Passive Perching and Landing Mechanism for Multirotor Flying Robot

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Abstract—This paper proposes a mechanism for a multirotor unmanned aerial vehicle to perch at the tip of a cylindrical object. The proposed mechanism does not require an additional actuator such as a motor by converting its own weight into a gripping force at the time of perching. It also shows that a gripping force larger than its own weight can be generated based on a boost mechanism by appropriately selecting the design parameters. In addition, the proposed mechanism has a structure that can be not only used for perching at the tip of a cylindrical object, but also as a landing gear when landing on flat ground. Furthermore, we attached a depth camera to the proposed mechanism and obtain color and depth images of the target object to be grasped while flying so that automatic positioning can be executed based on the acquired images. Through indoor and outdoor experiments, it was confirmed that the expected perching and landing could be performed.

I. INTRODUCTION

Multirotor unmanned aerial vehicles (UAVs) have become a standard platform and are now commonly used not only for hobby applications, but also for industrial use such as civil engineering surveys, infrastructure inspections, monitoring, security, agriculture, and logistics. Manipulating objects and physical interaction using UAVs in flight is called aerial manipulation, and many studies have been conducted so far [1]. Work at height, such as maintenance of bridges, tunnels, wind turbines, dam walls, and high-rise buildings, can be a dangerous for human workers, and replacement and assistance by UAVs is a promising application for that. Our research group has developed some different types of multirotor-based flying robots for aerial manipulation as well [2], [3], [4].

There are some general challenges with aerial manipulation that we have experienced through these researches. These challenges include the low positional holding accuracy of the airframe in relation to the workspace, shaking of the machine body due to propeller stress and because of the overall small payload capability a limit of the battery capacity and hence short deployment time [5]. If the multirotor body is fixed to a well grounded object without the need for constant hovering, these restrictions can be alleviated. This brings us to the topic of perching for aerial vehicles. If landing is possible not only on flat ground but also when perching to various targets, such as the tip of a pillar and the top of a block wall, it helps small UAVs extend their time of operation by saving battery power.

There are several research works on perching on the underside [6], [7], [8], [9], [10], [11], upper side [12], [13], [14], [15], [16], [17], or lateral side [18], [19], [20] of the airframe. In [9], mechanisms specific for UAV perching on fence posts in an agricultural setting were explored. In [12], magnetic adhesion was used for perching on the ceiling. The UAV in [19] perches on a vertical wall surface using a mechanism with two spiny feet and tail. In [21], a micro UAV adheres to the ground and then uses a winch to pull heavy objects. By using this strategy, the UAV is able to tug up to 40 times their mass while adhering to a surface. In [16], we proposed a flying robot that holds on to an object near a certain workspace by perching the object with a gripper mounted on the top of the airframe and is then able to execute manipulation tasks with another manipulator mounted to its underside. Since the propeller can be stopped after the aircraft is fixed, battery consumption is reduced and it is possible to continuously work with the manipulator on the same task for a prolonged time. Furthermore, since the propellers are stopped, the robot overcomes a general limitation of aerial manipulators and can reach into upper and lateral side workspace with a underside attached manipulator. The perching mechanism on the upper side of the airframe has one degree of freedom of rotation that is the yaw direction. Together with the robot arm attached to the underside of the airframe that employs two degrees of freedom, the complete system creates a 3-axis articulated robot when perched [16].

Most of these studies require additional actuators to drive the device for perching, and some consume power to maintain gripping force during perching. In this study, we propose a passive perching mechanism that does not require an additional actuator to reduce power consumption during perching. The proposed mechanism converts the weight of the flying robot itself into a gripping force for perching. In addition, this mechanism can automatically start gripping as the aircraft descends for perching. It can also be used as is for landing on flat ground. We prototype such a perching device, mount it on a multirotor platform, and verify its effectiveness through experiments.

II. SYSTEM DESIGN

A. Overview

The major purpose of perching in small UAVs is to stop the propellers and reduce power consumption. Therefore, it is desirable that the device itself used for perching also consumes as little power as possible. In this study, the gripping force required for perching is generated by the weight of the flying robot. This eliminates the need for an additional actuator for driving the perching mechanism to generate a gripping force, and can reduce power consumption. In addition to that, another purpose is to fix the flying robot...
body at a high place to accomplish accurate and long-time work. Therefore, it is necessary to perform perching with a sufficiently strong gripping force and to stably fix the aircraft even if the propeller is stopped. Furthermore, it is desirable to have a landing function on flat ground as a basic function of the UAV. In this study, we propose a perching mechanism that can satisfy these three requirements at the same time.

In this study, the upper part of a cylinder was assumed as the target of perching. This is because columnar buildings, such as utility poles and fence poles, are often found in the city and in the suburbs. It is also possible to target pillars installed in the sea or lake. The proposed perching mechanism is mounted at the bottom of the hexarotor platform (DJI F550 airframe), with three fingers placed every 120 degrees and is specialized to grasp from the top of a cylinder (Fig. 1 upper and Fig. 2 left). As described in the next subsection, when the airframe descends from the top of the cylinder and the bottom surface of the airframe is pushed by the cylinder, a part of the proposed mechanism is weighted and the three fingers close. Sufficient gripping force is generated to support the weight of the aircraft against a cylinder of the assumed diameter, and the aircraft can be fixed even if the propeller is stopped. In this design, the diameter of a cylinder that can be gripped is 100 mm to 150 mm.

