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Review

A Survey of Wall Climbing Robots: Recent Advances and Challenges

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Abstract: In recent decades, skyscrapers, as represented by the Burj Khalifa in Dubai and Shanghai Tower in Shanghai, have been built due to the improvements of construction technologies. Even in such newfangled skyscrapers, the façades are generally cleaned by humans. Wall climbing robots, which are capable of climbing up vertical surfaces, ceilings and roofs, are expected to replace the manual workforce in façade cleaning works, which is both hazardous and laborious work. Such tasks require these robotic platforms to possess high levels of adaptability and flexibility. This paper presents a detailed review of wall climbing robots categorizing them into six distinct classes based on the adhesive mechanism that they use. This paper concludes by expanding beyond adhesive mechanisms by discussing a set of desirable design attributes of an ideal glass façade cleaning robot towards facilitating targeted future research with clear technical goals and well-defined design trade-off boundaries.

Keywords: wall climbing robot; façade cleaning robot; nested reconfigurable design principle

1. Introduction

Robots have been advancing exponentially over the last three decades, moving beyond the traditional bounds of industrial applications into service missions sharing social spaces with humans. Frey and Osborne have estimated that 47% of total U.S. employment will be replaced by robots and/or artificial intelligence (AI) in the near future [1]. Early evidence points to significant improvement in productivity and safety over a number of service tasks that are dull, dirty and/or dangerous [2]. Façade cleaning of high-rise buildings and skyscrapers offers enormous opportunities for the use of robots. In recent decades, skyscrapers, as represented by the Burj Khalifa [3–6] in Dubai and Shanghai Tower [7–9] in Shanghai, have been built due to improvements in the construction technologies and processes. Even in such newfangled skyscrapers, the façades are generally cleaned by humans. In the case of some skyscrapers, including the Burj Khalifa, equipment, such as gondolas, is not installed, and humans are employed to clean the façade by hanging down from a rope. Use of manual workforce poses a high degree of the risk of falling, accidents and even resulting in human fatalities. Numerous incidents of accidents have been reported even with the use of gondolas in façade cleaning jobs. One such situation involved a gondola being uncontrollable due to a gust of wind at Shanghai World Financial Center [10]. In another instance, the gondola became suspended in mid-air at a 240-m height at One World Trade Center in New York [11]. Robotic solutions offer enormous potential in significantly minimizing risk to humans, as well improving productivity in façade cleaning jobs.

One of the fundamental components of any façade cleaning robot is its adhesive mechanism, which enables the robot to attach itself to the wall surface. Such a mechanism should also be adaptive enough to allow the robot to be mobile so as to cover the required area. This paper presents a detailed review of such adhesive mechanisms for wall climbing robots, categorizing them into six distinct classes. This paper concludes by expanding beyond adhesive mechanisms by discussing a set of the desirable design attributes of an ideal glass façade cleaning robot towards facilitating targeted future research with clear technical goals and well-defined design trade-off boundaries.

2. Wall Climbing Method

A number of literature works on wall climbing robots have been reported. This section categorizes the adhesion principles in wall climbing methods and summarizes the robot precedence for each of the adhesion principles. The six adhesion principles identified include suction cup adhesion, suction cup crawler, vacuum pump adhesion, magnetic adhesion and bio-inspired adhesion. Each of these principles presents a unique set of advantages and disadvantages viz-à-viz the nature of traversing terrain and application settings.

2.1. Suction Cup Adhesion

This method works effectively for fine-textured wall surfaces with less asperities, such as in the case of glass.

