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Development of a wall-climbing drone with a rotary arm for climbing various-shaped surfaces

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Abstract – In this paper, a novel wall-climbing drone installed with a rotary arm is proposed for climb operation on various shaped walls. Robots that can climb the wall are applicable to many operations such as structural health monitoring of high-rise buildings, bridges, nuclear power plants; maintenance of solar panels and glass walls; and visual inspection of the aircraft and vessels. Traditional wall-climbing robots use magnetic, vacuum, or bio-inspired methods mimicking gecko foot for those purposes. However, those methods cannot be applied to various-shaped walls like inclined, and an obstacle existing walls such as window frames. To solve this problem, unmanned aerial vehicle (UAV)-type wall-climbing robots have recently been developed, but those types have disadvantages in terms of energy efficiency and impact in attaching and detaching processes. Therefore, in this paper, a wall-climbing drone with a rotary arm is proposed. The angle of the rotary arm is controlled depending on the slope angle of the wall to achieve energy efficiency. The drone was prototyped and tested in indoor environment to verify the feasibility of the mechanism.

Keywords – UAV (Unmanned Aerial Vehicle), drone, wall climbing, wall attaching, aerial robot

1. Introduction

Many researchers and industries have tried to develop a wall-climbing robot for several decades because it has a potential for several fields like SHM (structural Health Monitoring), maintenance of civil structures, security, and so on [1], [2], [3], [4]. One of the wall-climbing technology is thruster force assisted approach, in which the thruster applies a pushing force to the wall and a friction force at a contact point and a moving mechanism allows the robot to climb the wall [5]. As drone technology gets popular, some researchers have tried to use the drone as a wall-climbing or a wall-sticking robot platform by applying thrusters of a drone to the wall [6], [7], [8], [9]. Considering a low level of frictional coefficient in the real world, applying a force to the wall in normal direction is not favorable in terms of energy efficiency. For that reason, we propose a system can control a slant angle of the robot to the wall using a rotary arm, by which it can control the direction of the thrust force. Besides that, the design of the proposed approach can climb various-shaped surfaces, because the tilt arm allows the robot to get different posture according to the wall condition.

2. Concept of the Mechanism

Since our previous wall-climbing drone called CAROS [10], [11] depends on only the friction force generated by a normal force from thrusters, the required level of thrusters is different according to the change of friction coefficient. Therefore, it could overuse energy or fail to climb the wall, in that it is hard to estimate the friction coefficient at the contact point.

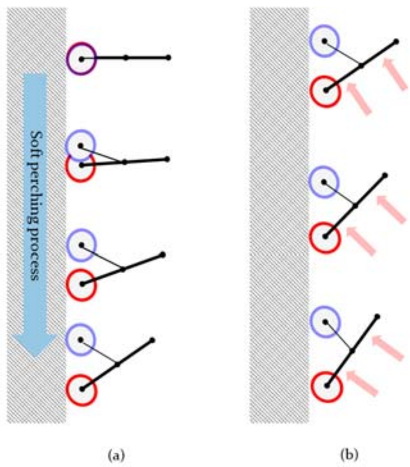


Fig. 1. Concept of wall-climing and wall-perching (a) soft perching process (b) various pose on the wall

To mitigate this problem, the concept of the proposed system aims to control the direction of thrusters to the wall as shown in Fig. 1. The figure also describes the perching process using the arm, which allows soft attaching and detaching to the wall. Another purpose of a 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 direction of thruster (α). As shown in Fig. 2, the thrust force (F) is divided into two elements, where m, g, μ are a mass of a robot, gravity, and a friction coefficient at the contact point, respectably. One is the force that compensates a gravity and another is the force generating friction. Therefore, it is stable because the change of a minimum thrust level relying on change of friction coefficient decreases as shown in Fig. 3.

