2024 IEEE International Conference on Robotics and Automation (ICRA 2024)
May 13-17, 2024. Yokohama, Japan

Autonomous Perching on Flat Surfaces for Free-Flying Robots with Gecko Adhesive Gripper

Daichi Hirano[1], Nobutaka Tanishima[1], and Tony G. Chen[2]

***Abstract*— Gecko-inspired adhesives have the advantage of being able to grasp and release flat surfaces in a vacuum using their microwedge structures. This makes them an especially attractive solution for perching on and grasping flat objects in space for free-flying robots. To grasp and anchor onto these flat surfaces, the gripper must ensure contact between the gecko adhesives and the surface before applying the appropriate forces to activate their adhesion. However, in the case of a free-flying robot in microgravity, physical contact with the surface induces reaction forces, causing the robot to quickly bounce away from the surface. To solve this issue, we propose a simple passive mechanism and a control method of a robotic arm on a free-flying robot with a gecko adhesive gripper. The gripper utilizes a single-motor controlled tendon-driven mechanism mounted at the end of a robotic arm equipped with controllable stiffness joints and a linear spring-damper system. A free-flying robot on an air-bearing platform can successfully perch on a flat surface with a velocity of up to 72.5 mm/s and with an approach angle misalignment of up to 33.0 degrees.**

I. INTRODUCTION

Robotic grippers with gecko-inspired adhesives are able to grasp flat or gently curved surfaces, which are normally difficult to impose a force or a form closure constraint on. Directional gecko-inspired microwedge structures allow us to turn on and off the adhesion by applying and removing the shear load on the adhesive. Several researchers have proposed solutions with such controllable gecko-inspired adhesives to grasp objects [1]-[4], climb walls [5][6], and perch on surfaces [7]. In particular, space applications with gecko-inspired adhesives have also been studied for capturing a free-floating object and anchoring on a large spacecraft in microgravity [8]-[11]. Furthermore, gecko-inspired adhesive materials have been validated for use in space in a reusability test [12], a thermal vacuum test [13], and on the International Space Station (ISS) [14][15]. This research builds on previous investigations to explore a gecko-inspired adhesive gripper in space applications, particularly for a free-flying robot to perch on a flat surface on walls and devices in the ISS, as shown in Fig. 1. This enables a different modality for traditional free-flyers, to be able to perch on walls to perform monitoring tasks stably without complicated maneuver control that causes acoustic noises and consumes power.

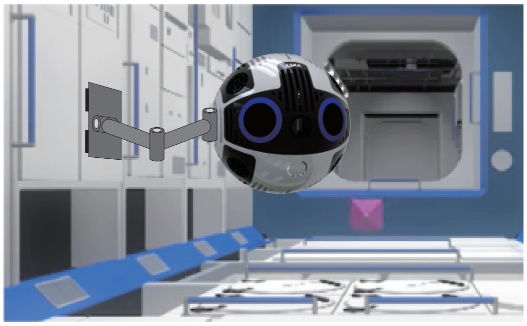

Fig. 1. Concept image of a free-flying robot Int-Ball2 perching on a flat wall using a robotic arm and a gecko adhesive gripper in the ISS.

To utilize the adhesion of gecko adhesives, the gripper must carefully align the adhesives against the target surface, providing a small normal force before activating the shear force. However, in the case that a robot and/or a target object are free floating in microgravity, we must address such alignment and contact carefully to prevent rebound. To this end, we propose a free-flying robot's control scheme utilizing a newly designed tendon-driven gripper along with a suspension and a passively controlled robotic arm, which enables the robot to autonomously perch on a flat surface without rebounding in microgravity. The mechanism and control of the robot arm are designed independently from the robot's primary propulsive control; therefore, they can be easily integrated into existing free-flying robots in the ISS with simple propulsive force control.