A series of Skycleanershave been developed to clean and locomote on a glass wall by utilizing vacuum suction cups [12,13]. The Skycleaner is installed with the suction cups on both ends of actuators, like an X-Y stage, and these suction cups are connected to a vacuum pump [14]. Additionally, the robot adheres to the glass wall using the suction force. One of the important characteristics in this case is that the robot is totally driven by pneumatic actuators. The use of pneumatic actuators offer the advantage of payload reduction. The segment variable bang-bang control has been proposed in order to control the position of the pneumatic actuator precisely [13,15,16]. Another precedent involving a wall climbing robot with an ankle joint is presented [17]. Thus, even if the façade design of the building has curvature and a small angle exists between neighboring glasses, such robots would still be capable of adapting to such situations [18]. Furthermore, the trajectory generation method, which covers all areas of the wall, and its evaluation method have been proposed [19,20].

Wang et al. have proposed a new suction method utilizing the suction cup [21]. By applying a vacuum pump principle, the suction cup is capable of keeping its inward vacuum continuously, even if the air leaks from outside. In particular, sinusoidal or square wave vibration is added to the suction cup. The proposed method has been analyzed utilizing Bernoulli's principle; the suction pressure depending on vibrations with different parameters has been formulated, and the effectiveness of the proposed method has been verified through the experimental results. The experiments also have shown that the proposed method is effective on a glass wall, which allows the suction cup to keep the suction force on a variety of surfaces, including concrete, cabinets and wooden board.

Kawasaki et al. have developed a hexapod wall climbing robot with the suction cups on its toes [22]. The robot adopts a parallel linkage mechanism for the leg, which is optimized by the genetic algorithm (GA), and is able to realize wall climbing by using only one degree-of-freedom. In addition, the prototype has been implemented, and it has been verified that the wall climbing locomotion can be realized through a series of experiments.

Yano et al. have developed a biped-type wall climbing robot utilizing scanning type suction cups [23]. The adhesive mechanism consists of the suction cups, cam mechanism and a vacuum pump. A key characteristic of the suction system is to be able to keep the suction force, even if there is small steps or cracks, with the level change of the suction surface. As the mechanical feature, a valve that is activated by the cam mechanism is installed between the suction cups and the vacuum pump. With this cam mechanism, the valve is opened periodically, and the vacuum pump generates the suction force to provide the adhesive force needed to attach to the wall surface [24]. The effectiveness of the developed self-contained robot has been demonstrated through an exhaustive set of experiment [25].

Zhu et al. have developed a wall climbing robot that uses the suction cup principle. The developed platform is capable of self-localization and obstacle avoidance utilizing a CCD camera and a pair of laser diodes [26]. For achieving locomotion, the robot is equipped with an X-Y stage mechanism, as well as a rotational joint. Furthermore, small linear actuators are installed into the suction cup, which enables vertical motion. In addition, this work also presents a window frame crossing method. The effectiveness of the developed robot and the proposed strategies has been demonstrated through field trials at both of the City University of Hong Kong and the British Broadcasting Corporation (BBC) [27]. The efficacy and validity of the developed system have been demonstrated through a range of experiments [28].

From the above set of literature works, it is evident that leg-based mechanisms are often preferred while using the suction cup adhesion principle. Both the Skycleaner robot series, as well as the robot developed by Zhu et al. adopt a multi-legged tripod gait with respect to the robot's locomotion [29–31]. Another robot platform developed by Kawasaki et al. possesses a morphology of hexapod robots [32–34]. Furthermore, the robot developed by Yano et al. uses a biped structure.

The literature presented also points to this method being effective for a fine textured wall surface with less asperities. Suction cups possess an internal structure that easily lets air out, but restricts air incursion, since its edge faces outside. Thereby, it generates high levels of negative pressure inside the chamber; i.e., a highly normal force is seamlessly generated against a wall surface. It prevents the suction cups from slipping, as it is equivalent to generating a high friction force between the robot and the wall surface. With this mechanisms, the control of legged robots as summarized above on the vertical wall surface becomes very close to that in the case of the horizontal floor. Given that the suction cups are constantly moving together with the robot platform, the performance of the suction mechanism greatly depends on the nature of the traversed terrain. One critical deficiency of this mechanisms is the depression of the negative pressure due to air leaking. To overcome this particular issue, both the Skycleaner series and the robot developed by Zhu et al. connect vacuum pumps to the suction cups to generate negative pressures. Wang et al. have proposed a method that generates negative pressure by pressing the suction cup periodically based on the principle of the vacuum pump. Yano et al. have proposed the scanning type suction cup and demonstrated the ability of the developed robot to maintain the suction force on a bubblysurface. Another common disadvantage while using suction cup adhesion principles is that of slow moving speed. In the case of ground-based legged robots, they can switch the idling leg and the supporting leg smoothly as the platform guarantees the friction forces of the toes by utilizing its own weight. However, in the case of wall climbing robots that use the suction cup adhesion principle, there is an additional time delay arising from the need to vary the negative pressure inside the suction cups for its control.