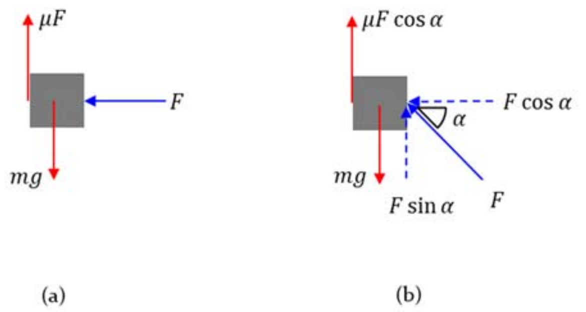


Fig. 2. Freebody diagram according to a direction of thrusters (a) normal direction case (b) a specific angle case

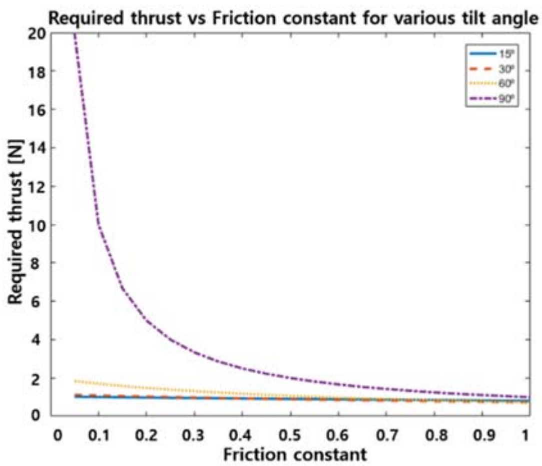
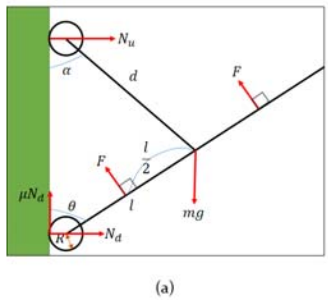


Fig. 3. Graph for required thurst vs friction constant for various tilt angle

3. Robot Kinematics

4.1 FBD analysis



m	Mass of the UAV
g	Gravity acceleration
F	Thrust force
N_u	Normal force to the free wheel
N_d	Normal force to the actuated wheel
μ	Friction constant (< μ_{static})
d	Length of the link
l	Distance from the center to the wheel
θ	Angle between the wall and the UAV

(b)

Fig. 4. Wall attaching situation

When an unmanned aircraft is attached to a wall, the thrust from the motor and the propeller and the friction between the wheel and the wall on the front of the body can offset gravity and prevent it from flowing down. Therefore, to obtain the appropriate thrust, the equilibrium of the force and the torque should be calculated. For the calculation, the free body diagram is obtained as shown in Fig. 4. In addition, since the weight of the UAV is about 4kg and the weight of the link and the end wheel is about 0.3kg, it is assumed that the center of gravity is in the middle of the UAV.

To calculate the thrust force required for maintaining a certain attaching angle on the wall, first let d_n as the distance between N_u and N_d.

$$d_n = d\,cos(\alpha) + l\,cos(\theta)$$

The force and the torque equilibrium for each axis can be written like below.

$$N_u + N_d = 2F\,cos(\theta)$$
$$mg = 2Fsin(\theta) + \mu N_d$$
$$d_n N_u + lmg\,sin(\theta) = 2lF$$

So each normal forces can be calculated in terms of force and the attaching angle.

$$N_u = \frac{2lF - l\,sin(\theta)mg}{d_n}$$
$$N_d = 2F\cos(\theta) - N_u$$

Using the fact that the normal force cannot be under zero (if normal force is under zero, that means the robot isn't on the wall)

$$\frac{\sin(\theta)}{2}mg \le F \le \frac{1}{2\sin(\theta)}mg$$

So the minimum thrust force can be calculated like below.

$$F = \frac{(d_n - \mu l \sin(\theta))mg}{2(d_n \sin(\theta) + \mu d_n \cos(\theta) - \mu l)}$$

In this situation, the friction constant on the equation is calculated by the equation

$$\mu = \min(\frac{1}{\tan(\theta)}, \mu_{static})$$

3. Robot Design

3.1 Mechanical design of a rotary link

In order to control a 1-DOF rotary link, one actuator is installed on the robot. As shown in Fig. 5, the arm supports a normal force against a wall for wall-sticking and wall-climbing, and the level of torque at the axis of the link could be large. Therefore, if the actuator operates on the axis, there must be a reduction gear with high ratio or high torque actuator is needed. This approach is not a favorable considering limited payload of a drone platform.