Contributions: This paper presents the design of the proposed gripper and robotic arm, detailing its mechanism and control scheme. Furthermore, we introduce a theory to predict an allowable approaching velocity to inform the control strategy of the free-flyer. A mission scenario for a camera-equipped free-flying robot called Int-Ball2 is also introduced as a practical utility example of this technology. Most importantly, unlike previous investigations that focused on the demonstration of gecko adhesives in space with limited trials, the effectiveness of the proposed technique was experimentally validated with a wide variety of different initial velocities and angular misalignments on an air-bearing table. This is crucial for building confidence in the use of gecko adhesive technology in space, paving the way for future applications outside the ISS.

II. RELATED WORK

A. Gecko-Inspired Adhesive Grippers

Gecko-inspired dry adhesives have developed significantly over a decade, and have been studied extensively in many

---

This work was supported by JSPS KAKENHI Grant Number JP19K14955.

[1] D. Hirano and N. Tanishima are with Research Unit II, Research and Development Directorate, Japan Aerospace Exploration Agency (JAXA), 2-1-1 Sengen, Tsukuba, Ibaraki, 305-8505, Japan. `hirano.daichi@jaxa.jp`, `tanishima.nobutaka@jaxa.jp`

[2] T. G. Chen is with the Department of Mechanical Engineering, Stanford University, Stanford, CA, 94305, USA. `agchen@stanford.edu`

979-8-3503-8457-4/24/$31.00 ©2024 IEEE

robotic applications. Although there exist several types of gecko-inspired adhesives, including mushroom-tip adhesives [16], directional dry adhesives have a controllable form of adhesion that is activated by an applied shear force on the contact surface and are deactivated by removing the applied shear force. This allows the gripper with these directional gecko adhesives to grasp and release gently.

Various grippers that use such directional adhesives have been proposed in different applications. For example, simple parallel grippers lined with gecko adhesives can lift delicate objects without squeezing [1][2]. However, since these grippers exploit gravity to produce the shear load to activate adhesion, they are unsuitable for space application in microgravity. Other examples include a soft gripper in [3] and a soft exoskeleton gripper with gecko adhesives in [4]. Although these grippers achieve a versatile grasp of complex shapes, they cannot grasp objects that are too large to pinch or envelop. There are also grippers designed for curved surface grasping proposed in [1] and the underactuated gecko adhesive gripper in our previous research [18]. These grippers can grasp objects of a broader range of sizes using flexible gecko adhesive films that adapt their shape according to the target object. However, this exact adaptability makes these flexible gecko adhesives unsuitable for grasping completely flat surfaces. The same adhesive can be attached to a more rigid backing such as fiberglass or aluminum for flat surface grasping [14][15].

B. Space Applications

Gecko-inspired adhesive grippers have several attractive features for space applications. First, the gripper can capture a larger target with only a small contact area, making the grasping system compact and lightweight, reducing launch and maneuver costs. Second, the gripper has the capability to grasp common spacecraft features such as a flat surface on solar panels and a curved surface on the rocket's fuel bodies, which are very effective for capturing a noncooperative target without specifically designed docking structures. In fact, several grippers for orbital servicing and space debris removal have been studied in [8]-[11].

In recent years, several free-flying robots have worked to assist astronauts and perform experiments in the pressured sections of the ISS [19]-[21]. Gecko adhesive grippers for NASA's free-flying robot, Astrobee, have been developed and demonstrated successfully on the ground [22]. This gripper was also launched to the ISS, and a pull-off force of the gripper perched manually on a flat aluminum plate was measured using a force gauge [15]. However, autonomous perching using Astrobee was not demonstrated.

The gripper presented in this paper is also designed for free-flying robots to perch on a flat surface in the ISS. It utilizes a tendon-driven mechanism, which allows a single actuator to control the activation and deactivation of the adhesion. The proposed robotic arm serves as a suspension, enabling the gripper to align gently on a target surface and mitigating the rebound after a dynamic perching maneuver. This makes it possible to autonomously grasp and anchor to a flat surface without coordinated thrust force control of a robot's main body.

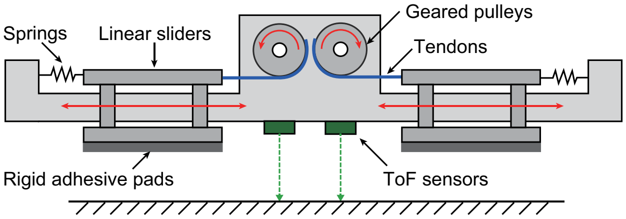

Fig. 2. Mechanism of the tendon-driven gripper with gecko adhesive pads on linear sliders. The single actuator can apply and remove the shear loads via the tendons.