2.2. Suction Cup Crawler Adhesion

This method involves installing the suction cups on the tracks of a crawler. The mobility of the robot is achieved through the use of the crawler rotation while maintaining the suction forces. Hence, this method overcomes the low speed issue faced in the case of the suction cup adhesion principle.

Kim et al. have developed a wall climbing robot using the suction cup crawler principle wherein mechanical valves are installed onto the suction cups [35]. The robot platform uses two tracks with twelve suction cups on each track, and these suction cups are activated by a novel mechanical valve design [36]. The mechanical valve is composed of a spring and a cam mechanism. The valve is opened mechanically while the suction cup moves to the bottom of the track. This work also features the optimization of the vacuum pressure using the Taguchi method [37,38]. In addition, efforts have been taken to modularize the robot design, and a platform with three core modules has been developed [39]. Each module is equipped with the above-mentioned suction cup crawlers, by controlling each of these modules based on kinematic analysis, a transition control between two orthogonal surfaces has been realized and validated through field experiments with the developed robot [40].

Serbot AG, an industrial company in Switzerland, has developed a wall and solar panel cleaning robot, GEKKO [41]. GEKKO is equipped with a vacuum suction cup crawler, which rotates horizontally. The crawler has a semi-circular shape, which has a straight line on one side and an arc line on the other side, with both linear and rotational motions being realized. By changing the number of brushes and the crawlers, the developed robot can be manually reconfigured to adapt to different wall areas.

Zhu et al. have developed a wall climbing robot with suction cup installed crawlers [42]. The robot has two crawlers, and each crawler has installed two columns of suction cups. A steering mechanism is installed using a front pulley, and the robot is capable of limited turning motion.

Shafts supporting the suction cup are equipped with springs that enable the robot to overcome small obstacles, such as the window frame. In addition, a vision system utilizing a CCD camera is installed to perceive the external environment. This work also presents the kinematics and the stability analysis of the developed robot mechanism. Experiments have been conducted to analyze the payload capacity and safety factor for the developed robot [43].

The suction cup crawler principle greatly improves the slow speed issue present in the case of Section 2.1 by varying negative pressure while the suction cups are passing under the crawlers. This principle allows for increased payload and stability, as the suction force is maintained even if air leaking occurs in some suction cups due to asperity. One common deficiency with this approach is the difficulty in turning. This is due to the high frictional force, which prevents slipping, as mentioned in Section 2.1, while the latter is needed in order to turn. To overcome this issue, Kim et al. have adopted a modular-type design and installed a waist joint. In the case of Zhu, a steering mechanism on the front pulley has been designed to overcome the turning issue. GEKKO has a horizontal crawler track, which is semi-circular in shape, where both linear and turning motions have been realized by switching the suction mechanism accordingly.

2.3. Vacuum Pump Adhesion

This method uses a negative pressure between the robot and the wall generally through the use of a pump. Numerous precedents exist for this principle demonstrating very high levels of mobility.

