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Advances and Future Directions in Robotic and Automated Façade Maintenance and Construction

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Abstract. Cities occupy just 3% of the Earth's land but account for 60–80% of global energy consumption and 75% of carbon emissions, as highlighted in Sustainable Development Goal 11. Improving energy performance in urban areas is crucial for sustainable regeneration. In this context, buildings play a central role, with façades acting as the primary interface for heat exchange. Renovating these components can significantly reduce energy losses and contribute to energy-efficient cities. Advances in robotics and automation offer promising solutions, providing more efficient, precise, and scalable systems. This paper examines the state of the art and future trends of robotic and automated systems for façade operations, focusing on their technical challenges and limitations.

Keywords: SDG11 · façade operations · robotics and automation

1 Introduction

The Sustainable Development Goals (*SDG*s) represent a global call to action, urging nations to foster economic growth and social well-being while safeguarding the environment. Among these objectives, SDG11 focuses on creating inclusive, safe, resilient, and sustainable urban environments. Cities are increasingly central to global living, with the world's population reaching 8 billion in 2022, over half residing in urban areas. This trend is projected to intensify, with an estimated 70% of the global population expected to live in cities by 2050 [1].

Notably, the building and construction sector accounts for over one-third of global final energy consumption and nearly 40% of total direct and indirect

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CO_2 emissions (Fig. 1). This underscores the critical importance of integrating sustainability principles into the design and maintenance of buildings [4].

Two complementary approaches can be pursued to enhance the energy performance of buildings. The first involves constructing new housing developments that adhere to contemporary energy standards [5], but this solution is often challenging to implement in densely populated urban areas, and the demolition and removal of older structures plus the erection of new structures can have a detrimental environmental footprint. Alternatively, targeted renovations aim to improve the operational efficiency of existing buildings as the majority of them is simply old, e.g. for Germany [6]. In this regard, façades play a critical role as the primary interface for thermal exchange with the external environment. Despite their potential benefits, current façade renovation practices rely heavily on manual labor, making them resource-intensive during both planning and execution phases. This often leads to inefficiencies and elevated costs [7].

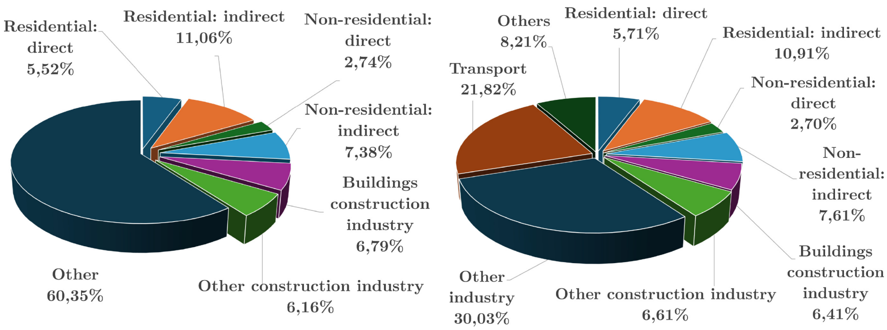

Fig. 1. Buildings and construction's share of global energy-related CO_2 emissions (left) and global final energy consumption (right). Adapted from IEA material [2,3], Licence: CC BY 4.0

To gain deeper insights into the technical challenges that robotics must address for effective façade operations, this paper provides a review of state-of-the-art of robotic and automated solutions proposed in recent years. It examines various tasks commonly performed on building façades, such as cleaning, painting, maintenance inspection, module installation, and other specialized activities. By analyzing these applications, the paper identifies recurring issues and limitations faced by current systems. Additionally, this work explores potential future directions, promoting a broader dialogue among researchers and engineers about the evolving role of robotics in façade operations.

To address these objectives, Sect. 2 provides a detailed review of robotic and automated solutions for façade construction and maintenance. Section 3 analyzes the principal features of these systems, offering a foundation for a broader discussion on potential strategies to tackle existing challenges. Section 4 outlines future trends, emphasizing the evolving role of robotics in façade operations, while Sect. 5 concludes the study.