III. MECHANISM DESIGN

A. Design Requirements

The design principles and requirements for the presented gripper and its robotics arm are described in this section. First, the gecko adhesive pads must contact the grasping surface before applying the shear force to activate adhesion. This means that any angular misalignment between the gripper and the grasping surface during the approach can result in a grasp failure. Therefore, a mechanism designed to passively conform to the grasping surface to ensure the contact between the gecko adhesives and the grasping surface is preferred. Second, the kinetic energy of the relative velocity between the free-flying robot and the surface must be absorbed for any perching maneuver, which leads to a damping system that reduces the peak impulse force and mitigates rebound. Additionally, the gripper needs to detect that the gecko adhesive pads are contacting the surface in order to apply the shear force to activate adhesion. When detaching from the surface, the gripper must be able to release the grasped surface, which is accomplished by removing the applied shear force.

B. Gripper

The proposed gripper mechanism is illustrated in Fig. 2. The rigid adhesive pads are attached to two separate sliders, opposite each other. These sliders allow the adhesive pads to move linearly on a main frame through tendons connected to pulleys. The pulleys are synchronized by a gearing mechanism and controlled by a single motor. The tendons are pre-tensioned by extension springs to avoid slack and excessive degrees of freedom. Two Time-of-Flight (ToF) proximity sensors are mounted on the gripper's face to measure the relative distance between the gripper and any surface. These sensors serve two purposes: to detect the exact moment of contact between the gecko adhesive pads and the surface and to calculate the angular alignment between the gripper and the surface. After contact, adhesion can be activated by turning the pulleys to pull the gecko adhesive pads inward, thus applying the necessary shear force. To release the gripper from the grasped surface, the shear force is removed by simply removing the torque applied on the pulleys. Therefore, the on/off of the adhesion can be easily controlled by a single actuator.

C. Robotic Arm

The gripper is mounted at the end of a robotic arm that consists of passive rotational joints and a spring-damper

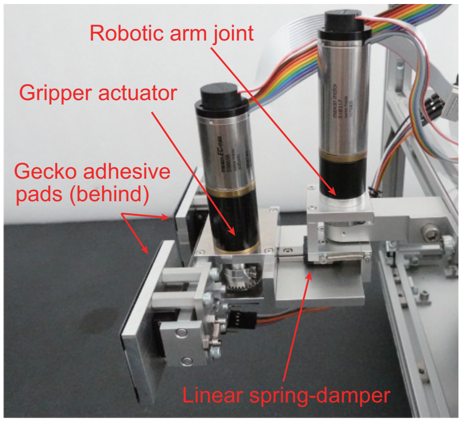

Fig. 3. Mechanism of the robotic arm with the gecko adhesive gripper. The gripper was connected through the linear sliders with the spring and damper.

system, as shown in Fig. 3. This robotic arm serves as the suspension for the gripper, with a back-drivable motor and gear systems that allow for passive alignment between the gripper and the grasping surface. A simple PD controller with a maximum torque limit is used to control the joints. The spring-damper suspension system is used to dissipate excess kinetic energy during the perch maneuver. Low stiffness springs are chosen for two primary reasons: (i) making the contact duration longer, which helps to cover the timing error from the ToF sensors, and (ii) decreasing the rebounding force, which needs to stay lower than the maximum normal force generated by the gecko adhesive.

