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# Drone-Type Wall-Climbing Robot Platform for Structural Health Monitoring

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**ABSTRACT**
Though civil structures need constant maintenance and inspection of the structural health condition and safety of the users, the accessibility is getting harder and harder because of their gigantic height and size. To overcome this problem, several approaches for wall-climbing mechanism have been introduced for many decades; however, there is no assured solution yet. One of the reasons why existing wall-climbing robots haven't been put to practical use is the risk of accidental fall due to operational failure from the harsh environment like gust and surface's uncertainty. Therefore, we propose a drone-type wall-climbing aerial robot platform that can approach to any place of the structure by flying and sticking to the target place with pose change and perching mechanism. Not only that the robot is equipped with a moving mechanism like other wall-climbing robots to move on the vertical surface of the structure, but also this paper suggests the wall-climbing mechanism for an aerial robot, its pose change and wall sticking mechanism, and the way to move on the surface of a structure.

**KEYWORDS:** *SHM, robot, wall-climbing, drone, inspection*

## 1. INTRODUCTION

Nowadays, drones have come into the spotlight due to its broad possibility and versatile usability in that many type of drones are now being used and tested in the field of military, delivery service, media, agricultural industry, and service industry. Most common type of the drone is the quadrotor, literally, which has four rotors and also consists of flight controller, motor drives, motors, battery, and frames. By controlling the speed of each rotor, the drone can change its pose; roll, pitch, yaw in body frame and move to specific direction. For the normal flight, excessive pose changes are not necessary, but for perching and wall climbing, other control mechanism should be added. Due to the limitation of carrying payload, it's not easy for MAV (micro aerial vehicle) to be installed with heavy or complicated equipment, therefore efficient design with light weight and high strength is essential [1]. This paper introduces the mechanical design and control algorithm of the drone-type wall-climbing robot which can fly, perch, climb, and monitor the surface of the wall-like structure [2].

## 2. BASIC CONCEPT OF A DRONE-TYPE WALL-CLIMBING ROBOT

Wall climbing mechanism of the aerial robot is based on a combination of the thrust force and wheel drive force by maximizing friction between the wheel and the surface [3, 4, 5]. When friction coefficient is higher than 1, the robot can attach to the vertical surface with the thrust force toward to the wall. We simulated this mechanism with WORKING MODEL 2D software and conducted the indoor experimental test. Figure 2.1 shows the process of the wall-sticking and the wall-climbing mechanism.

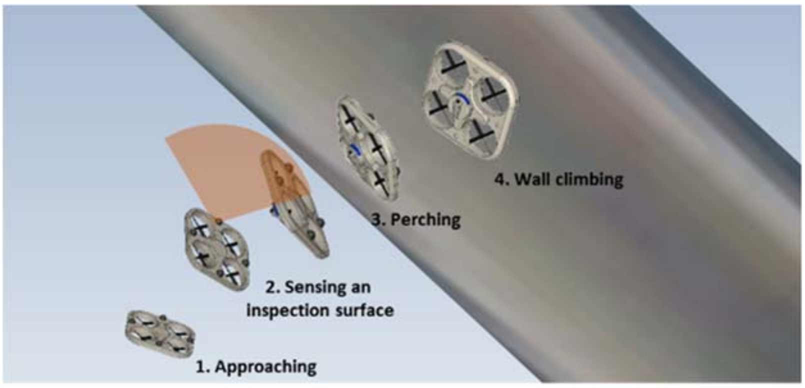

Figure 2.1 Concept of Wall-Climbing

## 3. DESIGN OF A DRONE-TYPE WALL-CLIMBING ROBOT PLATFORM

The payload capacity of the MAV is very limited and also the self-weight has an impact on the operation time and the controllability. In order to increase the payload capacity, the rotor size should be increased as well as increasing the motor power and electric power. The MAV with a large rotor and a high power motor would be dangerous to be operated in urban space in that the rotating rotor can cause serious injuries on the human body. Therefore, efficient platform design with minimized weight of the equipment for additional specific tasks and minimum moment of inertia will be feasible and will guarantee controllability.

### 3.1. Basic Robot Frame Design

The materials of robot frame is same with those of the commercial drone frame kit like center carbon fiber plates, carbon fiber pipes, and other joint elements. The torque of a motor should be high as long as it is compatible with other parts like frame, rotor, battery and motor drive in order that the rotor instantly reacts to control signal and the aerial robot can be precisely controlled with additional equipment installation. A rotor guard is designed to protect the rotation of the rotor from contact with the wall, which is made with EPP (Expanded Polypropylene) that is shock-absorbing material with elastic characteristic. Figure 3.1 shows the structure of the robot frame.

