Propeller-type Wall-Climbing Robots: A Review

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Abstract. Many efforts have been exerted in the robots field which have ability to climb vertical plane. The result was various types of climbing robots. These robots have a mixture of different principles of adhesion and locomotion in many applications. Propeller thrust is one of the approaches that has been developed to generate the required adhesion force to enable the robot to climb walls. Due to the promising merits of this principle, the current paper deals with propellers-type wall-climbing robots (PRWCRs) and introduces features, applications and challenges for these robots. PRWCRs are examined depending on a set of given requirements. This mechanism has connected between two wide fields: wall climbing robots (WCRs) and unmanned aerial vehicles (UAVs). For many reasons, each adhesion mechanism has more preference than others for a specific job; surface requirements are the main of them. Propeller-type WCRs are less affected by the nature of the surface, where it can climb many types of vertical planes: smooth, rough, and ferromagnetic or not. On the other hand, most of the introduced designs still have some problems and issues like transition operation, mission time and payload limitation.

Keywords. Propeller-type climbing robots, drone-type climbing robots, propeller thrust force, design aspects.

1. Introduction
The tendency of utilizing mobile robots is growing every day in different tasks such as construction, maintenance, wall- scrub of high-rise structures and screening of storage tanks, and damage observation of different structures like ships and planes [1,2]. Therefore, many studies have been conducted along years to develop wall-climbing mechanisms.

In general, wall climbing techniques such as magnetic [3], suction module [4,5], adhesive material [6][7][8], mechanical claws [9], microspine [10], pneumatic-adhesion [11][12], and tether-supported climbing methods [13,14] are dependent on the material or the shape of the surface. In addition to the mentioned pneumatic mechanisms, the thrust force of propellers is used as another approach. Propellers-type wall-climbing robot (PRWCR) utilizes the propellers thrust in order to generate the required adhesion force. As is well known, the climbing robot applications grow with its ability to handle different types of surfaces. Therefore, these robots will have a wide utilization in both military and civilian areas. This paper presents the current state-of-the-art in robots which used aerodynamic thrust generated from propellers, to climb vertical planes. Usually, research categorizes the WCRs according to the locomotion type as well as the adhesion mechanism. Since this work is restricted to a certain type of adhesion principle, the robots will be classified according to their flying ability. The locomotion types of climbing robots and the other adhesion principles are well explained by [15–20].
To our knowledge, no prior study covered this type of climbing robots adequately. Even those which are concerning in pneumatic systems, they were limited to one or two robots of this type.

2. The general requirements in PRWCR design
Climbing robots must have the ability to mobilize on the interested vertical plane and ability to hold itself to the surface when it is necessary. To achieve that, the design of PRWCR should meet some conditions. In this section, these requirements will be discussed.

2.1. Drag torque
As mentioned before, in PRWCRs, the required adhesion force is generated by high speed rotors and a drag torque is produced as a result of this mechanism. This torque tends to rotate the robot body around the spinning axis of rotors in opposite direction. This undesirable torque should be eliminated by a reversal torque of another rotor system spinning in counter direction. Therefore, the number of rotors, their speed and distribution on the robot body should be taken into account.

2.2. Transition
Transition operation in PRWCT has two definitions depending on the flying ability of the robot. Where, in drone –type wall climbing robot (DRWCR) deals with “transition between modes”: flying and climbing. For non-flying robot, it is concerned with “transition between planes”: like ground, wall and ceil. The design of these robots (non-flying type) will determine whether the robot can achieve one or more of these transition modes. Also, the robots differ in their degree of dependence on propeller thrust during this process. It is assumed that transition happens gradually to minimize the collision intensity with the wall.

2.3. Weight
Lightweight is an important condition in the flying world; therefore steadily shrinking microprocessors, actuators and sensors cause an explosion in the popularity of MAV (micro air vehicles). Moreover, a robot that functions in two distinct locomotory modes must make compromises in weight and complexity to accommodate the different interaction mechanics, control approaches, and power requirements for the modes of interest. Therefore, a key research problem in the design of PRWCR robots is to maximize the ratio between thrust output and vehicle weight.