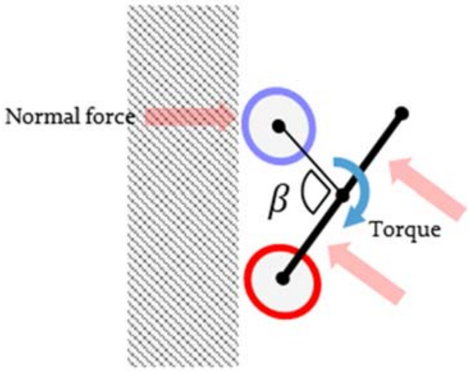


Fig. 5. Torque at the rotary link axis

To solve this problem, a rotary arm mechanism is designed with a reel, a pixed pulley, a wire and an actuator. When a robot attaches to the wall, the rotary axis is loaded by only a torque that increases the angle of an arm (β). To correspond this, a reel bar with servo motor winds the wire. At the same time, a rotary encoder measures the angle of the arm as shown in Fig. 5. Since there is no load torque other than the wall climbing condition, the angle of an arm (β) cannot be maintained and controlled under the circumstances. Therefore, a rubber wire is placed on the rotation axis of the link to apply a torque that increases the angle of an arm (β).

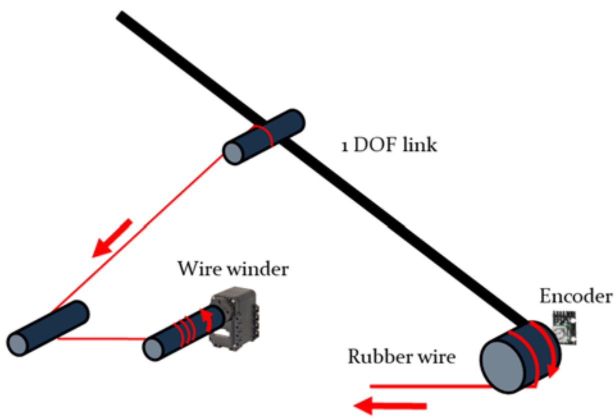
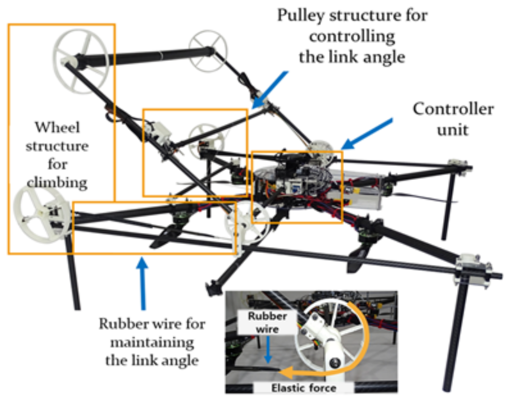


Fig. 6. A mechanical design of link control

As shown in fig. 6, the arm has two unpowered standard wheels at each side, while motorized wheels are installed in the front part of the robot body to minimize not only the weight of the entire robot but also a weight of link to minimize the load applied for adjusting the link angle. A wire reel and motor marked as wire winder on fig. 7 are attached to loosen and tighten the attached wire and control the link angle through the pulley.



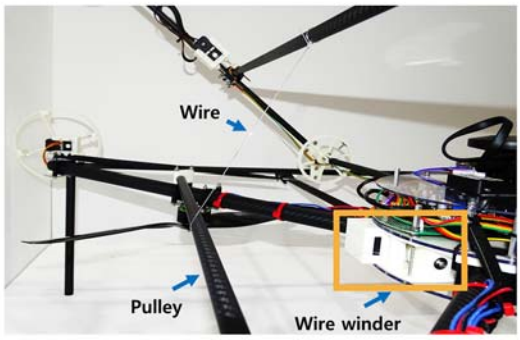


Fig. 7. Prototype of the robot (a) overall view of the robot (b) a detail view of link control mechanism

3.2 Control system

An overall system for control is described in Fig. 8. The main PC manages all driving units like motors for a wheel drive, a motor for link control, and motors for flight. The operation system of the main PC is Linux Ubuntu 14.04 installed with ROS(Robot Operation System) Indigo and PX4 firmware. The flight controller is a commercial developer product (Pixhawk) which receives control commands of ROS and sends flight status data. All electric parts are installed on the center plate as shown in Fig. 9.