2 Robotic and Automated Solutions for Façade Operations

Analyzing robotic solutions developed for different façade tasks, such as cleaning, painting, and inspection, reveals shared technical challenges that must be addressed for these systems to effectively and efficiently replace traditional methods. Key challenges for façade operations include:

- Exposure to unpredictable external conditions: façade operations are affected by wind [8] and weather, requiring robotic systems to have large mechanical stiffness and high safety factors for external force resistance.
- Human-hazardous environments: façade tasks in dangerous or hard-to-reach areas demand robotic systems that ensure safe, straightforward installations while adhering to strict safety standards like DIN 5692 [9].
- Complex façade features: balconies, windows, and railings necessitate robots with advanced sensing and adaptive capabilities to navigate and address such complexities effectively [10].
- Diverse geometries and scales: robotic solutions must offer flexibility and precision to handle façades of varying shapes, from small planar surfaces to large curved structures [11].

Given the above diverse challenges, numerous robotic solutions have been proposed, each addressing specific requirements. The following subsections provide a review of the current state of the art in robotic and automated systems for façade operations, organized according to the specific tasks they are designed to execute.

2.1 Cleaning Task

Robotic solutions for façade cleaning have been widely explored, yet no single commercially dominant solution has emerged [12,13]. Seo et al. [14] analyzed climbing mechanisms, cleaning methods, and challenges, identifying key performance criteria: obstacle-overcoming capability and cleaning efficiency. Several notable systems demonstrate innovative approaches. A gondola robot introduced by Hong et al. [15] employed elastic actuators and tristar wheels to mitigate impact forces when overcoming obstacles. This design enhanced durability and efficiency by converting impact into rotational energy. Rope-based mechanisms, such as the Sypron robot [16], used dual units: a rooftop robot for vertical lifting and a cleaning robot for surface operations. However, single-wire systems faced instability under external forces. Chae et al. [17] addressed this issue of instability by employing dual ropes for enhanced mobility and resistance to external forces without additional infrastructure.

Recent advancements have extended the functionality of climbing robots to include detection and operational capabilities, like bio-inspired biped robots. In [18] the authors presented a versatile obstacle-overcoming climbing gait, enhanced by powerful joint motors, vacuum footpads, and air pressure sensors for stable surface adherence. Additionally, an integrated electromagnet and visual camera facilitate precise visual-based manipulation.

2.2 Painting Task

Painting tasks on building façades share many technical challenges with cleaning operations but differ primarily in the design of the end-effector. Most robotic systems for painting employ anthropomorphic arms due to their flexibility and precision. A compact, lightweight, and highly adaptable automatic spraying robot was proposed in [19]. This system featured a hollow-skew wrist with three degrees of freedom, ensuring sufficient maneuverability for complex surface geometries. This robotic arm was also integrated into a two-axis Cartesian robot, creating an alternative architecture for façade painting tasks [20].

In addition, robotic systems have been applied to specialized applications, such as marking walls at construction sites. A marking robot was introduced in [21] to draw precise lines indicating installation positions for equipment. The system combined an XY plotter-type robot, a motor-driven total station, and a wireless controller, significantly reducing manual surveying efforts.

2.3 Inspection Task

Drones, or Unmanned Aircraft Systems (UAS), represent a primary robotic solution for building-façade inspection. Their capabilities include capturing detailed thermal and visual data from diverse angles and altitudes, significantly reducing inspection time and labor [22]. UAS have been used for crack detection on walls with open-source photogrammetry and deep learning, though their ability to identify fine cracks remains limited [23]. However, limitations include GPS-dependent localization causing navigation inaccuracies and regulatory requirements for operator oversight, restricting autonomy and range.