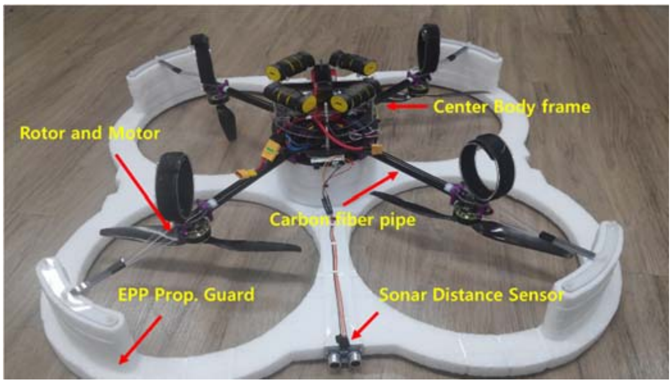

Figure 3.1 Basic Robot Frame

### 3.2. Frame Design for Wall-sticking and Wall-climbing

We considered three candidates on the frame design for installing moving mechanical parts like motors, wheels, or suspensions. Since combined load of thrust forces and gravity will be concentrated when the robot perches to the wall and climbs the wall, the candidates should be located in solid components like a main center body or arms that are composed of a carbon fiber plate and carbon pipe, respectably. Each location has both advantages and disadvantages at the same time as shown in Table 3.1.

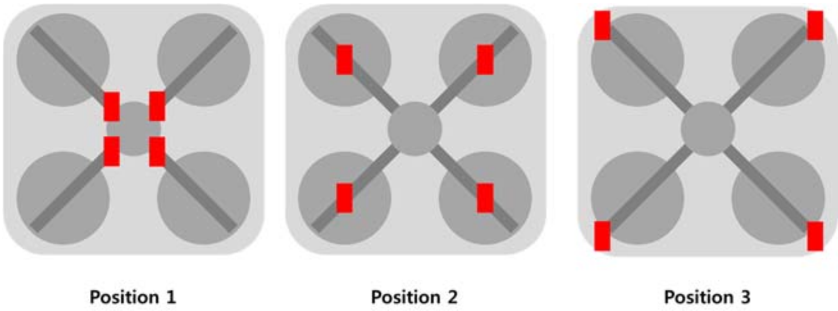


Figure 3.2 Install Location Candidates for Wall-Climbing Mechanical Part

The closer to the center of the frame, it's more favorable for the aerial robot to be precisely controlled with the low moment of inertia. However, when the robot perches or climbs the wall, it is not easy to balance on the surface with narrow contact points and failure rate might increase. In case of position 2, it is a quite stable structure with moderate area of the contact point. However, since locomotion equipment and the rotor blade area overlap each other in some place, air flow for thrust force can be disturbed. Finally, we adopted the location of position 3, where thrust force is not interfered by any structure of the equipment installed on the robot and it can guarantee maximum contact area for stable perching and climbing. The only problem is a high moment of inertia caused by the mass of the equipment and the distance from the center. By minimizing the mass of the equipment, the problem can be solved.

Table 3.1 Advantages and Disadvantages Depending on the Install Location

| Location | Descriptions | Advantages | Disadvantages |
|---|---|---|---|
| Position 1 | On the center frame | ➢ Low moment of inertia<br>➢ High flight controllability | ➢ Unstable structure for perching and wall-climbing |
| Position 2 | On the place motor installed | ➢ Moderate moment of inertia<br>➢ Moderate flight controllability | ➢ Disturb air flow for thrust |
| Position 3 | On the margin | ➢ Stable structure for perching and wall-climbing | ➢ High moment of inertia<br>➢ Low flight controllability |

### 3.3. Wheel Drive Mechanism for Wall-Climbing

As mentioned before, payload limitation is a very critical issue for aerial vehicles and wall-climbing itself requires quite large power to carry the self-weight of the robot against gravity. There are many commercial high torque servo motors for hobby or research. The major advantages of the servo motors are space saving design and low weight considering their performance. However, most of them is not continuous-rotation type and have a specific moving range with an end-gear and a variable register. Since, there are few commercial continuous-rotation type product with high torque, the normal servo motors are modified to the continuous-rotation type servo motor by fixing register value and giving variable PWM (pulse width modulation) signals.