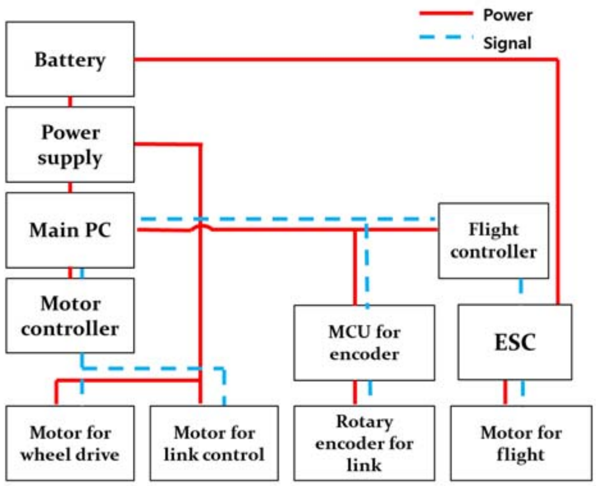


Fig. 8. Control architecture

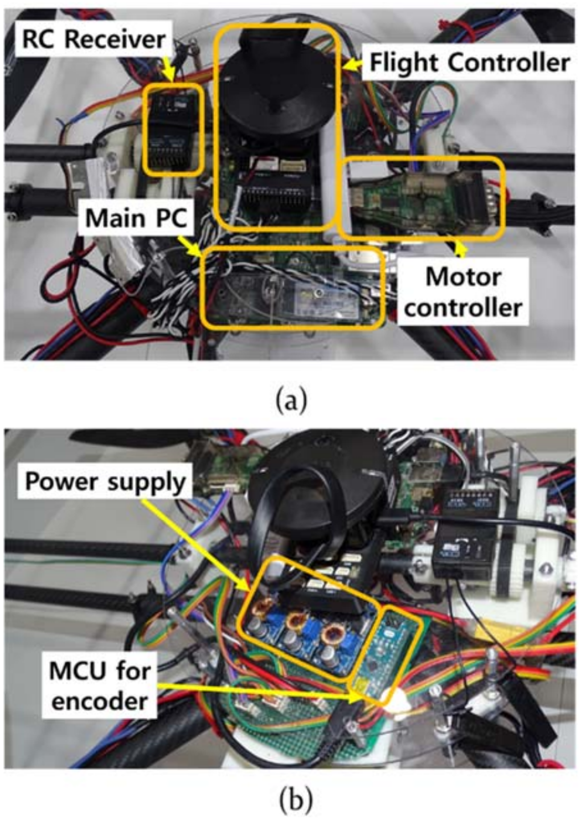


Fig. 9. Electrical parts (a) front view (b) rear view

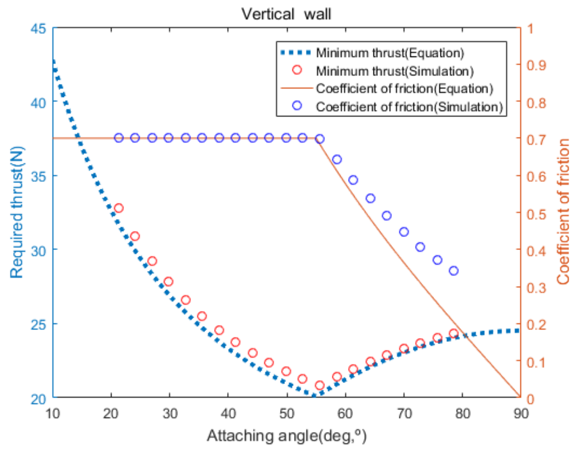


Fig. 10. Required thrust vs attaching angle

As shown in the Fig. 10, the required thrust data according to the angle of attachment obtained in the simulation is almost same with the value obtained from the required force equation.

5.2 Link angle control

To validate the feasibility of the rotary link mechanism for wall climbing, we conducted link control tests and wall-climbing tests for various wall slopes.

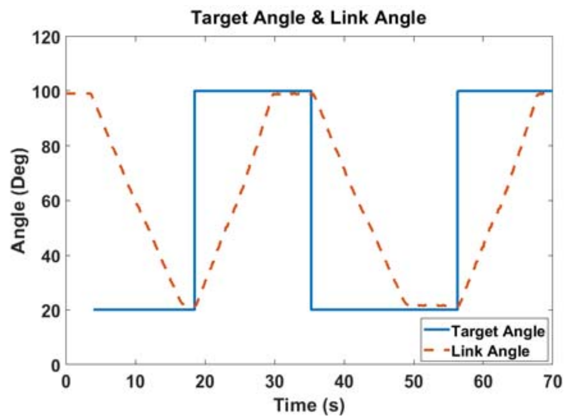


Fig. 11. Result of rotation link control

As shown in Fig. 11, the proposed link mechanism controls the angle of the link to follow a target angle.