Wall-climbing robots constitute the second category of robotic systems for façade inspection, offering distinct advantages in stability and precision. For example, Moon et al. [24] developed a climbing mechanism that navigates vertical guide rails installed along building edges. Its hook system ensured secure docking and stable movement, mitigating risks of accidental falls. Similarly, Koh et al. [25] introduced a teleoperated robot designed for the preventive maintenance of high-rise gas pipes. These robots excel in tasks requiring high precision and physical contact with the façade but face challenges in adapting to diverse building geometries and maintaining stable operations under variable external forces.

2.4 Module-Installation Task

The installation of façade modules, essential for energy-oriented refurbishments, presents several technical challenges that demand automation. Key issues include ensuring precise positioning, secure operations at height, and efficient material storage and supply. Current methods often rely on manual tools and techniques, which are labor-intensive and prone to safety risks. Researchers have proposed various robotic solutions to address these challenges, focusing on adaptable and modular systems to accommodate diverse building types and façade materials.

For example, Iturralde et al. [26] outlined requirements for automated support systems, emphasizing stability, security, rapid installation, and affordability.

Curtain Wall Modules (*CWM*s) for high-rise buildings exemplify another area where automation could mitigate risks and improve efficiency by reducing manual handling during installation [27]. A notable contribution is the Hephaestus project [28], which developed a cable-driven parallel robot for construction tasks like CWM installation. This system demonstrated significant advantages, including a large operational workspace, high payload capacity, and modularity, addressing key limitations of traditional methods while enabling safer and more efficient processes. The main disadvantages stem from the prolonged installation time and elevated costs resulting from the machine's increased complexity.

3 Evaluation of Robotic Solutions

The robotic systems analyzed in this study can be categorized based on their locomotion mechanisms, adaptability to diverse building surfaces and materials, and the specific tasks they are designed to perform on façades. These solutions exhibit various capabilities, such as navigation, obstacle avoidance, transitioning between vertical and horizontal planes, handling curved surfaces, manipulating objects, overcoming barriers, and ensuring self-protection [29]. Table 1 presents a summary of the robotic solutions cited in this work. Although these systems demonstrate significant technical advancements and optimization for specific tasks, they reveal limitations when evaluated against the practical requirements of the construction industry.

A critical factor contributing to the limited effectiveness of these solutions is the misalignment between their design focus and the overarching constraints of the construction sector [30]. While these robots exhibit advanced functionalities, they fail to address industry-wide challenges such as high costs, a risk-averse culture, and the fragmented structure of the sector. For example, while capable of navigating complex façades and performing precise tasks, high capital costs make these technologies inaccessible to most small and medium subcontractors, as few can justify such expenses on narrow profit margins.

Additionally, many robotic systems lack the adaptability required for the highly variable nature of construction projects. Differences in design, materials, and operational constraints demand significant customization, which current solutions often fail to provide. Their task-specific design limits versatility, complicating efforts to achieve a favorable return on investment. This limitation weakens the business case for robotics, especially in an industry where solutions must be transferable across diverse projects to remain economically competitive.

Technical and cultural challenges further complicate the integration of robotic systems in construction. Effective collaboration between human workers and robots remains underdeveloped, limiting the ability of these systems to integrate into construction workflows. While robots excel in isolated tasks such as obstacle navigation or façade component installation, they struggle to adapt to dynamic site conditions that rely heavily on human supervision and manual

Table 1. Summary of the robotic solutions for façade operation

Robotic Solution	Robot Locomotion	Application	Robot Capability
Kite Robotics [12]	Cables	Cleaning	Obstacle avoidance
Shenxi [13]	Wheels	Cleaning	Navigation
Gondola Robot [15]	Cables	Cleaning	Obstacle avoidance
Sypron Robot [16]	Single cable	Cleaning	Obstacle avoidance
Edelstro-M2 [17]	Cables	Cleaning	Self-protection
Bio-robot [18]	Adhesion	Cleaning	Curved surfaces
Spraying Robot [19]	Wheels	Painting	Manipulation
Cartesian Robot [20]	Guide rail	Painting	Manipulation
Marking Robot [21]	Wheels	Painting	Navigation
UAS [22]	Flying system	Inspection	Navigation
UAS [23]	Flying system	Inspection	Data analysis
Climbing Robot [24]	Guide rail	Inspection	Self-protection
Climbing Robot[25]	Pipe rail	Inspection	Navigation
CDPR [28]	Cables	Module-installation	Adaptability

adjustments. Current technologies lack the necessary customization, real-time adaptability, and robust human-robot interaction capabilities to address these challenges.