D. *Motion Sequence*

Fig. 4 shows the grasping motion sequence. In the first step (A), the gripper, mounted on a free-flying robot, approaches the flat target surface with constant velocity. Once contact is made with the surface in step (B), the joint rotates passively so that the gripper aligns with the surface. Subsequently, in step (C), the gripper is continuously pushed into the surface by the inertia of the moving robot while absorbing the robot's relative velocity with the spring-damper system, thus providing the necessary normal force for the adhesives to engage. In step (D), the gripper detects that the relative distances measured using the ToF sensors are equal to zero, which means that the gecko adhesive pads have made contact with the target surface. Then the shear forces on the gecko adhesive pads are immediately loaded to activate adhesion. A remarkable feature of this approach is that thrust control of the robot's main body is not needed during the grasping phase, and the only required control input to the robot is the initial velocity to approach the target surface. With the gripper and this motion sequence, existing free-flying robots inside the ISS can grasp and anchor to any flat surface.

E. *Maximum Approaching Velocity*

This section derives the maximum approach velocity for successful grasping, which determines the initial control input of the free-flying robot.

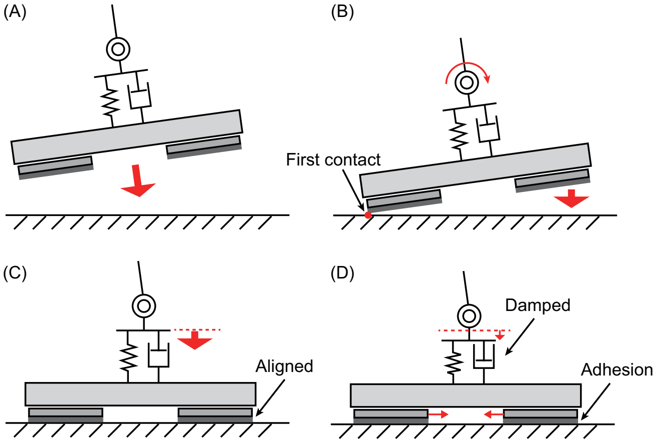

Fig. 4. Gripper's motion sequence to anchor at a flat surface. The proposed system allows the gripper to passively adapt its attitude after first contact, and absorb the relative velocity for activating the adhesion.

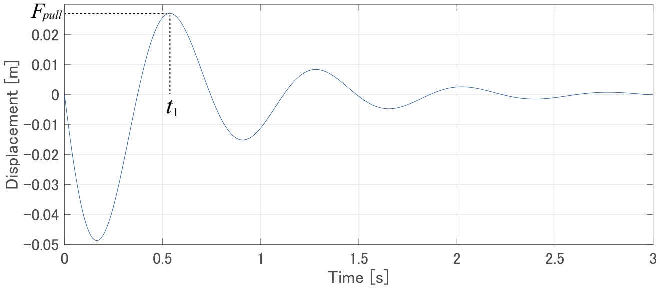

Fig. 5. Position profile of the underdamped system with an initial velocity. The pulling force is required during the displacement is positive.

The linear motion perpendicular to the surface is modeled approximately as a simple mass-spring system with robot mass m, damping coeffecient c and spring stiffness k. The displacement from the equilibium point $x(t)$ of the underdamped system can be derived from the initial conditions (i.e. $x(0) = 0$, $\dot{x}(0) = -v_0$) as follows:

$$x(t) = -\frac{v_0}{\omega_d} e^{-\zeta\omega t}\sin(\omega_d t), \tag{1}$$

where v_0 stands for the initial contact velocity, ζ denotes for the damping ratio given by $c/2\sqrt{mk}$, ω indicates the natual frequency given by $\sqrt{k/m}$, and ω_d is given by $\omega\sqrt{1-\zeta^2}$. An ideal position profile of this system is depicted in Fig. 5. In this profile, the girpper's pulling force is required during the displacement is positive. When there is muximum displacement at the $\frac{3}{2}\pi$ phase ($t_1 = \frac{3\pi}{2\omega_d}$), the required pulling force F_{pull} is largest, and its value can be expressed as follows:

$$F_{pull} = -kx(t_1) = \frac{kv_0}{\omega_d}\exp(-\zeta\omega\frac{3\pi}{2\omega_d}). \tag{2}$$

When F_{pull} exceeds the maximum adhesion provided by the gecko adhesives, the grasp fails, causing the gripper to bounce off the surface. To prevent this from happening, the initial velocity of the free-flyer and the spring stiffness should be as low as possible to decrease the magnitude of this force. However, this is a balancing act, as a spring with lower stiffness needs a longer travel to absorb the same amount of kinetic energy, thus increasing the size and mass of the suspension. Then, from (2), the maximum allowable initial