2.4. Safety
To meet the requirement of increasing the robot payload capacity, the electric power needs to be maximized and the rotor size and motor power should be increased. This design with a high power motor and a large rotor would be unsafe to serve in urban area, where serious injuries on the civilian can occur because of the rotor. Therefore, a rotor guard must be designed for protection and to prevent any unintentional contact with the structure. The guard is preferred to be made with a shock-absorbing material with elastic characteristic like EPP (Expanded Polypropylene). In addition, the robot must attach to the protection rope to protect the hardware of the robot in case of losing contact with the surface especially in the performance testing phase. To increase the mission life, the power can be supplied and sensor signal and the control signal can be uploaded through the safety rope if that does not conflict with the task.

2.5. Coefficient of friction
The value of friction coefficient is a crucial issue in wall climbing as its value will specify the maximum allowable total weight of robot. As it is known, flying vehicles depend on the weight of the system only, while, in climbing, in addition to the weight, surface topography is also a significant parameter. The vehicle will have sticking capability on the wall, if the total weight is less than the product of the total thrust force and friction coefficient between the wall and the wheels of mobile robot. If the frictional force is higher than the critical value, the mobile robot will hold on the wall. To maximize friction between wheels and the surface and to minimize dependence on rotor thrust force, wheels themselves should have adhesive characteristics. The required level of thrusters is different
according to the change of friction coefficient. In the real world, it is hard to estimate precisely the friction coefficient at the contact point. Therefore, it could overuse energy or fail to climb the wall. Although too much thrust force produces high frictional force but it is inefficient in terms of energy consumption. To be efficient, the total thrust force should be controlled according to the robot pose, disturbance, and frictional coefficient and then the robot can operate longer. The accelerometer signal can be processed and thrust force is controlled to prevent slip, where detecting a drop in vertical acceleration means change in friction value mostly.

2.6. Power source
In PRWCR, the required thrust force is generated by brushless DC motors. These motors consume a high level current. Therefore, it is necessary to secure a sufficient current to power these motors and to provide a stable power source to feed the motors driving wheels.

2.7. Center of mass location
In addition to flying requirements, the robot center of mass (COM) should be close as possible to the centroid of the body. Also in climbing mode, it is more favorable to keep COM at the nearest point to the wall.

3. Drone-type wall-climbing robot (DRWCR)
In the past years, multi-propeller aerial robots have attracted a great interest in civilian and military applications because of their versatile usability and wide possibility. At a recent time, many papers have examined the potential of drone to be a wall climber. The flying -climbing mechanism depends on the ground vehicle system and the multi-rotor system. Quadrotor is the most common in DRWCR. It is a well-known VTOL (Vertical Take-Off and Landing). The fundamental idea of DRWCR depends on utilizing propeller thrust to provide the essential force to adhere on the wall in addition to flying. Based on the combination of the wheel drive force and thrust force, the friction between the wheel and the wall can be maximized.

3.1. Encouragement
Many reasons have encouraged the development of DRWCRs; these are:

1. Other adhesion principles cannot be applied to various material walls. Meanwhile, these robots are independent of nature of target wall and do not need any extra infrastructures.
2. Both functions, flying and climbing, are mutually supportive. Thus, unique environmental conditions like powerful wind gusts often make it difficult for traditional drones to hover to complete the task. Therefore, landing on wall is necessary until the situation be suitable. On the other hand, if the robot lose contact with wall during climbing for any unexpected accidents, the robot can simply fly safely to the ground. Also, some types of infrastructure inspections require stable contact with structures, and drones are undesirable for these missions.
3. DRWCR can reach the remote target directly without the need for crawling along the surface, which makes these robots have high maneuverability. Furthermore, flying enables the robot to overcome the obstacles that exist on walls such as window frames.
4. A single multi-purpose robot is cost-effective than multiple dedicated robots. Finally, as a result of the close correlation, all works in UAV like innovative designs and researches can be employed to improve DRWCRs design, also saving cost, time and increase the effectiveness.