Gao et al. have developed two kinds of wall climbing robots utilizing the wheel system with negative pressure generated by a vacuum pump which acts both as an impeller or a propeller [44]. The robots basically consist of one sealed central body, two wheels for mobility and two vacuum pumps [45]. For propeller systems, the generated negative pressure from the propeller and interspace between the seal and the wall is calculated and analyzed based on the dynamics and the relationships between the robot parameters and the air leaking into vacuum chamber [46]. A time constant and a responsiveness curve are also simulated utilizing an analogy between fluid dynamics and the electric circuit [47]. As for the impeller system, the suction principle of the impeller is elucidated, and the stability of the robot is discussed based on the static and dynamic analysis on the wall [48]. The technical specifications of the robot is decided based on these analyses, and the minimum suction force needed to adhere the robot to the wall is calculated [49].

Miyake et al. have developed a small wall climbing robot that is capable of being used in domestic indoor environments by improving the sealing ability and decreasing the friction forces of the suction cup through the use of a liquid substance [50,51]. Experiments have been performed to validate the relationships between the friction forces and the suction force of the vacuum system on a wet surface [52,53]. A novel suction system based on this method has been developed in order to be integrated with the robot [54,55]. Robot demonstrations involving successful integration of the vacuum pump adhesion onto a wheeled robot and locomotion trials have been performed. A trajectory to clean a rectangle-shaped window has been generated utilizing a trajectory generation method based on patterns, and the effectiveness of the robot has been demonstrated through real experiments [56,57].

Zhao et al. have developed a wall climbing robot with a vacuum pump and a circular body [58]. The robot consists of a vacuum pump, circular body, four wheels and a sealing module. A mechanism that uses both air and regulating springs has been designed to achieve adjustable negative pressure in a vacuum chamber. In addition, an airflow model has been developed by utilizing fluid network theory, and its characteristics have been discussed in detail [59]. It has been demonstrated that the developed platform reliably adheres itself to wall surfaces, as well as achieves mobility [60].

This method offers high levels of mobility by utilizing commonly-used mobility mechanisms, such as wheels. Such an approach greatly reduces the control complexity as the locomotion control theories from general purpose wheeled robots can be directly applied. Such robots have to be able to maintain optimal negative pressure, as lower values of negative pressure result in the robot slipping off, whereas higher values of negative pressure inhibit robot mobility. To overcome such issues, Gao et al. and Zhao et al. have modeled the negative pressure generated by the vacuum pumps by utilizing the fluid network theory. Simulation studies has been run to study the performance and stability of the robot under varying negative pressure conditions. Miyake et al. have decreased the friction force of the suction cup by utilizing a liquid substance. The use of a liquid-based substance also increases the sealing ability of the suction cup.

2.4. Magnetic Adhesion

This method is often adopted for walls that have high levels of magnetic permeability. Since most of the prior work in this area uses permanent magnets, this eliminates the need for any additional devices, such as power supply. This results in improved payload capacity.

Gao et al. have developed a wall climbing robot for the maintenance of boiler water-cooling tubes [44]. Theoretical studies have been undertaken to analyze the situations that lead to robots falling off based on which a physical robotic platform using permanent magnets has been designed [61]. Experiments have been performed at a thermal power plant to validate the merits of the proposed approach [62].

Lee et al. have developed a modular wall climbing robot with a crawler utilizing permanent magnets [35,63,64]. This platform is characterized by its high payload capacity and wall transition ability. A robot platform comprising six links has been developed based on rigorous static and dynamic analysis [65]. A second iterated robot platform has been developed taking a modular approach comprising three torsos, a head-mounted arm and a tail-mounted arm [66]. Links connecting each module consist of a passive joint with torsion springs and an active joint [67]. The use of passive joints and tail-mounted arms to achieve the transition between two wall surfaces has been demonstrated with rigorous static and dynamic analysis [68].

Xu et al. have developed a wall climbing robot with magnetic tracks [69]. The permanent magnets and metal blocks are placed alternatively in the crawlers mounted on the robot. A novel elastic torso has been designed that allows for traversing concave-convex wall surfaces. In addition, a parallelogram mechanism has been adopted to further improve the adaptability of the robot. A rigorous study on system safety has been done as part of this research work.