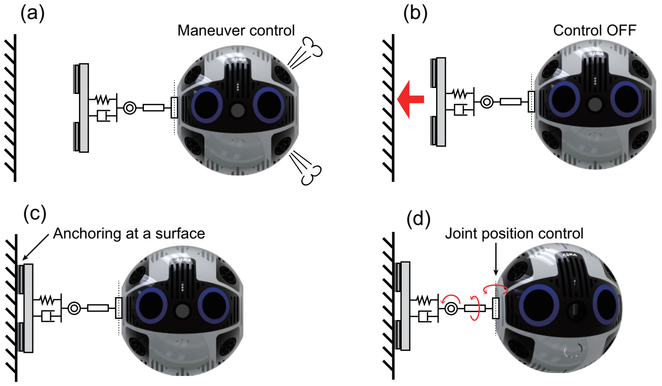

Fig. 6. Control sequence of the free-flying robot. After perching on the wall, the camera view direction is adjustable by controlling the robotic arm's joint angles.

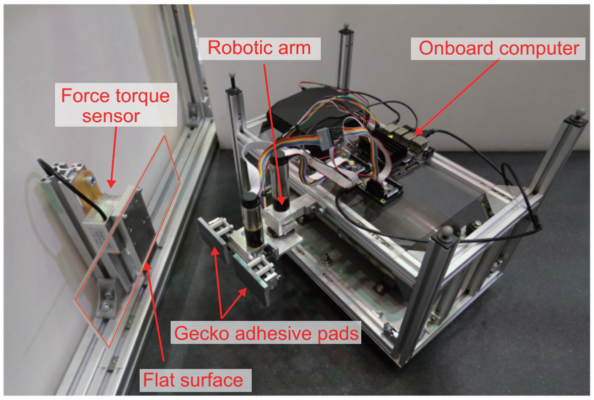

Fig. 7. Experimental setup of the free-flying robot and a flat surface with a force torque sensor.

velocity is given by:

$$v_0^{max} = \frac{F_{adh}^{max}\omega_d}{k\exp(-\zeta\omega\frac{3\pi}{2\omega_d})} \tag{3}$$

where F_{adh}^{max} denotes the maximum adhesive force. This maximum adhesive force is gripper specific and must be measured experimentally.

IV. MISSION SCENARIO

This section discusses a particular mission scenario using a free-flying robot named Int-Ball2. This robot is equipped with propellers for maneuvering in microgravity and utilizes a camera to monitor astronauts' tasks or experiments. To capture images or record video from a fixed point of view, the robot's pose must be kept steady through controls, which can be disturbed by external airflow. This position control consumes the limited battery life of the free-flyer, reducing the operation time while producing noises that disrupt astronauts' daily activity and communication. This problem can be solved by anchoring the free-flyer to a flat surface such as the wall of the ISS, which can be achieved by the presented gripper and motion sequence.

Fig. 6 illustrates a practical procedure for autonomous perching on a wall while controlling the camera view using Int-Ball2. In the first step (a), the robot's attitude is controlled using propeller thrusts to ensure that the gripper faces the wall. Subsequently, the initial velocity for approaching the wall is provided by the propeller thrusts. Once the initial velocity is given, the robot's maneuver control is turned off so that the robot approaches the wall at a constant velocity (step (b)). Autonomous anchoring is performed in step (c) when Int-Ball2 is in contact with the wall. After the perching is completed, in step (d), the camera view provided by the free-flyer can be adjusted through the control of the robotic arm. The aforementioned sequence from the step (b) to (c) is verified experimentally in the following section.

