeongdo Ahn, and Chanhun Park	This research presents a tri-spoke wheel combined with a supporting leg for an electric wheelchair, focusing on stability and speed. Unlike robots focused on cargo delivery, this design prioritizes human mobility in challenging environments, offering a high degree of stability with simple mechanical design.
Design of Stair-Climbing Electric Wheelchair With Tri-Spoke Wheel and Supporting Leg	TaeWon Seo, Sijun Ryu, Jee Ho Won, Youngsoo Kim, and Hwa Soo Kim	This paper provides a comprehensive review of stair-climbing robots, categorizing the various locomotion mechanisms such as legged, tracked, wheel-legged, and wheel-linkage. It highlights challenges such as the limitations of current systems in providing fast and reliable stair-climbing capabilities. The paper also proposes evaluation criteria for assessing the performance of stair-climbing robots, and compares existing robots qualitatively to help guide future research.

IV. Conclusion

The development of goods transport stair-climbing robots has made significant strides in recent years, offering promising solutions for material handling in multi-level environments. These robots have the potential to improve efficiency, reduce human labor, and enhance safety in various sectors, including logistics, healthcare, and construction. Through the integration of advanced sensor technologies, artificial intelligence, and innovative design approaches such as wheeled, legged, and hybrid systems, these robots are becoming increasingly capable of autonomously navigating complex terrains, including stairs and obstacles. Despite the progress made, several challenges remain in the development of these robots. Ensuring stability while carrying loads on stairs, particularly on uneven or irregular surfaces, is a critical issue that requires further attention. Energy efficiency is another key challenge, as climbing stairs and maintaining balance while transporting goods requires substantial power, limiting operational time and range. Additionally, the safety of these robots, particularly in environments where they interact with humans, remains a significant concern, necessitating the integration of fail-safes, collision detection systems, and other safety measures. In conclusion, while significant progress has been made in the design and deployment of goods transport stair-climbing robots, addressing the remaining technical challenges and expanding their capabilities will be key to their widespread adoption. This literature review highlights both the advancements achieved thus far and the promising directions for future research, emphasizing the potential of these robots to revolutionize material transport in challenging environments.

V. Statements And Declarations

Author contributions: Every author contributed to the research topics by conducting a thorough analysis of all relevant research papers through a comprehensive literature review. The tasks of data collection and analysis were executed by NS, NP, RR, and TS, under the supervision and guidance of LG and MV. The first draft of the manuscript was written by RR and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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