This method does not require any additional devices, such as a power supply, to navigating wall surfaces, as only permanent magnets are needed to generate the required suction force. This load saving helps with improving the payload capacity, as witnessed in the literature summarized above. The major drawback with this approach is that the robot can only operate on wall surfaces with high levels of magnetic permeability. Even with metal surfaces, there is a high risk of damage due to robot slippage. In order to overcome this problem, Gao et al., Lee et al. and Xu et al. have extensively studied the slippage and stability in robots that use the magnetic adhesion principle.

2.5. Rope and/or Rail Gripping

This method utilizes a rope ascender from the upper section or specialized equipment installed on the wall to support the navigating robot platform. Humans generally adopt this technique when they clean façade windows. This approach ensures a high degree of safety, as the robot is always secured to the wall or roof through a rope or cable, which at times even helps with robot mobility.

Zhang et al. have developed a wall climbing robot in order to clean a spherically-shaped façade [70]. The developed robot is aimed at use at the International Grand Theatre in China. The developed robot consists of two frames, and by use of which, it can climb up the spherically-shaped façade by gripping the sliding rods, which are equipped on the wall surface [71–73]. Stability and safety have been studied through extensive kinematic and dynamic analysis both during climbing and cleaning phases [74]. The effectiveness of the developed robot and the proposed climbing approach has been verified through a number of practical tests.

Wang et al. have developed a cleaning robot for a reversed inclining glass façade [75]. The targeted infrastructure is the airport control tower at the Guangzhou Airport, where wall mounted rail lines and a conveyor belt mechanism have been put in place to support the mobility of the robot, as well as deliver power, detergent liquid and water needed for cleaning. The cleaning unit adheres and cleans the glass wall based on the vacuum pump principle, while the robot has two suction areas to overcome the asperity of the surface and gaps between the windows. Thus, the robot is capable of adhering safely to the glass surface even if the air leaks from either one of the suction areas.

Seo et al. has developed ROPE RIDE [76]. The ROPE RIDE enables climbing up a vertical surface by utilizing a rope dropped down from the top of the building, and two additional propeller thrusters are installed to adhere on the wall with certainty. Triangular-shaped crawlers are used for achieving mobility, navigating over or around obstacles. A rigorous quantitative stability analysis has been performed, and potential cases of instability have been identified. ROPE RIDE has been controlled based on kinematics analysis and task principles, and the effectiveness of the developed robot has been shown through real-world experiments. In addition, a novel control system has been developed to handle the cleaning task [77]. A new impedance control system has been proposed, and the effectiveness of the force control system to press brushes against the wall with a constant force has been shown through repeated experiments [78].

SIRIUS is a wall cleaning robot developed by Fraunhofer IFF, which is an industrial company in Germany [79–82]. SIRIUS realizes up-and-down motion by utilizing a crane that is installed on buildings for façade maintenance, and it adheres on the wall by a suction system that navigates like a linear actuator [83–86].

Fraunhofer IFF has also developed another wall cleaning robot, Filius [87]. Filius cleans arch-like roofs and navigates using wheels with a rope that secures the robot platform from the top of the building. The robot cleans the roof utilizing a brush installed on the front.

Qian et al. have developed a lifted type wall climbing robot via a rope from the roof without using any actuators on board [60,88]. The robot does not have independent actuation force; instead, it can move up and down by utilizing its own weight and a lifting force from a crane at the rooftop. The developed robot uses two vacuum pumps to adhere to the glass curtain surface. Two vacuum chambers are installed, one each at the upside and the downside, respectively, and a washing brush is wedged between the vacuum chambers. A rigorous stability analysis has been performed. Further analysis on negative pressure and fluids in the vacuum pumps has been done using the fluid network theory [59]. A closed loop fuzzy control system has been put in place to handle the negative pressure, and its effectiveness has been validated through well-designed experiments.