3.2. Aspects demand attention
Below some aspects should be taken into consideration:

1. The average mission time of the conventional MAVs is about few minutes. But actually, many tasks in urban area demand more than that.
2. Multi-function robots may have complexity in both structure and control. But for applications, where falling to death at any moment is a serious concern, it is probably worth all the hassle.
3. Although flying, perching and crawling operations confer advantages and provides synergies. It also can double the weight of the vehicle, so it is not easy to be installed with heavy or complicated equipment, in addition to a corresponding deterioration in flying performance. Therefore, efficient design with light weight and high strength is essential.

4. PRWCRs with flying ability

Most PRWCRs have ability to fly. This section presents and discusses these robots. The collaboration between Disney Research Zurich and ETH produced VertiGo [21][22], as shown in figure (1-a). VertiGo has the ability to achieve smooth transitioning between the ground and the wall. The robot chassis contains two adjustable tilting rotors of two degrees of freedom and has four passive wheels supplied with a suspension system. The front pair of wheels is steerable. The two rotors generate the force required to drive and attach the robot on floor and wall. Based on the information of a 6-axis IMU as well as two infrared distance sensors mounted in front of the robot, the onboard controller then devises the best positions for all actuators to achieve the orders of human operator with RC (remote control). For this design, it can be concluded:

- The reaction torque of the two propellers is hard to eliminate by each other. Because the rotational speed and tilt angle of each rotor are not necessarily identical. These two parameters are directly related with robot pose requirements.
- Including braking system was essential, especially on robots which use passive wheels and adopting aerodynamic force for navigation. Without this system, it is difficult to track a desired path accurately by these robots.
- In general, robots with passive wheels are less affected by surface friction coefficient.
- To drive this robot, it is need to control eight actuators. Therefore, this system is relatively complicated.

KAIST (Korea Advanced Institute of Science and Technology) has much support in the field of wall-climbing robot with a drone platform, called CAROS (Climbing Aerial Robot System). Figure (1-b) shows a prototype of drone equipped with four wheels which work as a differential drive framework [23]. According to robot design, the transition operation must happen very quickly without depending on any external structure, where the pose change is impossible to be achieved slowly, as it is easy to expect that the robot will fail. Therefore, a harsh impact on the wall surface is an inevitable consequence of this operation. To overcome this problem, a suspension system was adopted to reduce the collision intensity. For structural health monitoring (SHM) application, a wireless vision sensor is fixed to take the pictures of the structural wall surface.

Shin et al. [24] presented the micro-aerial vehicle type wall-climbing robot mechanism for the same application, as shown in figure (1-c). Feasibility has been seen with simulations and indoor experiments. This robot still has some problems that the system was unsuited for outdoor environment due to the vibration effect. The vibration effect makes the sensor data of IMU unstable. As a result, it makes control very hard. Also, the robot was prepared for planar walls and climbing the flat only. To address the difficulty and risk of wind blades inspection, a new design was proposed, as shown in figure (1-d), which is a quadcopter with four wheels. It can fly, stick, and move on a vertical and non-flat surface [25]. However, the proposed design was verified only throughout simulations where the manufacturing and the outdoor experiments were proposed as a future work.

Previous KAIST climbing drones [23] and [25] regard only the friction force generated by thrusters normal force. To mitigate this problem, W. Myeong et.al [26] proposed a drone equipped with a rotary arm for climbing, as shown in figure (1-e). The arm has two free rotating wheels at both sides, while driving wheels are installed at the front part of the robot body. The main concept of the proposed system is to control the thruster direction to the wall. In addition, the arm allows soft attaching and detaching to the wall. Another purpose of the rotary arm mechanism is to moderate the pose change speed. According to the angle of the arm, the robot can change its pose against the wall and divide the thrust force into two components; one is the force that compensates gravity and another is the force that generates friction. Comparing with a previous version of CAROS, the climbing speed is 8 times higher with a lower level of thrust force. However, the additional weight of a rotation arm and its high
moment of inertia are unfavorable factors in flying vehicles. This technique pushes COM of the robot away from the wall, which makes robot highly affected by the disturbances of the surroundings such as winds. Also, the work of some sensors requires keeping a constant distance to a target object which cannot be secured with this mechanism.