5.3 Wall climbing experiment

The experimental tests for wall-climbing was performed on the vertical and sloped walls as shown in Fig. 12. Not only that, we installed a bar-type barrier whose dimension is 30mm height and 60mm width in order to simulate irregularities of surface of exterior wall like window frames or curtain wall frames.

5. Experimental Test

5.1 kinematics simulation

To demonstrate the validity of the kinematics formulas, the simulation data are measured using a dynamics simulator
(WorkingModel 2D).

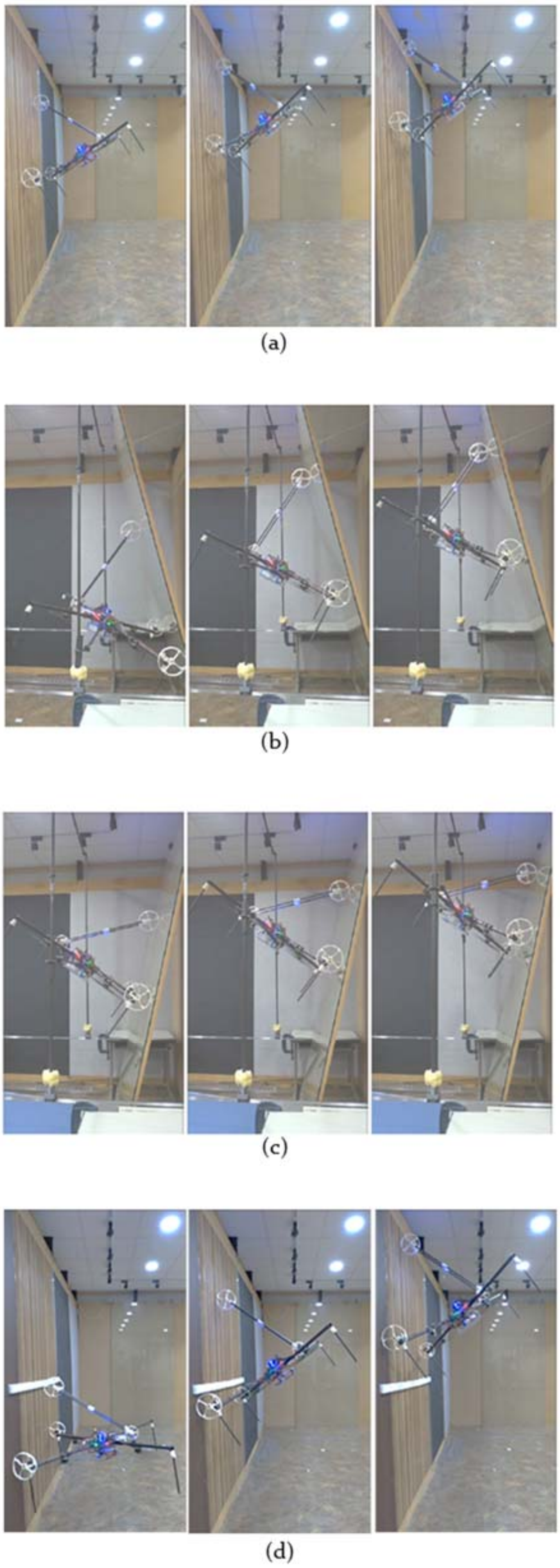


Fig. 12. Experimental tests for wall-climbing (a) vertical wall (b) negative-sloped wall (c) positive-sloped wall (d) vertical wall with a barrier

Depending on the angle of a slope, the robot controls the angle of the rotary arm and the robot's pose. Comparing with a previous version of CAROS the climbing speed is 8 times higher with the same motors for climbing units as following Table 1.

Table 1 Specifications and performance of wall-climbing mechanism

	Motor RPM (no load)	Wheel diameter (mm)	Maximum climbing speed (m/s)
Previous	100	30	0.109
Proposed	100	200	0.837 ○

5. Conclusions

From the wall-climbing test, the feasibility of the rotary link arm-based wall-climbing mechanism has been verified. It showed that the climbing speed is faster than that of the previous version of CAROS with a lower level of thrust force. However, the weight of a rotation arm and its high COG (Center of Gravity) position is an unfavorable factor for flight stability. As a future work, we will focus on the mitigation of this disadvantage. Not only that, one of the purposes of CAROS is structural health monitoring application and most of the sensor systems for that requires constant distance to a target object. Therefore the robot design should consider the location of a mount for sensors.

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