V. EXPERIMENTS

A. Experimental Setup

Fig. 7 shows the experimental setup including a free-flying robot and a target flat surface. The free-flying robot is equipped with air bearings and an air tank containing pressurized air to float up on a flat granite table for planar frictionless motion. The proposed robotic arm is mounted on the robot's main body with the proposed gecko adhesive gripper mounted at the end. Since this experiment is restricted to planar motion, the robotic arm has only one joint, while three joints are required for actual three-dimensional activities in space. The size of the two gecko adhesive pads is 60 mm × 35 mm. The gripper is also equipped with two VL6180X sensors as proximity ToF sensors. Maxon EC-max motors are used as actuators to control both the robotic arm and the gripper. These motors and sensors are controlled by a Jetson Nano, serving as the onboard computer. The joint is controlled in torque mode with constant stiffness. The total mass of the robot, including a battery, is approximately 7.4 kg with the suspension spring stiffness being 516 N/m and damping coeffecient being 22.0 N/(m/s), which were identified in a static load test and a numerical simulation. An acrylic surface is fixed rigidly to act as the perching target, with a force torque sensor to measure the interactive forces during the perch maneuver. The robot's trajectory is recorded by a motion capture system tracking optical markets placed on the robot.

B. Interaction Force Test

First, the maximum adhesive force is measured experimentally, which determines the maximum approach velocity. In this test, the gripper was initially pressed to the surface to ensure optimal contact between the gecko adhesive pads and the surface. The gripper was pulled manually from the surface until it was detached, with the force and torque sensor monitoring and recording the forces applied. This was repeated 10 times, reaching an average maximum adhesion value of 1.56 N in the normal direction. With this maximum adhesive force, the maximum approach velocity is calculated to be 62.4 mm/s using the results of (3).

C. Autonomous Perching Test

The second experiment is autonomous perching tests. Snapshots of the experiment are depicted in Fig. 8. In (A), the initial velocity was given to the free-flying robot to approach the flat surface. At the first contact in (B), the edge of the gecko adhesive pads made contact with the flat surface.

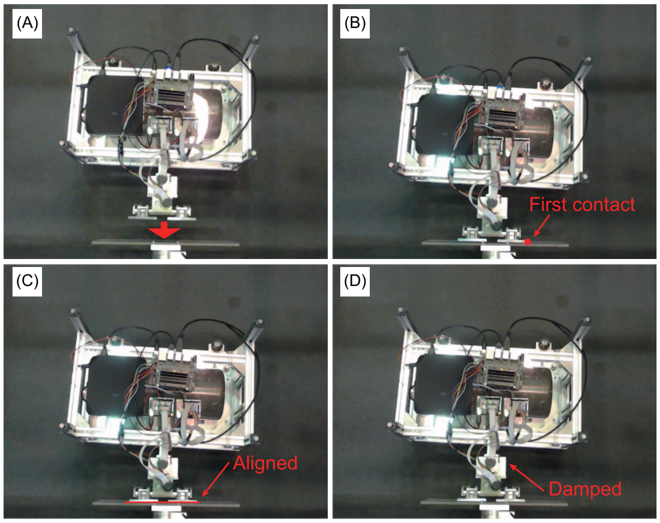

Fig. 8. Snapshots of grasping the flat surfaces. (A) The robot approached the surface. (B) The pad contact to the surface at first. (C) The gripper aligned with the surface. (D) The anchoring was completed by absorbing the relative velocity using the damper mechanism.

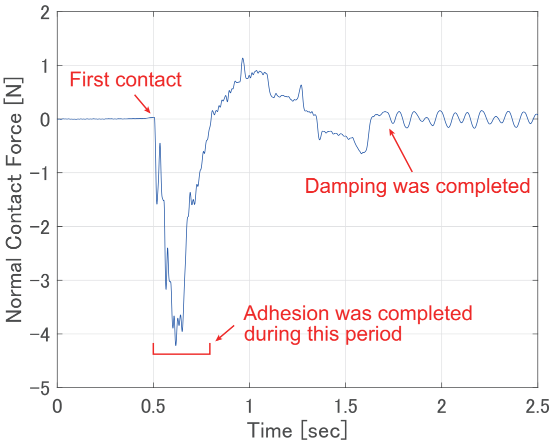

Fig. 9. Normal contact force on the flat surface. The gripper aligned and grasped the surface successfully when the pushing force had been exerted for few hundred milliseconds.

