Development of Robotics for Building Exterior Inspection: A Literature Review

Tianxi Chen[1], Mi Pan[1], Thomas Linner[2] and Honghao Zhong[1]

[1]Department of Civil and Environmental Engineering, University of Macau, Macau, China
[2]Department of Civil Engineering, OTH Regensburg, Regensburg, Germany
chen.tianxi@connect.um.edu.mo, mipan@um.edu.mo, thomas.linner@oth-regensburg.de
zhong.honghao@connect.um.edu.mo

Abstract –

The aging of buildings is a global concern, with potential risks to human safety and property. Building inspection and maintenance are crucial for ensuring structural integrity and safety. However, traditional manual methods are time-consuming and pose safety risks, especially for exterior inspection at height. Robotics offer a promising alternative to enhance building inspection efficiency and cost-effectiveness, but still in the early development stage. This paper aims to review and analyze the state-of-the-art design and development of robotics for building exterior inspection, referring to the literature published in the last two decades. Firstly, the review classifies different types of robots for building exterior inspection in terms of locomotion and adhesion modes, and discusses the capability of robots from navigation, obstacle surmounting, wall-to-wall/floor transition, curved wall climbing, grasping, barrier avoidance, and self-protection. Secondly, the paper examines the applicability of robots to various building materials for inspections and summarizes the most typical applications (i.e. glass curtain walls, tile walls, and concrete walls). Thirdly, the paper discusses the typical data collection and analysis methods for building exterior inspection using robots. The paper also explored potential enhancements for robotic inspection through the integration of building information modeling, augmented reality/virtual reality, and the involvement of human-in-the-loop. Finally, the paper summarizes the typical application of robotics in building exterior inspection regarding robot types, inspection applications, data collection and analysis methods, discusses the challenges, and outlines the future directions.

Keywords –

Wall inspection; Building exterior inspection; Robotics; Locomotion; Adhesion; Non-destructive testing.