W. MYEONG and H. MYUNG [27] developed another approach to address the problem of fast landing speed in previous version of KAIST climbing robots. The proposed design based X-configuration quadcopter and a tilt-rotor mechanism is combined into the two axes such that the front thrusters and the rear thrusters are paired respectively, as shown in figure (1-f). This mechanism showed a soft landing on wall, and reduced the thrust force for climbing. However, the rotors configuration caused an air obstruction which led to losing about 25% - 75% of front rotors thrust. Also, KAIST developed FAROS (Fire-proof Aerial Robot System), as shown in figure (1-g). The robot can help in firefight work by detecting fire or people, as the robot platform is covered with aramid fiber. The robot design is based on CAROS to navigate through narrow space in case of fire disaster. When meeting narrow space, the robot is expected to pass through by climbing the wall [28].

To keep constant distance with wall surface which is an essential condition for inspection tools and considering a low level of frictional coefficient in the real world, Prodrone Co., Ltd. has developed PD6-CI-L [29]. It is a self-propelling surface-clinging drone that is able to inspect both ceilings and vertical surfaces for the civil infrastructure inspection market. It has an L-shape with six rotors: two rotors in horizontal plane and four rotors in vertical plane. Three pairs of wheels are distributed to the corner and both ends of the body to move on the surface during inspection, as shown in figure (1-h). PD6-CI-L does not inspect while hovering, but instead uses negative pressure to cling directly to the target surface. PD6-CI-L design has advantage in providing safe, smooth and quick transition from flying to climbing mode and between wall and ceiling. Yet, the L - shape keeps the COM away from target surface. This system contains high numbers of actuators, which requires a high degree of coordination between these motors to keep continuous contact with the surface.

MTMUR [30] was introduced to address the problems of inability of the robot to adapt to different terrains and reduce the cost of multiple dedicated robots. MTMUR is a bi-copter, multipurpose robot capable of flying, and moving on ground and water with wall climbing ability, as shown in figure (1-i). During climbing, the thrust of the propeller is directed in the opposite direction by changing the axis of rotation. Once the robot sticks against the wall, with the help of differential driven wheels, it moves over the surface of the wall. As the robot is supposed to deal with different terrains, MTMUR needs to satisfy many requirements, which may affect the general performance of the system such as mission time. However, MTMUR is only a suggested design and has not been implemented yet.

Figure (1-j) shows an aerial manipulation, MMAR, a robot designed by X. Ding et.al [31]. The structure of MMAR includes two identical manipulators and four fixed-pitch propellers. Each manipulator has two joints. The two joints rotate in a plane, which is normal to the main body of MMAR. The two manipulators of MMAR can be utilized as undercarriage when it touches down on land, and can be used as arms for operating when it is in flight mode. When MMAR is in wall-climbing mode, the robot will be in contact with the surface by two wheels at the end of manipulators and the manipulators can be used as legs to support it on the wall. The manipulators succeeded to provide safe and gradual transition to climbing mode, and control the thrust force applied to wall. But it has disadvantages of complexity of the control system, increasing the total weight and inertia of the robot, and coupling interference with the robot body [32]. Also during climbing, the arms joints must be powered enough to withstand the applied torque by the propellers thrust force.

The limitation in battery life can be compensated by perching mechanism, where the robots are turned off to extend the life of the battery. From this viewpoint, Pope et al. introduced SCAMP [33], as shown in figure (1-k). A small robot is SCAMP that combines a commercial quadrotor(Crazyflie2) with perching and climbing ability inspired by various animals like insects and birds. It can fly outdoors and land on unprepared walls made from stucco or concrete. However, the perching and climbing gears reduce the UAV’s flight time by 30%. SCAMP has two more different things than other DRWCR, the positive one: it is quiet during climbing, while the negative is that SCAMP still has restriction to the surfaces because of the use of spine for moving. Also, it has long tendons and the
propellers are installed at the robot side which is close to the surface. Therefore, there is possibility that those propellers or the tendons hit the surface with unexpected protrusion.

To protect the blades from touching the structures and keep a fixed distance with the target that will be inspected, a novel UAV with two wheels is introduced in [34]. This robot was designed for bridge inspections, and was tested on real bridges in [35], as shown in figure (1-m). The robot consists of a pair of steerable wheels. While testing the robot, two problems in the structure appeared: (1) the wheels and wheel shaft strength were low because these parts were built to be light as possible, (2) due to the design of wheels, the air resistance increases. The treatment of these issues was proposed by [36], as shown in figure (1-n). Where, a quadcopter is installed inside a cage of cylindrical shape. Two spokeless ring-shaped wheels were attached to the protector. Those wheels could rotate freely with respect to the quadcopter. This design reduces the air resistance and improves durability of the UAV.

There are some related designs introduced by Mizutani et al. and Briod et al. who developed a UAV inside a spherical shell rotating passively [37][38], as shown in figures (1-p,q). Their studies demonstrate that the spherical cage is efficient for flying through complex structures or in limited areas, where touching the surrounding environments is possible. However, according to these designs, it is difficult to constrain the locomotion on the plane surface because of protector shape. That means, operating the UAV manually is still hard. Also, the cage interferes with camera, which is installed on the UAV to capture images, due to passive rotating of protector around the robot. Kawasaki et al. improved a dual connected bi-Copter [39]. This UAV can effectively climb walls and run on the ground, but it requires a special flight controller and additional actuators to work because of its very specific structure, as shown in figure (1-r).

5. Unable to fly PRWCRs

This category of robots represents the oldest WCR introduced. Hence, Nishi [40] in 1991 developed a climbing robot adopting the thrust force of two rotors. The tilt angle of these rotors can be manually adjusted, as shown in figure (2-a). The robot was also equipped with two pairs of passive and non-steerable wheels. Therefore, the robot cannot make turn.

Kinki University developed climber robot which has two driving wheels and adjustable tilt rotor with a pair of AC brushless motors. These motors were attached to the set of coaxial propellers to provide the adhesion force. Also, two rollers with dampers and springs were connected to the rear caster wheels at the end of the robot, as shown in figure (2-b) [41]. By changing the tilt angle of the thruster, the robot has the ability to reversely vary its configuration top and bottom. This merit is helpful for quick and small turn in narrow environments with floors or walls. Because the thrust force was insufficient, the climbing test on a vertical wall is not carried out for this model. But, it is experimented that the robot will not slip down on an inclined wall with an angle of 60 degrees. On the other hand, the caster wheel which has been used in the robot may hinder the robot movement, since it is difficult to steer this type of wheel on wall and its direction will be submitted to gravity effect.

For visual inspection, EJBot-I [42] and EJBot-II [43] were introduced, as shown in figures (2-c,d) respectively. The experimental tests showed that robots are able to overcome obstacles up to 40mm. EJBot-II used a flat track to increase the friction. Nevertheless, tracks are not efficient during transition between ground and wall, as the flat tracks configuration would not pass inner corners without a high torque [3].
Figure 1. Propeller-type wall climbing robots with flying ability.

Kasetsart university produced climbing robot which is broadly similar to VertiGo with less capabilities, as shown in figure (2-e) [44]. Where, this robot design does not include steering and suspension system. Also, each rotor has one degree of freedom. The advantage of this design is simple to control than VertiGo but with sacrifice the maneuverability and other operations like transition, turning and flying.

Many studies have been conducted to develop infrastructure-based wall-climbing robots because of their features. ROPE RIDE [45] is one of these robots with cable-driven and triangular tracks to climb obstacles. Two propeller thrusters are adopted, in order to efficiently keep the contact with the wall during climbing, as shown in figure (2-f). But ROPE RIDE has relatively heavy weight, huge size and trouble in detachment/attachment of the cleaning unit. To improve these shortcomings, a new platform has been introduced in [46], as shown in figure (2-g). Where, the overall weight and size of the new platform are decreased approximately by 50% and 17% respectively.

University of Technology (Baghdad/Iraq) presented UOTWCR-II. It is a novel design of PRWCR which can climb different surfaces. UOTWCR-II design supported two ground navigation modes. Also, these modes provided two various transitioning scenarios between ground and wall, as shown in figure (2-h). To extend the robot mission life, the limitation on power source was overcome by proposing mechanism of perching [47-57]. Finally, Table 1 presents a complete list of climbing robots according to the above mentioned classes with application tasks.
Figure 2. Unable to fly propeller-type wall climbing robots.

Table 1. PRWCs including classification of their locomotion, application and flying ability.

| ROBOT     | REF | Country     | Application                                                                 | Locomotion | Flying ability |
|-----------|-----|-------------|------------------------------------------------------------------------------|------------|---------------|
| VertiGo   | [21]| US/Switzerland | Filming as well as a fun product                                             | Passive wheel | yes           |
| - [22]     |     | - [23] South Korea | SHM                                                                         | Driven wheel | yes           |
| - [24]     |     | - [25] South Korea | Inspection of wind blades                                                  | Driven wheel | yes           |
| - [26]     |     | - [27] South Korea | SHM, maintenance and visual inspection                                    | Driven wheel | yes           |
| FAROS     | [28]| South Korea | Firefight                                                                    | Driven wheel | yes           |
| PD6-CI-L   | [29]| Japan       | Civil infrastructure inspection/shipment                                      | Driven wheel | yes           |
| MTMUR     | [30]| India       | Search and rescue, mapping, surveillance military purposes                | Driven wheel | yes           |
| MMAR      | [31]| China       |                                                                                 | Legged wheel | yes           |
| SCAMP     | [33]| US          | Rescue, Surveillance                                                         | Feet with small spines | yes           |
| - [34]     |     | - [35] Japan |                                                                                 | Passive wheel | yes           |
| - [36]     |     | - [37] Japan |                                                                                 | Spokeless wheel | yes           |
| - [38]     |     | - [39] Japan |                                                                                 | Spherical Shell | yes           |
| - [40]     |     | - [41] Japan |                                                                                 | Spherical Shell | yes           |
| - [42]     |     | - [43] Egypt |                                                                                 | Spherical Shell | yes           |
| EJBot-I/II | [44]| Egypt       | Inspection of petrochemical vessels                                         | Wheel/track | no            |
| ROPE RIDE | [45]| South Korea | Cleaning/painting/ inspection                                                | Rope | no            |
| - [46]     |     | - [47] Iraq |                                                                                 | Rope | no            |

(a) Robot by [40].  (b) Robot by [41].  (c) EJBot-I [42].  (d) EJBot-II [43].  (e) Robot by [46].  (f) ROPE RIDE [45].  (g) Robot by [46].  (h) UOTWCR-II [47].
6. Conclusions and future work
In this study, a review for propeller-type climbing robots applied in different applications has been introduced. According to their flying ability, which represents the most distinguishing feature for this type of climbing robots, these robots have been classified. Also, a comprehensive table of the studied robots has been presented along with their applications, locomotion mechanism, and flying ability. From this study, it can be stated that:

- Propeller-type WCR has no surface constraints and can trade with various kinds of surfaces: smooth, rough, and magnetic and non-magnetic. Yet, it has restriction in life assignment.
- PRWCRs have large-scale applications and can be found with most types of locomotion principles.
- DRWCRs are multimodal robots and have intrinsic ability to maneuver, but this was at the expense of significantly increasing in the vehicle weigh, besides the adverse impact in flying mode performance.
- Despite the success of adjusting the thrust direction in variable-tilt rotor mechanism, it has drawbacks in complexity, and serious coupling interference with motion of the main body.
- The drones inside cages have non-continuous contact to the wall surface and it can be said that they hover near the wall more than climbing.
- The main disadvantage of dispensing with the driving wheels and entirely dependent on aerodynamic system for moving is that it is hard to have a precise gait.
- Generally, propeller-type WCRs face challenges in transition operation, and the proposed solutions often lead to increasing the total weight, inertia, the height of robot center of mass and system complexity.

With regard to the future work, it is significant to build WCRs with more capabilities such as high speed of operation, high energy efficiency, and sufficient payload.

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