Subsequently, the gripper was rotated passively to align with the surface, as shown in (C). After that, the relative velocity was damped by the robotic arm's mechanism in (D). Finally, the robot was successfully perched on the surface without rebounding.

The force sensor measured the normal force exerted on the flat surface. Fig. 9 shows an example. In this graph, the negative values represent the robot pushing on the surface, while the positive values indicate the force pulled by the gripper. After the initial contact, the robot continued pushing on the surface for a few hundred milliseconds. During this period, the gripper was aligned to the surface, and the adhesion was activated. After this adhesion, the gripper kept in contact with the surface, sustaining the rebound force from the dynamic interaction. After the damping, vibrational force oscillated around a structurally flexible point in the force sensor, intentionally designed elastically to measure low forces sensitively.

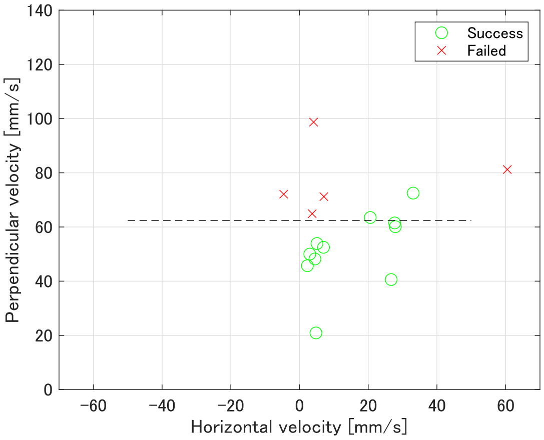

Fig. 10. Grasping results in different contact velocities. Green circles denote successful perching, while red crosses stand for failed cases. A dotted line shows the predicted maximum velocity.

We also performed this experiment with different initial velocities and approach angles, plotting results in Fig. 10. In this figure, the theoretically derived allowable approaching velocity is depicted as a dotted line. This serves as a sufficiency region for successful perching, similar to the concept presented in [23]. A sufficiency region highlights the region with the highest probability of success, in this case, in the velocity space for perching success. When the approach angle is around 0 degrees (the horizontal velocity is nearly 0), the robot has the highest probability of a successful perch when the initial velocity is lower than the estimated maximum approach velocity. This result indicates that our modeling presented in the previous section can effectively predict the maximum approach velocity of the free-flyer. On the other hand, the robot is also tolerant to angular misalignment as shown in Fig. 11, up to 33.0 degrees. These results affirmed that the proposed system can grasp a flat surface robustly even with very limited sensing and control authority. Even when the perpendicular velocity exceeded the predicted maximum approach velocity, perching was successfully performed with large angular misalignment. This is attributed mainly to the fact that the linear momentum is absorbed by the suspension and distributed to the rotational motion of the joint.

Finally, we confirmed that the gripper easily released the surface by reversing the motor. However, during this release process, the remaining adhesive forces are unequally distributed between the two gecko adhesive pads, which slightly induces unfavorable rotating motion into the robot. Consequently, the robot prefers to be maneuvered immediately after releasing the surface, while this control is not addressed in this research.

VI. CONCLUSIONS

This paper introduced a mechanism and control of free-flying robots to grasp flat surfaces using a gecko adhesive gripper driven by a single motor and a tendon-driven mechanism. The proposed gripper and robotic arm system is designed to easily adapt to existing free-flying robots on

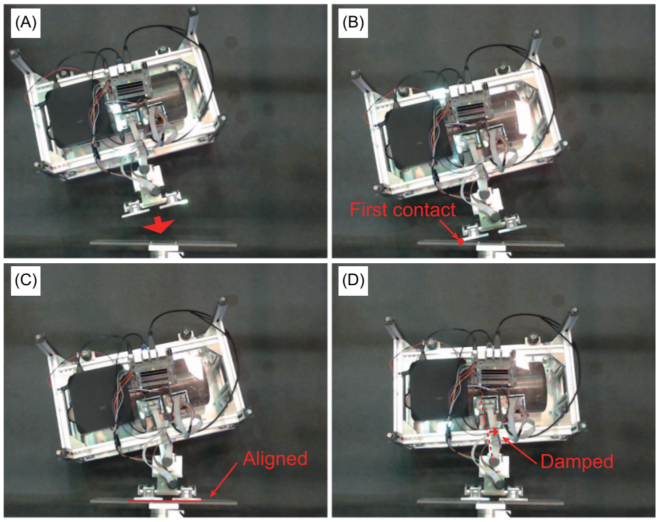

Fig. 11. Demonstration to grasp the flat surface when the approach angle was 33.0 degrees. The motion sequence from (A) to (D) was the same as in Fig. 8.