The proposed perching mechanism can also be used as a landing gear when landing on level ground. In this case, the three fingers spread out and can stably support the aircraft (Fig. 1 bottom and Fig. 2 right).

B. Mechanism of the perching device

Fig. 3 shows a simplified mechanism diagram of one finger of the proposed perching mechanism. The two upper joints are fixed to the bottom of the fuselage with which the cylinders come into contact. When the cylinder pushes up the bottom of the fuselage, the weight of the fuselage is applied to the middle joint fixed to the multi-rotor body side. This own weight is expressed as $F$. As a result, this joint
is pushed down, and in conjunction with this, the link of length \((L_3 + L_4)\) rotates counterclockwise with the upper right joint as the center of rotation. The lower tip of this link can come into contact with the cylindrical side surface of the target and provide a gripping force \(f\). In this way, the proposed mechanism passively achieves perching using its own weight without using an additional actuator.

The relationship between the weight \(F\) of the flying robot and the gripping force \(f\) can be obtained as follows. The weight of the flying robot is \(F = ma\). This force is applied to the joint between the links of length \(L_1\) and \(L_2\). The component force in the direction of the link of length \(L_2\) and the force \(F_2\) of pushing the link of length \((L_3 + L_4)\) are expressed as follows.

\[
F_2 = \frac{\cos \alpha}{\sin(\beta - \alpha)} F
\]

The moment around the joint at the base of the link of length \((L_3 + L_4)\) is expressed as follows.

\[
F_2 \sin(\beta - \theta) = f(L_3 + L_4)
\]

From the above two formulas, the grasping force \(f\) is

\[
f = \frac{L_3 \cos \alpha \sin(\beta - \theta)}{(L_3 + L_4) \sin(\beta - \alpha)} F
\]

Table I summarizes the length of each link and movable range of each joint. Weight of the perching device is 640 g. In this prototype, the three fingers were made of aluminum pipe, and the other mechanical parts were made of ABS resin.

**TABLE I**

**SPECIFICATIONS OF THE PERCHING MECHANISM.**

<table>
<thead>
<tr>
<th>Length (L_i)</th>
<th>30 mm</th>
<th>40 mm</th>
<th>30 mm</th>
<th>85 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movable range</td>
<td>(-15^\circ \leq \alpha \leq 30^\circ)</td>
<td>(30^\circ \leq \beta \leq 90^\circ)</td>
<td>(-30^\circ \leq \alpha \leq 15^\circ)</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>640 g</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The hexarotor platform’s flight controller (DJI N3) supplies control signals to the propulsion system based on signals \(\alpha\) as follows. For joint angle \(\alpha\), the position of the joint J1 \((x_1, y_1)\) is

\[
(x_1, y_1) = (L_1 \cos \alpha, L_1 \sin \alpha)
\]

Then, the position of the joint J2 \((x_2, y_2)\) is an intersection of two circles, one is with radius of \(L_2\) and center \((x_2, y_2)\), and another is with radius of \(L_3\) and center \((B, 0)\). This point can be given as a solution to the following simultaneous equations.

\[
\begin{align*}
(x_2 - x_1)^2 + (y_2 - y_1)^2 &= L_2^2 \\
(x_2 - B)^2 + y_2^2 &= L_3^2
\end{align*}
\]

(5)

Using \((x_2, y_2)\), \(\beta\), and \(\theta\) can be calculated as follows.

\[
\beta = \tan^{-1} \frac{y_2 - y_1}{x_2 - x_1}
\]

\[
\theta = \tan^{-1} \frac{x_2 - B}{y_2}
\]

(6)

(7)

By substituting \(\beta\) and \(\theta\) obtained in this way into Eq.(3), the gripping force \(f\) can be calculated.

The link part of length \(L_1\) and \(L_2\) has a boost mechanism (or a toggle mechanism), and pushes the long link on the right side with a force larger than its own weight. This force is reduced by the balance of \(L_3\) and \(L_4\) and used as a gripping force. By properly selecting these design parameters, it is possible to generate a gripping force larger than its own weight. Fig.4 shows a simulation analysis of \(\beta\), \(\theta\), and \(f\) for changing \(\alpha\). It can be seen that as the values of \(\alpha\) and \(\beta\) approach, \(f\) increases sharply. In the design of the prototype in this study, when perching into a cylinder with a diameter of 114 mm, each joint angle is \(\alpha = 25^\circ\), \(\beta = 46.4^\circ\), and \(\theta = 8^\circ\), and the gripping force \(f\) is approximately 3.3 times its own weight \(F\).