4 Future Trends in Robotics for Façade Operations

This section suggests potential future trends for integrating robotic systems into construction, particularly for façade operations, to better align these technologies with the industry's practical needs (Fig. 2). One possible direction involves defining a flexible robotic architecture that address key limitations of existing systems, such as high costs, installation complexities, and limited task capabilities. Deployable and reconfigurable robots [31], emphasizing modular and cost-effective designs, might simplify deployment and operation. By potentially reducing upfront and operational expenses, these systems could make advanced automation more accessible to smaller subcontractors. Additionally, incorporating multi-functional capabilities may allow robots to perform diverse tasks thereby reducing dependence on specialized systems. This approach could enhance productivity while also easing management challenges by streamlining maintenance and operational processes.

Another potential trend is the adoption of automated Building Information Modeling (*BIM*) planning. BIM is an integrated process that involves managing 3D digital representations of physical and functional characteristics of construction projects [32]. Many façade renovation projects lack automated BIM planning or depend on highly-skilled personnel for advanced planning tools. By integrating time and cost dimensions, BIM could enable precise scheduling and budget

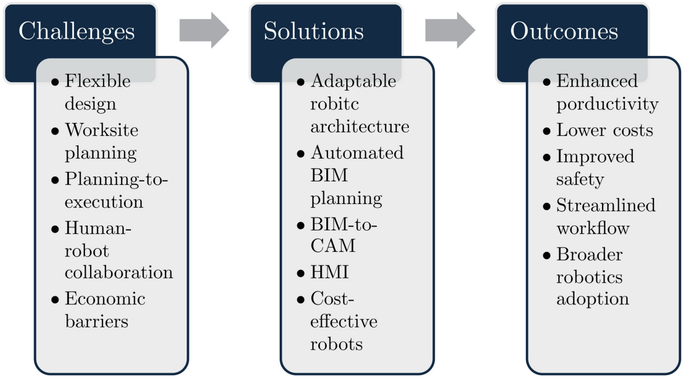

Fig. 2. Robotics for façade operations: challenges, solutions and outcomes

forecasting, simplifying worksite management, reducing waste and dependence on specialized expertise, and accelerating project initiation by enabling better-informed decisions throughout a project's life cycle.

Moreover, given the high costs associated with reprogramming robots for each deployment, exploring robot autonomy and automatic programming becomes essential. A planning-to-execution framework integrating CAD/CAM functionalities into façade renovation workflows could address robotic constraints, optimize energy consumption, allocate tasks between robots and workers, and automate robot programming. A sequential, parametric, and algorithmic CAD/CAM approach may streamline workflows for efficient execution.

The final step toward efficiency is operational control. Once a robot program is available, a cooperative control framework could optimize workflow execution while ensuring worker and equipment safety. Effective workflows rely heavily on interactions between robots and workers. A Human-Machine Interface (*HMI*) could support this by assigning tasks, facilitating data exchange, and addressing real-time issues. This interface would enhance operators' awareness of task management and activity progress. Through seamless interaction between the worker, serving as the robot supervisor, and the HMI, quality control remains a human-driven process.

5 Conclusions

In conclusion, this paper provided a concise review of the main robotic and automated solutions for façade operations, highlighting their advantages and limitations within the context of the construction industry's economic and technical landscape. It discussed future trends aimed at overcoming the economic, technical, and cultural barriers to robotic adoption. The proposed strategies offer a framework for aligning robotic innovations with industry needs, promoting sustainable façade operations, and contributing to the development of more efficient buildings and cities in the coming years.

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