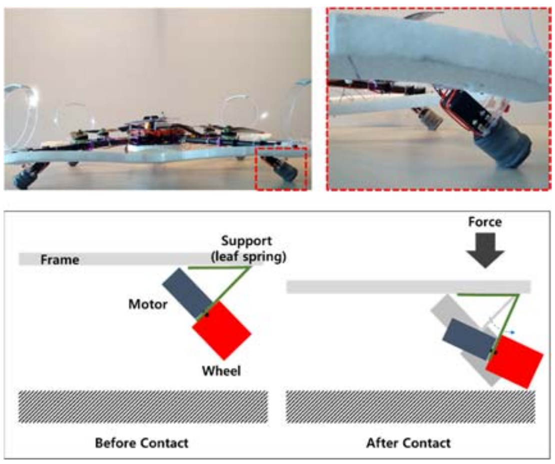


Figure 3.3 Wheel Drive

To minimize self-weight, additional reduction gears are not applied, but wheels with small diameter are used. Since the wheels are directly connected with servo motors, it's not easy to secure contact between wheels and the wall. For these reasons, the wheel is inclined to the frame about 45 degrees with the polycarbonate sheet support which has little elasticity, consequently when the robot lands on the surface the polycarbonate support transforms like a leaf spring as a suspension and the wheel with adhesive material gets more contact with an angle of about 25 to 30 degrees.

## 4. WALL STICKING AND CLIMBING FOR SHM

In this section, the robot system and the control algorithm are explained for wall sticking (perching), climbing, and detaching. For SHM (structural health monitoring), these abilities are necessary to closely approach to structural surface and monitor it.

### 4.1. Wall Sticking (Perching)

A differential equation-based pose change control algorithm is developed which could be categorized as an open-loop control, assuming that pose change occurs in an instant. Without relying on any external structure, pose change cannot be accomplished with slow motion and it's easy to fail which can be proven mathematically. Once the robot approaches to the vertical surface of the structure, it tries to detect the distance and calculate the proper thrust force of each rotor with a differential equation where dimension, mass, and moment of inertia of the robot are known. The ratio of thrust force of front to rear, the amount of thrust force, angular acceleration, and finally perching trajectory can be calculated. The simplest assumption is phase change with a constant amount of thrust force and ratio with some constraints like landing condition. For the safe perching, the speed along x-axis and z-axis in the world frame should be close to zero as possible as they can. With a simple mathematical equation and low computational process, this approach can instantly calculate the control input right after sensing the proper distance from the wall. Figure 4.1 shows parameters of the equations and the robot dynamics.

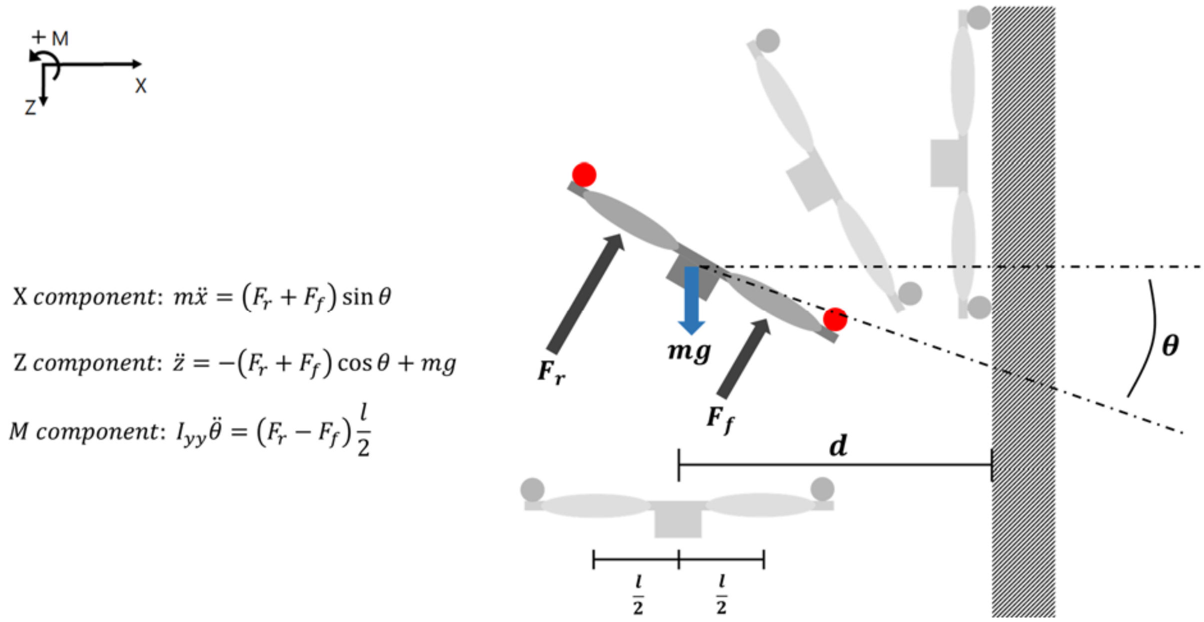


Figure 4.1 Robot Dynamics for Perching

### 4.2. Wall Climbing and SHM Operation.

Among four wheels, two wheels on the left side and right side constitute one pair respectively, so that they operate as a differential drive system. Once the robot is attached to the wall it changes its mode to "wall-climbing mode", in which control signals from the flight will be used to control the differential drive system. The power system for wheels is separated from a flight power system for stable electric current supply by adding extra batteries. For structural health monitoring, in our robot, a wireless vision sensor is installed to capture the images of the surface of the wall structure. Not only that, other lightweight sensors can be modularized to be carried by the robot and they also can be utilized for the robot localization.