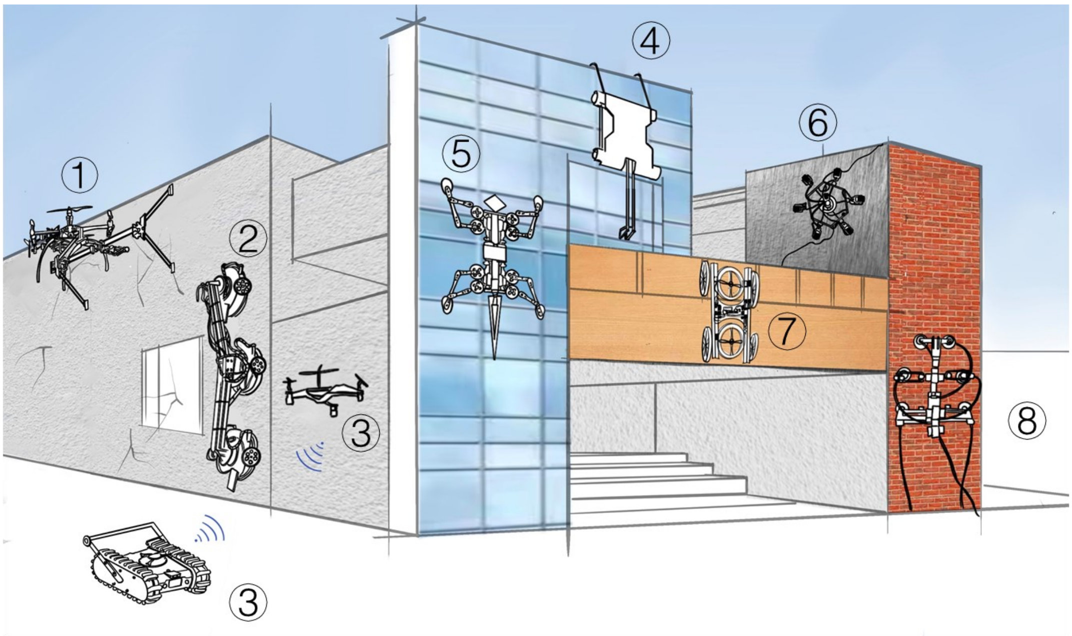
1 Introduction

The phenomenon of building aging presents a significant global concern, as it entails the gradual deterioration of both interior and exterior walls, leading to potentially severe consequences for human safety and property [1]. Compared to interior walls, exterior walls are more exposed to environmental factors and external forces with issues such as deterioration or delamination. Thus, the demand for robotic inspection targeting exterior walls is relatively stronger than for interior ones. Compared to interior wall inspection, the demolition and reconstruction of building exteriors require significant financial and labor resources. Traditional approaches for inspecting building walls typically involve manual visual exams or hammering tests [2]. The inspection tasks are performed by human operators who ride on gondolas suspended in mid-air and utilize various handheld facilities together with telescopes and cameras for the inspection [3]. However, these methods present safety concerns, particularly when working at elevated heights. In recent decades, there has been a growing trend towards the adoption of robots for building inspection. In particular, robotic inspection offers several advantages, including enhanced efficiency and consistency in inspection results and presenting a cost-effective alternative to manual inspection methods [4]. Human operators can remotely operate robots from a secure location and obtain the data and images from the facilities mounted on the robots [5]. However, robotics for building exterior inspection is still an emerging area with limited real-world applications. How different types of robots could be effectively developed and applied to inspect building exterior walls to ensure building safety and functionality remains unexplored.

This paper aims to review and analyze the state-of-the-art design and development of robotics for building exterior inspection, referring to the literature published in the last two decades. The objectives were to i) explore the different types of robots that are used in exterior wall inspection of buildings and the specific inspection applications conducted by robots, ii) examine the methods for robots to inspect and detect building exterior defects, and iii) identify challenges and future directions of robotics for exterior wall inspection of buildings.

2 Methodology

The study was conducted in three major stages. Firstly, a comprehensive literature review was conducted to collect information on the utilization of robotics in inspecting exterior walls in buildings, focusing on their specific applications. Web of Science (WoS) and Scopus databases were utilized to search for relevant papers. The keywords (robot* OR aerial OR drone OR uav OR "unmanned aerial vehicle") AND (wall OR building) AND (inspection OR maintenance) were used. Secondly, data screening and supplementation were conducted on the identified papers. Only relevant publications regarding robots for building exterior wall inspection were kept. Additional articles identified by cross-referencing were supplemented. Thirdly, content analysis was performed to extract relevant information from the included papers regarding the types of robots and their capability, inspection applications, inspection methods, and challenges regarding robots for building exterior inspection.



Notations:

① Aerial robot for contact inspection tasks
② Three-module wheeled robot
③ Hybrid system with a crawler robot and a microdrone
④ Double-chamber wheeled robot
⑤ Wall-climbing robot with adhere mechanism inspired by Cicada and Gecko
⑥ Multi-legged robot with twist-based crouching
⑦ Double-propellers wall inspection robot
⑧ Multi-legged robot with suckers

Figure 1. Exemplars of robots utilized in exterior wall inspection.

3 Robots for Building Exterior Inspection

This section focuses on the classification of robots and their capability in practical scenarios.

3.1 Classification of Robots

The classification of robots for building exterior inspection considers two key aspects: locomotion and adhesion mechanisms. Locomotion refers to the capability of the robot to move, while adhesion refers to its adaptability to building surfaces and materials. Figure 1 shows some examples of inspection robots developed in various types.

3.1.1 Modes of Locomotion

The locomotion systems allow the efficient and autonomous mobility of robots during the inspection of exterior walls. The selection of suitable locomotion depends on the structural and built environment. The primary types of locomotion for robots applied for building exterior inspection can be classified into wheeled, tracked, legged, cable-driven parallel, aerial, and hybrid.

Wheeled robots, inspired by automobiles, offer fast speed and efficient movement. However, the presence of large gaps and inconsistencies on wall surfaces often prevents proper contact between the wheels and the building surface [6].

Tracked robots, inspired by tanks, utilize continuous treads to achieve basic movement and improve climbing stability by ensuring contact with the wall surface. However, this locomotion method may lead to increased frictional resistance and higher energy consumption [7].

Legged robots, including bipedal (two-feet), quadrupedal (four-feet), and hexapod (six-feet) locomotion systems, offer superior adaptability for wall surface inspection [8]. However, the utilization of multiple legs increases the complexity of locomotion and adhesion force control.