C. System structure

A block diagram of the entire system is shown in Figure 6. The hexarotor platform’s flight controller (DJI N3) supplies control signals to the propulsion system based on signals...
from receivers that receive control commands from remote operators. In addition, the output of the RGB-D camera (Intel Realsense D435) attached to the bottom of the parting mechanism is sent to the onboard computer (AAEON UP board) and used for image analysis for positioning with respect to the target. The result can be used to control the flying robot via the flight controller. ROS was used for communication between the onboard computer and the flight controller.

### III. Vision System

In order to automatically position a target cylinder and realize perching, it is effective to measure the relative position error between the target and the flying robot with a vision sensor. For this reason, the proposed mechanism is equipped with an RGB-D camera.

In the perching operation, positioning is performed with respect to the target under the flying robot. Therefore, it is desirable that the camera be mounted downward on the bottom of the flying robot. Therefore, a camera was installed between the three fingers of the perching mechanism so that the position of the target with respect to the center of the aircraft could be easily measured (Fig.7).

An RGB-D camera (Intel Realsense D435) is used to enable simultaneous acquisition of monocular color images and depth images. Fig.8 shows the time series of camera output images during perching operation. The color image is convenient when the color of the object is used for recognition or when the remote control operator confirms the object. On the other hand, depth images are useful for detecting and positioning perching targets. As shown in the right column of Fig.8, the cylinder, which is the target of perching, is higher than its surroundings, so it can be easily detected in the depth image and can be used for positioning the flying robot. In the depth image on the 4th line, the distance of the cylinder cannot be measured because the target cylinder is too close to the camera. The measurement range of the depth camera used this time could not be measured at a distance closer than 20 cm. If the flying robot can be positioned above the cylinder at a distance of 20 cm, it can descend to the upper part of the cylinder with almost no change in position, so there is no problem in performing the perching operation.

### IV. Experiments

The perching experiment was carried out outdoors. The target cylinder used in the experiment was a vinyl chloride pipe with a diameter of 114 mm and a height of 1.8 m. The experiment was carried out manually while the operator directly visually observed the flying robot.

Fig.9 shows the results during perching. A flying robot flew from the sky, approached the target, and descended from directly above. When the tip of the target hit the bottom of the flying robot, the three fingers of the perching mechanism passively closed and grabbed the cylinder. After that, even if the propeller was stopped, the aircraft was stably fixed to the upper part of the cylinder.

When the propeller was rotated again and the propulsion force became larger than its own weight and the flying robot was lifted, the cylinder was separated from the bottom of the flying robot and three fingers were passively opened. The
flying robot smoothly separated from the cylinder and was able to fly again (Fig.10). Since the opening and closing operations of the three fingers of the perching device are automatically performed when the bottom surface of the flying robot comes into contact with the object, the operator does not have to worry about the opening and closing timing.

Fig.11 shows how the flying robot lands on a flat ground. The fingers of the perching mechanism are open during flight and remain in contact with the ground during landing. Like the general landing gear, it was able to support the flying robot in a stable manner.

V. ROBUSTNESS IN PERCHING BEHAVIOR

The proposed perching mechanism closes with three fingers interlocking. This operation produces the effect of aligning the center of the airframe with the center of the cylinder when perching is started with the target cylinder slightly deviated from the center of the airframe. At the start of perching, it is assumed that the center of the airframe $C_r$ and the center of the cylinder $C_o$ are offset by $\delta$ (Fig.12). It was experimentally investigated to what extent $\delta$ showed the effect of alignment. In the experiment, perching was performed while changing $\delta$ by 10 mm from 10 mm to 70 mm.

As a result of the experiment, when $\delta$ was 40 mm or less, the success rate of perching was 100%. When $\delta$ was 50 mm, 60 mm, and 70 mm, the success rates of perching were 75%, 50%, and 0%, respectively (Table.II). From this, it was found that when the misalignment is less than 50 mm, the alignment effect in perching can be expected. Having a margin for such perching-capable alignment leads to the robustness of the perching operation.
VI. CONCLUSIONS

In this study, we proposed a passive perching device equipped with a mechanism to convert its own weight into gripping force. By stopping the propeller after perching, battery consumption can be reduced, which is especially effective when waiting is required for the desired task. The device can be used not only as a perching on top of a cylindrical target, but also as a landing gear for landing on level ground. By introducing a boost mechanism, a gripping force larger than its own weight can be generated and the aircraft can be stably fixed, so it can be applied to the implementation of complicated and long duration aerial work. In this study, assuming perching to the tip of a cylinder, the structure is composed of three fingers. The proposed passive mechanism can be configured to be suitable for perching into a horizontally placed cylinder or prism by changing the number and arrangement of fingers. Furthermore, by attaching a flexible part such as a rubber sponge to the fingertip, not only the frictional force can be improved, but also the shape of the perching target can be adjusted to improve the gripping performance.

As a vision system, an RGB-D camera was placed in the middle of the lower part of the aircraft for automatic positioning. This makes it easy to measure the error between the position of the target and the position of the aircraft. This camera may be used not only for positioning, but also for contact determination based on the brightness of the entire field of view. Autonomy of flying robots using these visual systems, state sensing during perching, and application to aerial work are future tasks.

REFERENCES