## 5. EXPERIMENTAL TEST AND ITS RESULT

To validate the concept of the drone-type wall-climbing robot platform for SHM, we developed a quad-rotor-based robot platform and conducted indoor experimental tests.

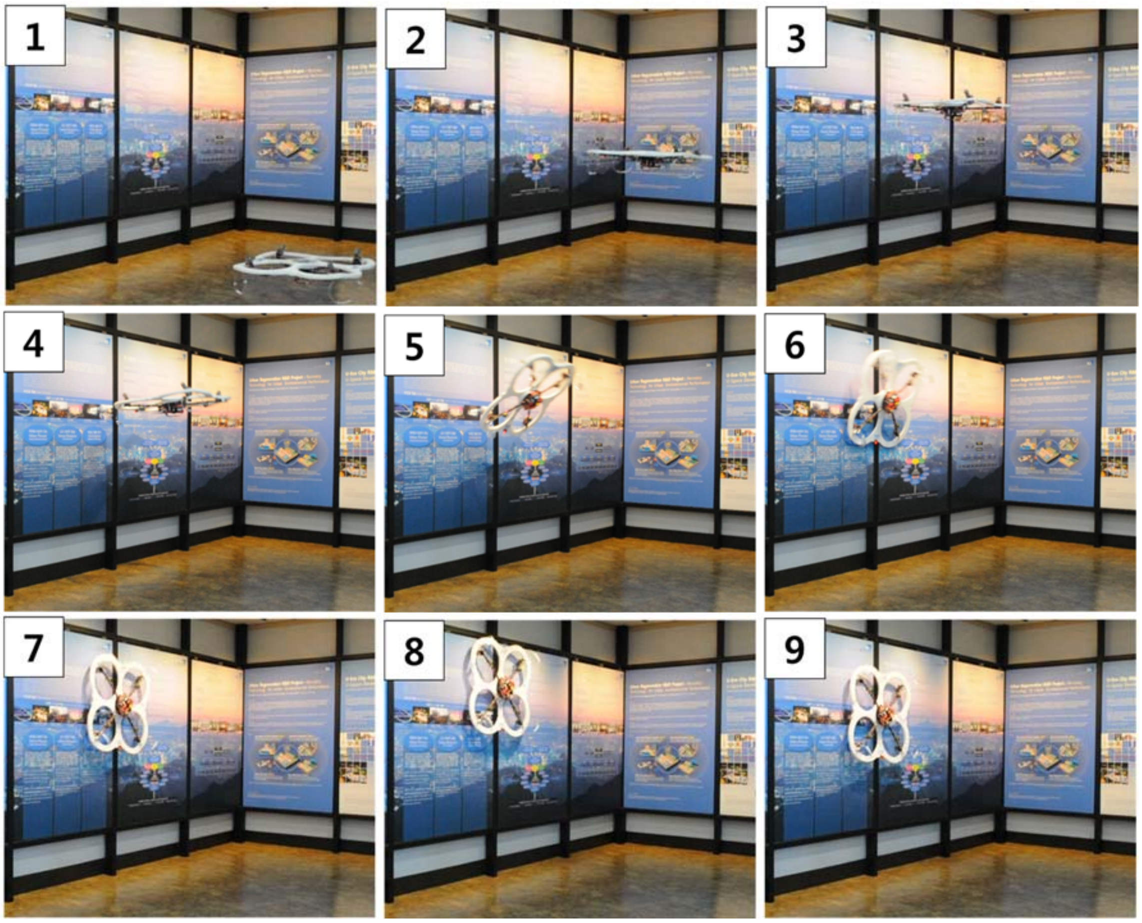


Figure 5.1 Robot Dynamics for Perching

As shown in Figure 5.1, the robot will take off and hover to approach to the target wall (1-3). When it's close to perching target (4) it starts to change its pose and sticks to the wall. After that, the robot can move on the wall inspecting the surface with a vision sensor. The success rate of wall-sticking was more than 90 percent.

## 6. CONCLUSION

From the indoor test, the feasibility of the wall-climbing robot platform has been verified with high success rate. We expect that this robot can be used as a platform for SHM and further applications like maintenance or repair with a robotic actuator. There are a few things to improve. The most critical issue is the operation time in that the average operating time of the recent MAV is about 10 to 15 minutes. However, many operations in urban space would need more than that. Also, safety, localization on the wall, and limited payload should be overcome.

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