the ISS. Our approach allows autonomous perching on a flat surface without complex control. Furthermore, we derived the maximum allowable approaching velocity, which is an important parameter for a suitable initial velocity control of the robot. The actual performance of the proposed method was experimentally demonstrated on a planar microgravity test platform using air bearings. These tests validated that the proposed mechanism and control were capable of grasping a flat surface without rebounding even when there were errors in the approaching velocity and direction.

Future work includes improving the hardware, namely the accuracy of the proximity sensor to avoid false triggering, and expanding the sufficiency region to further predict perching success. Another future work area includes applying this gripper and robotic arm to an actual free-flying robot in the ISS, upgrading to satisfy hardware's safety requirements and reduce its size and mass for retaining robot's control stability.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI Grant Number JP19K14955. The authors thank Prof. Mark Cutkosky in the Biomimetics and Dexterous Manipulation Laboratory (BDML) and Prof. Marco Pavone in the Autonomous Systems Laboratory (ASL) at Stanford University for providing the gecko adhesive materials and for discussions on the gripper design and experimental evaluation.

REFERENCES

[1] E. W. Hawkes, H. Jiang, D. L. Christensen, A. K. Han, and M. R. Cutkosky, Grasping Without Squeezing: Design and Modeling of Shear-Activated Grippers, *IEEE Trans. on Robotics*, Vol. 34, Issue 2, 2018, pp. 303–316.

[2] J. P. Roberge, W. Ruotolo, V. Duchaine, and M. R. Cutkosky, Improving Industrial Grippers With Adhesion-Controlled Friction, *IEEE Robotics and Automation Lett.*, Vol. 3, No. 2, 2018, pp. 1041–1048.

[3] P. Glick, S. A. Suresh, D. Ruffatto, M. R. Cutkosky, M. T. Tolley, and A. Parness, A Soft Robotic Gripper With Gecko-Inspired Adhesive, *IEEE Robotics and Automation Lett.*, Vol. 3, No. 2, 2018, pp. 903–910.

[4] J. Hashizume, T. M. Huh, S. A. Suresh, and M. R. Cutkosky, Capacitive Sensing for a Gripper with Gecko-Inspired Adhesive Film, *IEEE Robotics and Automation Lett.*, Vol. 4, No. 2, 2019, pp. 677–683.

[5] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, D. Santos, and M. R. Cutkosky, Smooth Vertical Surface Climbing With Directional Adhesion, *IEEE Trans. on Robotics*, Vol. 24, No. 1, 2008, pp. 65–74.

[6] M. A. Estrada, E. W. Hawkes, D. L. Christensen, and M. R. Cutkosky, Perching and Vertical Climbing: Design of a Multimodal Robot, in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA)*, Hong Kong, 2014, pp. 4215–4221.

[7] E. W. Hawkes, D. L. Christensen, E. V. Eason, M. A. Estrada, M. Heverly, E. Hilgemann, H. Jiang, M. T. Pope, A. Parness, and M. R. Cutkosky, Dynamic Surface Grasping with Directional Adhesion, in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, Tokyo, Japan, 2013, pp. 5487–5493.

[8] H. Jiang, E. W. Hawkes, V. Arutyunov, J. Tims, C. Fuller, J. P. King, C. Seubert, H. L. Chang, A. Parness, and M. R. Cutkosky, Scaling Controllable Adhesives to Grapple Floating Objects in Space, in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA)*, Seattle, WA, US, 2015, pp. 2828–2835.

[9] A. Bylard, R. MacPherson, B. