Novel Wall-Climbing Robot Capable of Transitioning and Perching

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Abstract. The main restriction facing wall climbing robots WCRs during travelling is the adaptation to specific type of surfaces. In general, the applications of climbing robots have been grown with their ability to deal with various surfaces. Motivated by this realization, this paper presents an innovative design of propeller-type climbing robot, where it can work on different types of surfaces. Also this work includes a comprehensive survey of propeller-type wall climbing PRWCR, where the robots of related works are analyzed in order to provide the required background to evaluate the major advantages and shortcomings of the current work. The proposed robot has two ground navigation modes; these modes supported two different ground-wall transitioning scenarios. To overcome the limitation on power source, the mission life was extended by proposing perching mechanism. The real climbing robot is manufactured, and the experiments are conducted in this research in order to check the robot performance.

1. Introduction
The last decades have been witnessed a great interest in the developing of a special robots which have the ability for climbing walls. Typically, the objectives are to raise the efficiency of the operations in risky environments or hard-to-reach locations, and to protect worker safety and health in dangerous areas. These robots with their unique ability in climbing vertical structures have been firmly demanded in different applications to achieve hazardous operations such as high-rise buildings cleaning, sand blasting and spray painting of gas tanks, inspection of aircraft and nuclear plants, reconnaissance and surveillance, and provide assistance in searching and rescuing firefighting operations. The benefits of climbing robots are not restricted to this limit but also to compensate the shortage of professional workforce as well as to minimize the high cost of conventional methods [1].

In climbing robots field, the adhesion mechanism is the most important issue to guarantee that the robot will stack to the target surface effectively without losing the maneuverability. Many articles throughout the world have been introduced to develop the adhesion principles which are mainly categorized in four types: magnetic adhesion, adhesion principles based on claws or spines, biological inspired adhesion and Pneumatic techniques. Magnetic adhesion is the most common attachment mechanism in climbing systems. Despite that electromagnets [2] or permanent magnets [3,4] are very reliable and provide sufficient adhesion forces, they useful on the ferromagnetic surface only. While the attraction principle based on claws or spines [5,6] has merit lies in low power consuming. But this system is used in the case of rough surfaces only where the claws can catch the asperities on the wall.

The third technique, climbing robots using material inspired from gecko foot [7], these robots can be applied for various type of surfaces and have energy efficiency. Nevertheless, this material degraded and contaminated by dirt within the time. That negatively impact on the adhesion performance and makes it not suitable for outdoor applications. Finally, the pneumatic wall-climbing robots which are generated the required adhesion force through the negative pressure by utilizing the
vortex mechanism [8] or the suction cups [9]. Their ability to deal with non-magnetic material is principal advantage. But they lose negative pressure in rough surfaces because of small leakages. So they are only suitable on smooth and flat surfaces.

Beside the classic pneumatic principles, other approach used the thrust force of propellers to generate attraction has been raised [10,11]. This technique looks to be a quite promising as it is robust concerning different surfaces. This mechanism connects two huge worlds: unmanned aerial vehicles (UAV) and wall climbing robots (WCR). As a result of this connection, all efforts in UAV like researches and innovative designs can be exploited to support development of these robots, thus saving time, cost and enhanced the effectiveness. Due to these advantages, the aim of this paper is to introduce new wall climbing robot which have the ability of transitioning between perpendicular surfaces and adopting the thrust force generated form the propellers to provide the required attraction force. To support the proposed design, next section will include comprehensive survey to previous related works.

This article is constructed as follows: in Section 2 a survey on the research of climbing machine is given, this survey focused on propeller wall climbing robot. Section 3 will introduce the overall structure of the climbing robot and discuss in detail the robot ability of ground-wall transitioning and wall perching. The experimental results are carried out in Section 4. Finally, in Section 5, the main conclusions and future work are outlined.

2. Related work

Recently, many researches have discussed the propeller-type climbing robots, and different kinds of products and experimental prototypes have been presented. One of the oldest attempts in this area was introduced in 1993, Nishi [10] developed a climbing robot of four free wheels using the thrust forces of propellers to move and to adhere to the surfaces, as shown in figure 1(a). Close to principle of Nishi robot but with one degree of freedom rotors system was introduced by [12], while VirTeGo [13,14] rotors system had 2-DOF and steerable front wheels, as shown in figure 1(b,c). figure1(d) shows a tilt-variable thruster with a pair coaxial propellers robot which has a pair of driving wheels was presented by Kinki University[15]. EJBot [16] has a pair fixed thrusters and used flat track system (figure 1(e)). Recently, many researchers have studied the potential of multi-rotor aerial robots to be a wall climber. The main concept of these robots based on using thrust forces not only to fly but also to generate the required adhesion force for stick on the wall. Drone-type wall-climbing robots DRWCRs have been built with various numbers of rotors of different degrees of freedom (DOF). In literature one can primarily note that the DRWCR of four rotors [17,26] the most common used. Two [27] and six [28] rotors are also existed.

Korea Advanced Institute of Science and Technology (KAIST) have many contributions in climbing aerial robot system field. Their early versions [21,22,29], shown in figure 1(f-h), has limitation in transition due to high impact on the wall caused by fast pose change and landing speed. This issue was addressed in subsequent releases, where the direction of thrust is controlled by rotary arm system in[20] and tilting-rotor in [19], as given in figure 1(i,k). The same technique for rotating the propeller angle of dual connected bi-Copter was also considered by Kawasaki et al. [23], shown in figure 1(q). Another two concepts to solve this problem were proposed: a drone has L-shape with 6 rotors in PD6-CI-L [28] and two identical manipulators in MMAR [26], shown in figure 1(n,o). Stanford University developed SCAMP [25], in figure 1(p), which combines a quadcopter with perching and climbing mechanisms, perching capability enhance the aerial vehicle resistance to harsh environment such unpredictable gusty wind. SCAMP differs than other DRWCR in two main things, the negative one: it is still restricted to specific surface due to depending spine for moving, the positive is noiseless during climbing.

Some studies provided design to prevent blades to be in contact with the structures, where wheels extended front the quadcopter body in [17], also the drone is installed inside cylindrical [18] and spherical [24,27] cage, see figure 1(r-t). Finally, some WCR used rotors thrust force for other purposes rather than supporting robot weight, such as damping vibration and keep contact with the wall surface as in a cable-driven robots ROPE RIDE [30], depicted in figure 1(v). From previous survey it can be mentioned that:
Propeller-type WCR is free of surface restrictions and can deal with different type of surfaces: rough, smooth and magnetic or not. But it has limitation in mission life.

- These robots have wide potential applications and can combine with different types of locomotion mechanisms.
- Multimodal robots like DRWCR offer substantial maneuverability, but also it will remarkably increase the vehicle weigh, in addition to the negative effect in performance of flying mode.
- Variable-tilt rotor mechanism success in adjusting the direction of thrust, but it has disadvantages in complexity mechatronics, and severe coupling interference with the main body motion.
- The drones with cages have unstable contact on the wall and it can be said that they are hovering close the wall rather than climbing.
- The main problem of absence of driving wheels and total dependency on aerodynamic system for moving is represented in the difficulty to get an accurate gait.
- In general, DRWCRs have problem in transition operation, and the suggested solutions almost lead to increase inertia, total weight, height of center of mass and complexity of system.

In next section, we will introduce UOTWCR-II which is based on ground differential drive vehicle used thrust force of propellers and to maximizing the friction force between the driving wheels and the wall.

![Propeller-type wall climbing robots.](image)

**Figure 1.** Propeller-type wall climbing robots.

### 3. UOTWCR-II Design

The robot consists of two rotors systems and two driving wheels, additionally a front steerable wheel is attached to the structure to support the robot. Fixed-pitch rotor system consists of a propeller driven
by one actuating motor. Two rotor systems are attached to the robot frame at the right and left of the robot chassis. Left rotor has a clockwise propeller while the right one has a counter-clockwise propeller, therefore, two rotors must rotate at different rotating directions in order to provide the down thrust force. The robot body will not rotate when robot is on to climbing surface if the surface’s friction is large enough. The CAD model of robot system is shown in figure 2.

3.1 Ground-wall transitioning mechanism
To achieve transition from walking on ground to wall climbing mode, the robot was equipped with an arm of L shape with miniature wheel at the free end, as shown in figure 3. The rotation of the arm can be freely controlled by 180° servomotor. The motor shift axis is collinear with axis of driving motor axis. Figure 4 shows the transition steps. Transition begins by stretching the arm away from the body, as the arm contacts the ground, the reaction torque will rotate the robot and increase the robot pitch angle. Then, the robot moves forward till the front wheel touches the wall and the arm is folded toward the body. Finally, the robot keeps moving along the remaining distance until its chassis becomes parallel to the wall. To prevent robot flipping, it is required to apply small thrust force by propellers simultaneously in order to keep the robot attached to the wall.

It is of importance to note that increasing robot pitch angle (figure 4(b,c)) can be achieved while the robot moving toward wall due to existing of the wheel at the free end of the arm. This mechanism allows the transition to be more rapidly and free from gyroscopic effect. But, it can be observed that this operation is more affected by the first few centimeters of the wall. Existence of small obstacle in the way of the arm may prevent front wheel to reach to the wall. To overcome this limitation, a new approach was proposed, this approach includes configuration the robot in a way so that the robot chassis is already parallel to the wall. Balancing the robot on its two driven wheel imposed restrictions on COM location, these restrictions may conflict with WCR requirements (which prefer the COM be closed as possible to the wall). Figure 5 depicts the robot leaning on short tail. The tail will support part of robot weight and reaction torque of driving wheels. This approach is inspired by Kangaroos, The authors called this situation Kangaroo mode. Tail wheel can serve as a caster wheel and adopt this mode for ground instead of front steerable one.
Both the arm and gravity contribute in transition from ground mode to Kangaroo mode. The arm elevates (increase the pitch angle) the robot tip to a specific level then the fame will rotate under the effect of the applied torque by the robot weight, as shown in figure 6. It can be observed that this approach, in contrast to the previous one, is independent on wall through transition between planes. Also, it can be transformed between different modes (ground, Kangaroo and climbing) easily. To reversely back to ground mode from Kangaroo mode, two methods can be adopted: either with help of wall, as shown in figure 7(a), or can be achieved without the need to vertical surface, as shown in figure 7(b).
3.2 Perching on wall
Unfortunately, propeller WCRs are generally hindered by a limited task life, which does not exceed a few minutes in case of vehicle of weight less than one kilogram [25]. Therefore, if these platforms supported by perching ability on the wall, their missions can be extended for extra time and give it a chance to achieve jobs which need relatively long time such inspection and surveillance. Small spines can be attached to the free end of the arm to catch on the surface asperities and share the robot load. As a result of spines-asperities engaging, it can provide the force required to carry the robot weight and compensate the rotating torque generated by the center of mass of the robot, as shown in figure 8.

4. Real robot building and experiments
After robot design is achieved, the real robot is manufactured. Robot consists of four parts; robot body frame, wheels, rotor system and electronics system. One of the main challenges is how to meet the design requirements of building a rigid and lightweight structure. To keep the design cost-effective as possible, entire robot body frame is manufactured from Plexiglass sheet of 2.5 mm, this material is relatively lightweight and high impact resistance. In addition, it is cheap and available in local markets. However, it is not rigid enough and to overcome this cons, carbon fibre tubes was used to support the frame due to their higher strength-to-weight ratio.

The robot structure consists of 3d printed and Plexiglass sheet parts, which are connected together to build the robot body. Where each component is designed in such a way as to ensure that it can be cut out from the sheet easily and combined using plastic nuts and bolts or super glue to get a rigid structure. Robot weight must be as small as possible. Therefore, robot wheels are made from the PLA thermal plastic. 3D printer is used to print the designed wheels. From the preliminary test, the rubber o-ring was used as the robot tire.
4.1. Electronics system

Rotor system consists of brushless actuator and propeller. 2200KV DC motor is selected as the actuating motor that generates thrust. This motor is operated at 12V. APC 6045 propeller is selected for the robot; the propeller is attached to the brushless motor inside a 3D printed holder. Two BLDC ESC is used as a brushless motor driver which can drive each brushless motor up to 40A continuous driving current. Three cells Lithium-polymer battery is selected as robot power source. Two pair of 6V servo motor type are used: two continuous type as driving motor and the other 180° type to control front wheel and the arm. The servos are power supplied through voltage regulator. Six channels radio receiver is integrated to the system in order to control the robot manually. The diagram of the electronics system is shown in figure 9. Finally, the total weight of the robot is 0.6 kg.

\[\text{Figure 8. Perching steps. (a) climbing on rough wall, (b) close the spine to wall by rotating the arm, (c) theoretically, the robot will slip slightly until the spine engage asperities.}\]

4.2. Performance Test and result discussion

In order to validate the effectiveness of the suggested design, UOTWCR-II has been constructed and tested in the laboratory environment, as shown in figure 10. The experimental tests were carried out on an acrylic sheet of 4 mm thickness. The robot is attached to the protection sling in order to protect the robot hardware when it is unstable and fall-out of the surface. The conducted tests on the prototype demonstrate that the robot successfully climbed the wall without losing adhesion and able to track paths in both directions parallel and perpendicular to gravity. Not only that, all the operations include: ground mode, Kangaroo mode, ground-wall transitioning and transforming between of them are tested. For the time being, wireless commands are sent by a human operator. While, the value of front steerable wheel angle is controlled and computed by the onboard microprocessor.

The perching mechanism has been tested under indoor conditions. A single fishhook is attached at the end of the arm and successfully engaged to the protrusion which resulting from attaching 4 mm
flat sheet to the wall. A video file of UOTWCR-II performance test is uploaded at the below link:

From the experimental tests that carried out on the prototype of UOTWCR-II, it can be noticed that:

- The robot design based on differential-drive system granted the high maneuverability in wall and decreased the robot weight.
- Using steerable front caster wheel help the robot to avoid the drag force generated from traditional caster wheel which is hard to steer, especially on the wall where its direction will always follow the gravity direction.
- Manufacturing the robot form acrylic sheet and supported the fame by carbon fiber grants sufficient rigidity and decreases the total cost.
- Although the robot can achieve the rapid transition, but the proposed mechanize has a limitation. In the case of wall-to-ground transitioning, it should carry out in certain configuration, where the driving wheel is in the front of the robot.
- The arm system added one degree of freedom to the robot, but also supported two ground moving style, two gradual ground-wall transitioning approaches and perching ability.
- In spite of the perching mechanism is still need further developing, but this ability reduced the drawn power which is the main drawback of propeller-type WCR and extends the life mission.
- Adopting fixed pitch rotor system lads UOTWCR-II to rely entirely on friction force in climbing, but this approach simplifies the controller design and reduces the possibility of presence the gyroscopic effect.

![Figure 10. Photo snapshots of UOTWCR-II on acrylic sheet of 4mm thickness. (a-c) Kangaroo mode. (d) Transitioning from Kangaroo to climbing mode. (e-h) The robot is climbing vertical line and steering right. (i-m) The robot is moving on ground and leaning on the arm. (n,o) Transitioning to climbing mode and tracking vertical line. (p,q) Perching on thickness surface of sheet. (r) The robot is powered down.](image)

5. Conclusion and future work

The principle design of Propeller type wall-climbing robot is illustrated in this article. A survey on the research of related climbing robots is given. The current prototype is based on a pair of rotor system and a deferential drive vehicle, named UOTWCR-II. This vehicle supported two ground traveling modes. It is detailed step by step the two ground-wall transitioning strategies. To address the restriction of battery life, the robot perching mechanism is proposed. UOTWCR-II has been tested under laboratory conditions and achieved all the stages successfully and with agility.
In terms of further research in the future, the control algorithms and robot dynamics will be focused. The arm will be redesigned to be able to hold multi-spine and the robot will be experimented in the outdoor environments. An Inertia Measurement Unit (IMU) and infrared distance sensors will be installed on the robot to achieve all the operations: transitioning, climbing and perching autonomously.

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