Cable-driven parallel robots, utilizing cables as actuators, offer a mechanism for vertical and inclined movement control in high-rise building wall inspection [9]. However, their reliance on secure anchoring points and complex setup processes distinguishes them from other wall inspection robots.

Aerial robots, such as drones and unmanned aerial vehicles (UAVs), offer straightforward control mechanisms. However, aerial systems encounter complexity in maintaining a consistent distance from walls during inspection, as challenges from external factors like wind and rain arise [10].

Hybrid robots, integrating multiple locomotion mechanisms, offer enhanced capabilities and increased mobility for rapid motion on wall surfaces, obstacle-spanning, and seamless mode switching [11]. Ogusu et al. [12] designed a robot system where a tracked robot moves to the front of a concrete wall, while a drone takes off and flies vertically against the wall, utilizing a camera to capture images. However, the integration of diverse locomotion modes and functionalities in hybrid robots often poses challenges to control mechanisms [13].

3.1.2 Adhesion Methods

Another distinguished feature of robots for building exterior inspection lies in the technologies for adhering to building surfaces, mostly applied for climbing-type inspection robots [6]. The adhesion methods can be classified as active or passive, depending on whether an external energy supply is needed to support the robot. A more general classification is based on the nature of adhesion forces required: pneumatic or air pressure, magnetic, biomimetic, and electrostatic [14].

Pneumatic adhesion methods, including vacuum or suction cups and negative pressure, are commonly used for climbing flat surfaces [14]. Vacuum adhesion, employing suction cups and vacuum pumps, offers simplicity and effective wall steps but can be problematic on rough or grooved surfaces [2]. Negative pressure adhesion, utilizing impellers or eddy currents, provides secure attachment but may face potential suction chamber leakage on vertical walls [15].

Magnetic adhesion is commonly used for inspection robots on ferrous surfaces, employing either permanent magnets or electromagnets. It allows for rapid locomotion and eliminates the need for power application but faces challenges in maintaining stable magnetic power on non-smooth surfaces and is limited in suitability for non-steel structures [16].

Biomimetic adhesion methods, inspired by climbing animals like cockroaches and cicadas, utilize robust dry adhesives based on Van der Waals forces [4]. These methods allow robots to attach to various surface materials and maintain attachment without power consumption. However, they have limitations in terms of payload capacity.

Electrostatic adhesion utilizes compliant electrode patterns to generate strong electrostatic forces between the robot and the wall surface, allowing for exceptional adhesion pressure on uncharged surfaces [17]. While this method offers minimal power consumption, and noise-free operation, it may face challenges of unstable adhesion and reduced reliability in the presence of external disturbances like wind and heavy rain.

3.2 Capability of Robots

The capability of robots for building exterior inspection considers seven aspects: navigation, obstacle surmounting, wall-to-wall/floor transition, curved wall climbing, grasping, barrier avoidance, and self-protection. Most of these abilities are particularly related to climbing-type robots.

3.2.1 Navigation Ability

Navigation ability is critical for robots to perform building exterior inspection, which includes localization and mapping, and path planning.

Localization refers to the estimation of robot position and orientation, while mapping denotes the creation of a digital representation of the robot environment, both are fundamental processes for robot navigation [18]. Robots utilize sensors such as RGB-D cameras, stereo cameras and Light Detection and Ranging (LiDAR) to gather the environment data for localization and mapping [7]. Simultaneous localization and mapping (SLAM) is widely used to enable the robot to create a map of its environment while simultaneously determining its position within the map [19].

Path planning determines the optimal path or trajectory for the robot to navigate from its current location to a desired goal location while avoiding obstacles [20]. Path planning for robots to conduct building exterior inspection often considers factors such as finding local optimal paths for defect detection to minimize the energy consumption of the robot and navigating the robot safely from building exterior and mid-air obstacles [20].

3.2.2 Obstacle Surmounting Ability

The obstacles on the exterior wall mainly include grooves and strips. For climbing robots, having a high ability to overcome obstacles is essential during the design stage of robotic gait planning. For example, Bian et al. [4] developed a robot with a gear transmission system inspired by cicadas and geckos, incorporating a stable gait design for obstacle surmounting.

3.2.3 Wall-to-Wall/Floor Transition Ability

The ability of wall-to-wall/floor transition involves smoothly navigating and changing position between vertical and horizontal surfaces, which is a key feature for mobility in inspection robots. Guan et al. [2] designed a modular biped robot that can smoothly transit between walls by adapting climbing gaits and utilizing suction modules for reliable attachment to different surfaces.

3.2.4 Curved Wall Climbing Ability

The ability of robots to climb curved walls can enhance the efficiency of inspections by enabling them to detect complex geometries and reach areas with limited human accessibility. Saito et al. [8] developed a flexible-legged robot with a sucker mechanism that allowed it to climb unknown curved walls.

3.2.5 Barrier Avoidance Ability

Autonomous barrier avoidance for robots in complex outdoor scenes should be considered, especially for unknown environments to prevent crashes or falls. For example, Chang et al. [19] developed a robust fuzzy logic controller for building inspection robots, enabling autonomous navigation and barrier avoidance to achieve precise wall-following behavior.

3.2.6 Grasping Ability

The setup of grippers is essential as the interacting grasping media between the robot and the object. The design of grippers should overcome the challenge of grasping exterior walls, considering their shapes, materials, and roughness [7]. Previous researchers have explored various grasping methods. For example, Xu et al. [21] designed a cross-structured gripper for climbing robot consisting of multiple claws and hooks that can slide along the wall surface to locate attachable uplifts.

3.2.7 Self-Protection Ability

Protective devices for robots are crucial to ensure their safety and stability during operation on the building exterior by protecting against overturning during climbing, falls, and external objects. For example, Altaf et al. [14] designed an inspection robot with protective devices, including a support frame, EVA shell, airbag, and established a mechanical model to analyze the forces involved during a fall.

4 Inspection Applications

The applications of robots for building exterior inspection are mostly considered for maintaining glass curtain walls, tile walls, and concrete walls.

4.1 Glass Curtain Wall Inspection

The inspection of glass curtain walls has gained increasing attention, driven by concerns surrounding the safety risks associated with accidental glass breakage and the subsequent hazards of falling glass. Scholars proposed a specific design of end-effectors for glass curtain wall inspections. Liang et al. [6] introduced a robotic system that utilizes vibration response signals obtained by knocking the glass with a mechanical arm.

4.2 Tile Wall Inspection

Robotic techniques also play a crucial role in the inspection of tile wall delamination, which occurs between the tiles and substrates due to aging and improper installation. Pan et al. [23] proposed an efficient method for inspecting the status of tile walls using forward-looking infrared technology and camera on UAVs. The combination of hammering tests and cameras is also commonly employed to identify tile delamination caused by bonding degradation and thin tile layers [9].

4.3 Concrete Wall Inspection

Concrete used for wall surfaces can deteriorate over time, resulting in issues such as peeling, lifting, and cracking. Traditional visual inspection methods for concrete surfaces primarily rely on human workers. Crack detection and inspection in walls benefit from advanced robotic techniques. For example, Wang et al. [24] developed an automatic detection of building surface cracks using UAV, demonstrating high accuracy and potential for practical application.

5 Inspection Methods

This section focuses on the inspection methods in terms of data collection and data analysis for robots to conduct building exterior inspection and defect detection.

5.1 Data Collection

Data collection methods primarily utilize non-destructive testing (NDT) techniques to gather information without causing damage to the building. Essentially, robots offer the platform to equip different NDT techniques for data collection, which could reduce the impact of human factors and achieve more efficient, accurate, cost-effective, and damage-avoided inspection of buildings. Typical NDT methods for building exteriors are as follows: 1) visual inspection utilizes cameras to examine defects that are widely employed in concrete wall crack detection [25]; 2) infrared thermography uses infrared thermal imagers to detect temperature variations for defect identification, which is commonly employed for wall moisture and air leakage detection [26]; 3) laser scanning emits laser beams to capture three-dimensional (3D) point cloud for defect detection, which suits for 3D crack dimension detection and localization [27]; 4) impact acoustic inspection analyzes sound waves generated by impacting the object for defect evaluation, and is mostly employed for tile wall debonding and integrity detection [9].

5.2 Data Analysis

Based on the collected data, a number of studies focus on the development of new algorithms to process and analyze different types of inspection data, like RGB and thermal images [26, 28, 29], point cloud data [27], and acoustic signals [30].

Image-based analysis has received the most attention. Early research works focus on simple image processing, such as greyscale for removing image color information and histogram equalization for adjusting image pixel value distribution [20]. Recently, deep learning techniques, especially convolutional neural networks (CNNs) have been successfully developed in the field of computer vision, and are widely applied for object detection and image segmentation for building exterior inspection [7]. For example, Hu et al. [7] proposed deep convolutional neural network (DCNN) with reduced parameters and low latency for feature extraction in the crack detection for an inspection robot; Woo et al. [28] utilized the fast and accurate YOLOv5 model for UAV-based crack detection system for concrete wall inspection; Wang et al. [24] proposed a UAV-based approach integrating ResNet50 and YOLOv8 for accurate detection of concrete cracks on building exteriors. Some studies combine traditional machine learning and deep learning to achieve more accurate inspection results. For example, Chaiyasarn et al. [31] proposed a crack detection system that combined support vector machines with CNN, achieving a detection accuracy of approximately 86% in validation images.

Point cloud-based analysis extracts relevant inspection information from 3D data in depicting object geometry for defect detection, which heavily relies on the quality of the point cloud data. Some relevant studies combined 3D point clouds with 2D images and employed image processing techniques for defect detection [7]. For example, Yuan et al. [27] developed a novel inspection robot with deep stereo vision for 3D concrete damage detection and quantification, which employed Mask R-CNN for the captured RGB imaging data for crack segmentation and localization and conducted spatial mapping from 2D plane to 3D space coordinates for damage quantification.

Acoustic signal-based analysis utilizes the acoustic signals generated by tapping the wall surface. Since the collected signals are generally not perfect with background noise and missing signals, different data processing techniques have been used to address the noisy environment and data quality issues. For example, Nishimura et al. [30] proposed a novel method to clarify the features of hammering sound and propeller noise and conducted acoustic analysis of recorded hammering sounds collected by a multi-copter type mobile robot for defect detection.

6 Integration with Other Advanced Technologies

This section discusses the integration of inspection robots with other advanced technologies such as building information modeling (BIM), augmented reality/virtual reality (AR/VR), and human-in-the-loop (HILP).

6.1 BIM

For managing inspection data and planning inspection paths, BIM can be integrated with robots to provide rich geometric and semantic information. Tan et al. [20] proposed BIM-based inspection area extraction, optimized UAV flight path using A star and genetic algorithms, and real-time crack identification through edge computing and a zoom camera.

6.2 AR/VR

AR serves as a valuable tool for visualizing the inspection process, enabling efficient remote inspections by overlaying models onto captured images [32]. The use of AR technology in wall inspection robots allows for virtual walkthroughs and real-time visualization. Nishimura et al. [30] developed a robot that utilizes an AR marker for localization, allowing for precise identification of the hammering position on a structure.

VR can simulate the real environment of buildings, enabling operators to identify issues and take appropriate actions in a virtual setting. It reduces the need for robotics, lowers risks and costs, and provides more practice opportunities. Albeaino et al. [33] developed a VR-based flight simulator for training drone operators in inspecting building exteriors, focusing on flying near targets, maintaining stable hovering, and collecting data.

6.3 HITL

HITL generally refers to interactive simulation systems that enable direct human intervention during the operation of robots or artificial intelligence models [3]. It combines human intelligence with machine or robot capabilities for risk-free and improved system performance, which is preferable for hazardous building exterior inspection tasks. For example, Saleem et al. [34] investigated human eye gaze patterns during a façade damage inspection using eye tracking which should facilitate information-sharing and decision-making for collaborative human-robot teams for building inspection.

Table 2. Summary of typical robots for building exterior inspection.

Example	Robot type	Inspection application	Data collection	Data analysis
A multi-chamber adhesive climbing robot [6]	Wheeled with pneumatic	Glass curtain wall defects	Impact acoustic	-
Alicia[3] [35]	Wheeled with pneumatic	Concrete wall defects	-	-
CROMSCI [15]	Wheeled with pneumatic	Concrete wall defects	Visual, cover meter, impulse radar	-
A four-wheel drive robot [27]	Wheeled	Concrete wall crack assessment	Visual, laser scanning	Mask R-CNN, statistical outlier removal filter, KNNs
An autonomous mobile ground robot [7]	Tracked	Concrete wall crack defects	Visual, laser scanning	DCNN, random sample consensus
A wall-climbing robot inspired by cicadas and geckos [4]	Legged with biomimetic adhesion	Stone and glass curtain wall defects	-	-
A semi-autonomous multi-legged robot [8]	Legged with pneumatic	Wooden and tile wall defects	-	-
An electro-adhesive wall-climbing robot [17]	Legged with electrostatic	Glass curtain wall defects	-	-
WICBOT [9]	Cable-driven	Tile wall bonding integrity	Impact acoustic	ANN
A UAV-based system [24]	UAV	Concrete crack defects	Visual	ResNet50, YOLOv8
Quasar™ [26]	UAV	General moisture, air leakage	Infrared thermography	Gaussian low-pass filter
A UAV-based system [25]	UAV	General crack defects	Visual	CNN
DJI MJ200 [22]	UAV	Concrete wall crack defects	Visual	CNN, CycleGAN
DJI Phantom4 RTK [28]	UAV	Concrete wall crack defects	Visual	YOLOv5
ABECIS [36]	UAV	General crack defects	Visual	Xception
DJI Phantom4 [31]	UAV	Masonry wall crack defects	Visual	CNN, support vector machine
Microdrone-equipped mobile crawler robot [12]	UAV+tracked	Concrete wall crack defects	Visual	AWS crack detection AI system
A multi-copter mobile robot [30]	UAV+wheeled	Concrete wall defects	Impact acoustic	Short-time Fourier transform

7 Discussions

Based on the review and analysis, a summary of typical robots for building exterior inspection is provided in Table 1, covering robot types, inspection applications, and methods for data collection and data analysis. The findings provide useful insights for research and development in robotics for building exterior inspection, and are elaborated as below.

Firstly, prior studies have demonstrated two major streams of research regarding robotics for building exterior inspection. The first stream focused on developing inspection robot prototypes and emphasized the mechanical mechanisms of the robots, but many did not cover specific data collection and analysis methods for inspection [4]. The second stream mainly employed UAV as the robotic platform and focused on specific data collection and analysis methods for inspection [24]. The future direction for improvement could be the integration of the two streams to develop comprehensive robotic solutions for building exterior inspection. These solutions could combine the high flexibility and adaptability of robot mechanics with advanced data collection and analysis methods for building exterior inspection.

Secondly, most of the research focused on the inspection application of concrete crack detection as concrete cracks are typically visible and possess distinct features that can be effectively captured using imaging techniques and analyzed with computer vision algorithms. However, many buildings, especially high-rise buildings, feature a variety of wall materials rather than being limited to a single wall type and still lack comprehensive and robust data collection and analysis methods. Besides, glass curtain walls and tile walls are more challenging to achieve timely and accurate defect detection [6, 9]. More efforts are required to develop adaptable and generic solutions for inspection robots integrating different data collection methods that are not limited to specific types of wall materials or defects.

Thirdly, only limited studies focused on the development of end effectors of the inspection robot to enable the multi-functional capability of the robot for multiple inspection tasks [7]. In this regard, the integration of repair or renovation functions with the inspection robots should be considered to guide the selection of robot body type and the design of different inspection and repair end-effectors as well as control mechanisms.

8 Conclusions

This paper reviews and analyzes the state-of-the-art design and development of robots for building exterior inspection. Specifically, these inspection robots are classified based on locomotion and adhesion modes, and their capabilities are discussed from navigation, obstacle surmount, wall-to-wall/floor transition, curved wall climbing, grasping, reflective and transparent barrier avoidance, and self-protection. The review further summarizes the most typical building exterior inspection applications for robotics considering the wall materials, namely glass curtain, tile, and concrete, and discusses the detailed data collection and data analysis methods for inspection. Furthermore, the paper explored the potential integration of BIM, AR/VR, and HITL for improving robotic building exterior inspection. Blending the review findings, useful insights are provided regarding robot types, inspection applications, data collection and analysis methods for building exterior inspection. Future research is needed toward comprehensive and tailored solutions for robotic building exterior inspection, adaptable and generic inspection robots that suit different wall materials and defect types, and multi-functional end effectors for inspection robots and integration with building repair capability.

Acknowledgement

We acknowledge funding support from University of Macau (File no. SRG2023-00006-FST).

References

[1] Pan, M., Linner, T., Pan, W., Cheng, H., and Bock, T. Structuring the context for construction robot development through integrated scenario approach. *Automation in construction*, 114, 103174, 2020.

[2] Guan, Y., Zhu, H., Wu, W., Zhou, X., Jiang, L., Cai, C., Zhang, L., and Zhang, H. A modular biped wall-climbing robot with high mobility and manipulating function. *IEEE/ASME Transactions on Mechatronics*, 18(6):1787–1798, 2013.

[3] Zheng, Z. J., Pan, M., and Pan, W. Virtual Prototyping-Based Path Planning of Unmanned Aerial Vehicles for Building Exterior Inspection. In *ISARC Proceedings of the International Symposium on Automation and Robotics in Construction*, pages 16-23, Kitakyushu, Japan, 2020.

[4] Bian, S., Xu, F., Wei, Y., and Kong, D. A novel type of wall-climbing robot with a gear transmission system arm and adhere mechanism inspired by Cicada and gecko. *Applied Sciences*, 11(9):4137, 2021.

[5] Bock, T., and Linner T. *Robot-Oriented Design: Design and Management Tools for the Deployment of Automation and Robotics in Construction*, pages 156 - 230. Cambridge University Press, Cambridge, 2015.

[6] Liang, R., Altaf, M., Ahmad, E., Liu, R., and Wang, K. A low-cost, light-weight climbing robot for inspection of class curtains. *International Journal of Advanced Robotic Systems*, *11*(7):106, 2014.

[7] Hu, K., Chen, Z., Kang, H., and Tang, Y. 3D vision technologies for a self-developed structural external crack damage recognition robot. *Automation in Construction*, 159, 105262, 2024.

[8] Saito, A., Nagayama, K., Ito, K., Oomichi, T., Ashizawa, S., and Matsuno, F. Semi-autonomous multi-legged robot with suckers to climb a wall. *Journal of Robotics and Mechatronics*, *30*(1):24-32, 2018.

[9] Luk, B. L., Liu, K. P., Jiang, Z. D., and Tong, F. Robotic impact-acoustics system for tile-wall bonding integrity inspection. *Mechatronics*, 19(8):1251-1260, 2009.

[10] González-deSantos, L. M., Martínez-Sánchez, J., González-Jorge, H., and Arias, P. Active UAV payload based on horizontal propellers for contact inspections tasks. *Measurement*, *165*, 108106, 2020.

[11] Sukvichai, K., Maolanon, P., and Songkrasin, K. Design of a double-propellers wall-climbing robot. In *2017 IEEE International Conference on Robotics and Biomimetics*, pages 239-245, Macau, Macao, 2017.

[12] Ogusu, Y., Tomita, K., and Kamimura, A. Microdrone-equipped mobile crawler robot system, DIR-3, for high-step climbing and high-place inspection. In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 1261-1267, Macau, Macao, 2020.

[13] Tokura, Y., Toba, K., and Takada, Y. Practical applications of HORNET to inspect walls of structures. *Journal of Robotics and Mechatronics*,

28(3):320-327, 2016.
[14] Altaf, M., Ahmad, E., Xu, Y., Liu, R., Li, Y., and Na, H. Design of a climbing robot platform with protection device. *International Journal of Advanced Robotic Systems*, 14(4):1–14, 2017.
[15] Hillenbrand, C., Schmidt, D., and Berns, K. CROMSCI: development of a climbing robot with negative pressure adhesion for inspections. *Industrial Robot: An International Journal*, 35(3):228-237, 2008.
[16] Phlernjai, M., and Ratsamee, P. Multi-Legged Inspection Robot with Twist-Based Crouching and Fine Adjustment Mechanism. *Journal of Robotics and Mechatronics*, 34(3): 588-598, 2022.
[17] Chen, R. A gecko-inspired electroadhesive wall-climbing robot. *IEEE Potentials*, 34(2):15-19, 2015.
[18] Tan, Y., Li, G., Cai, R., Ma, J., and Wang, M. Mapping and modelling defect data from UAV captured images to BIM for building external wall inspection. *Automation in Construction*, 139, 104284, 2022.
[19] Chang, S., Siu, M. F. F., and Li, H. Development of a Fuzzy Logic Controller for Autonomous Navigation of Building Inspection Robots in Unknown Environments. *Journal of Computing in Civil Engineering*, 37(4):04023014, 2023.
[20] Tan, Y., Yi, W., Chen, P., and Zou, Y. An adaptive crack inspection method for building surface based on BIM, UAV and edge computing. *Automation in Construction*, 157, 105161, 2024.
[21] Xu, F., Wang, B., Shen, J., Hu, J., and Jiang, G. Design and realization of the claw gripper system of a climbing robot. *Journal of Intelligent & Robotic Systems*, 89:301-317, 2018.
[22] Munawar, H. S., Ullah, F., Heravi, A., Thaheem, M. J., and Maqsoom, A. Inspecting buildings using drones and computer vision: A machine learning approach to detect cracks and damages. *Drones*, 6(1):5, 2021.
[23] Pan, N. H., Tsai, C. H., Chen, K. Y., and Sung, J. Enhancement of external wall decoration material for the building in safety inspection method. *Journal of Civil Engineering and Management*, 26(3):216-226, 2020.
[24] Wang, J., Wang, P., Qu, L., Pei, Z., and Ueda, T. Automatic detection of building surface cracks using UAV and deep learning - combined approach. *Structural Concrete*, 2024.
[25] Chen, K., Reichard, G., Xu, X., and Akanmu, A. Automated crack segmentation in close-range building façade inspection images using deep learning techniques. *Journal of Building Engineering*, 43, 102913, 2021.
[26] Gil-Docampo, M., Sanz, J. O., Guerrero, I. C., and Cabanas, M. F. UAS IR-Thermograms Processing and Photogrammetry of Thermal Images for the Inspection of Building Envelopes. *Applied Sciences*, 13(6):3948, 2023.
[27] Yuan, C., Xiong, B., Li, X., Sang, X., and Kong, Q. A novel intelligent inspection robot with deep stereo vision for three-dimensional concrete damage detection and quantification. *Structural Health Monitoring*, 21(3):788-802, 2022.
[28] Woo, H. J., Hong, W. H., Oh, J., and Baek, S. C. Defining Structural Cracks in Exterior Walls of Concrete Buildings Using an Unmanned Aerial Vehicle. *Drones*, 7(3):149, 2023.
[29] De Filippo, M., Asadiabadi, S., Kuang, J. S., Mishra, D. K., and Sun, H. AI-powered inspections of facades in reinforced concrete buildings. *HKIE Trans*, 30(1):1-14, 2023.
[30] Nishimura, Y., Takahashi, S., Mochiyama, H., and Yamaguchi, T. Automated hammering inspection system with multi-copter type mobile robot for concrete structures. *IEEE Robotics and Automation Letters*, 7(4):9993-10000, 2022.
[31] Chaiyasarn, K., Khan, W., Ali, L., Sharma, M., Brackenbury, D., and DeJong, M. Crack detection in masonry structures using convolutional neural networks and support vector machines. In *ISARC Proceedings of the International Symposium on Automation and Robotics in Construction*, pages 1-8, Berlin, Germany, 2018.
[32] Park, J., Chang, S., Lee, H., and Cho, Y. K. Inspection data exchange and visualization for building maintenance using AR-enabled BIM. In *ISARC Proceedings of the International Symposium on Automation and Robotics in Construction*, pages 483-490, Bogotá, Colombia, 2022.
[33] Albeaino, G., Eiris, R., Gheisari, M., and Issa, R. R. DroneSim: A VR-based flight training simulator for drone-mediated building inspections. *Construction Innovation*, 22(4):831-848, 2022.
[34] Saleem, M. R., Mayne, R., and Napolitano, R. Analysis of gaze patterns during facade inspection to understand inspector sense-making processes. *Scientific reports*, 13(1):2929, 2023.
[35] Longo, D., and Muscato, G. The Alicia/sup 3/climbing robot: A three-module robot for automatic wall inspection. *IEEE Robotics & Automation Magazine*, 13(1):42-50, 2006.
[36] Ko, P., Prieto, S. A., and de Soto, B. G. ABECIS: An automated building exterior crack inspection system using UAVs, open-source deep learning and photogrammetry. In *ISARC Proceedings of the International Symposium on Automation and Robotics in Construction*, pages 637-644, Dubai, UAE, 2021.