This approach ensures a high degree of safety from falling off the wall, as the robot is always tied to a rope attached to the rooftop, which also aids in improving the mobility performance. Due to the reduced need for additional components that provide active suction power, the developed robot platform is often compact in size and lighter weight. On the other hand, this method requires particular equipment, such as cranes and ropes. However, in most cases, rail-based wall cleaning robots are chosen due to the existence of this specific equipment as part of the concerned infrastructure. Even though, the use of rope facilitates movement of the robot in the vertical direction. It still poses a number of issues with respect to robot movement in the horizontal direction. Both SIRIUS and the robot developed by Qian et al. initially possessed only the ability to move in the vertical direction, while ROPE RIDE has installed crawlers for traversing in the horizontal direction. If the robots work on vertical surfaces or a reversed inclining wall, grip mechanisms, as well as suction mechanisms are necessary for adhering to the wall surfaces. Both ROPE RIDE and the robot developed by Qian et al. have additional installed mechanisms to adhere to the wall surfaces.

2.6. Bio-Inspired Adhesion

This approach mimics the characteristics of living species in nature that can navigate over vertical wall surfaces. This method uses bio-inspiration as its core principle for synthesizing new artificial mechanisms for wall climbing. Since species in nature have evolved over millions of years, artificial systems mimicking their locomotion over wall surfaces have the potential to offer a high degree of efficiency.

Funatsu et al. have developed a climbing robot that is able to climb up by hooking its claws [89]. This robot has been designed to be light in weight and compact in size, so that the robot climbs up walls only using its claws without any suction forces. Stability analysis has been performed in relation to the asperity of the wall surface, and the stable operating limits have been identified through simulations. In addition, experiments have been performed to validate the success of the developed prototype.

Mini-Whegs™ is a climbing robot with insect-inspired wheel legs [90,91]. The wall climbing ability has been experimented with several design variants of the Mini-Whegs platform, and the results have been discussed in detail. These platforms make use of adhesion means, such as claws, Scotch tape and micro-structured tapes, as well as sophisticated wheel-leg designs [92,93]. Experiments have been performed to verify the ability of these platforms to navigate over wall surfaces. In addition, experiments involving wall transitions, as well as having a complex angular relationship have been documented [94]. Furthermore, a robot with a body joint has been developed, and it has been shown that the robot is capable of transitioning between two orthogonal surfaces [95]. A legged robot driven by both spine and linkage mechanism has also been developed, and it has been shown that the robot can move over meshed surfaces [96].

Sitti et al. have proposed a gecko foot-inspired suction method [97]. Fiber arrays in varying morphologies have been developed using templates. Two popular approaches to this end include the use of a nanoprobe indented flat wax surface and the use of nanopore membranes [97]. A fiber array fabricated via micromolding followed by spatula tip formation via dipping has been made [98]. In addition, a directional and controllable fiber array has also been realized [99,100]. Using fiber arrays, adhesive pads that generate relatively higher adhesion force in one direction and lower in the opposite direction have been developed. By utilizing these adhesive pads, wall climbing robots called Geckobot and Waalbot have been implemented, and the effectiveness of the robots has been demonstrated through experiments [101–108].

This method is expected to develop robots of high ability by mimicking the characteristics of animals who can climb up walls, like geckos. Since no large-sized mechanisms are necessary for adhesion with bio-inspired approaches, the robots can be designed to be small and light weight. Standing examples of this case are the robot developed by Funatsu et al., Mini-Whegs™ and the robots developed by Sitti et al., which are relatively lighter and smaller than the robots that use other adhesion principles for wall climbing. Since most of the precedents use legged mechanisms deriving inspiration from living species, the locomotion of these platforms is often realized based on ground-based legged robotic platforms. Given that most living species that traverse over wall surfaces only carry their weight, robots developed deriving inspiration from them often follow suit to have a lighter payload capacity. However, with the advent of nanotechnology-based materials for adhesion, there is a renewed interest in the field of bio-inspired wall climbing robots.

2.7. Discussion

This paper presents a detailed review of wall climbing robots categorizing them into six distinct classes based on the adhesive mechanism that they use. These categories are suction cup adhesion, suction cup crawler adhesion, vacuum pump adhesion, magnetic adhesion, rope and/or rail gripping and bio-inspired adhesion. This paper also discusses the specific design approaches in synthesizing each of the six adhesion methods. The advantages and disadvantages of the identified six classes of adhesion methods for enabling robots to navigate wall surfaces are listed. Even though significant progress has been made towards the development of wall climbing robots and their component technologies, there still remains numerous challenges towards deploying them in a real-world setting for applications such as glass façade cleaning. This is mainly attributed to the diverse nature of the building types and the uncertain environment in which these robots are expected to operate [71–74]. One of the grand challenges associated with the design of wall climbing robots is that of developing a general purpose robot that can navigate over any type of wall.

2.8. Desirable Design Attributes

With most of the developed world aging rapidly and the simultaneous push for productivity improvement in job processes, these have significantly contributed to the advancement of robotics in a number of application domains. Glass façade cleaning is one such application domain that is witnessing increased interest due to the nature of the task being dull, dangerous and dirty. The glass façade cleaning tasks could be subdivided into the following phases:

- Navigating over the defined area.
- Adapting to window shapes.
- Washing/brushing windows.
- Wiping washing liquid.

However, not all of the above phases are used for every cleaning exercise. The choice of the phases greatly depends on the user requirements and prevailing environmental conditions. For instance, in hot and dry conditions, all of the phases are generally carried out. On the other hand, the washing phase may not be performed in rainy conditions. Furthermore, fugitive dust should be swept from buildings that are close to a desert by brushing.

Typically, it is easier for robotic platforms to complete each of these tasks individually. However, it is highly difficult for robots to possess all of these capabilities integrated into a single platform while being able to adapt in response to the façade cleaning tasks in real-world environments. The absence of a clearly-defined set of performance indicators for such robots further adds to the uncertainty in designing an efficient platform while making optimal trade-offs between competing design criteria. By rigorous analysis of 28 reported research papers on glass façade cleaning robots, we derived the following set of desirable design attributes for an ideal glass façade cleaning robot:

- Minimize total time to cover a given wall area
- Maximize the total wall area covered
- Minimize the wall area cleaned multiple times
- Minimize wall slippage
- Minimize energy consumption
- Maximize fault tolerance
- Maximize perceptible information
- Minimize noise
- Maximize dust removal
- Maximize safety
- Maximize user interaction
- Minimize infrastructure changes needed for robot deployment

With the rising interest in façade cleaning robots and related research topics, the identification of desirable design attributes, such as the ones presented above, becomes highly critical in facilitating targeted research with clear technical goals and well-defined design trade-off boundaries. This set of design attributes can also be used as metrics for comparing robot performance in glass façade cleaning tasks.

3. Conclusions

In the current paper, we presented a detailed survey of adhesion principles adopted in wall climbing robots. We categorized the adhesion principles found in the literature into six broad categories, namely: suction cup adhesion, suction cup crawler, vacuum pump adhesion, magnetic adhesion and bio-inspired adhesion. We further summarized the impact of each of these adhesion mechanisms on various robot design considerations, including locomotion, stability, infrastructure needs and perception by deriving specific cases from the literature. Going beyond the adhesion issues in wall climbing robots, we also put forward a set of desirable design attributes for glass façade cleaning robots for the first time derived from rigorous analyses that has the potential to facilitate targeted future research with clear technical goals and well-defined design trade-off boundaries. Such a set of design attributes also offers significant potential for use as performance metrics in evaluating façade cleaning robots, as well as comparing competing designs. A novel nested reconfigurable approach to the design of glass façade cleaning robots is currently being studied where the proposed set of desirable design attributes drive the core of the concept formulation. Our long-term aim is to develop highly efficient glass façade cleaning robots that are able to seamlessly adapt to the dynamic needs of the operating environment, task and occurrence of faults.

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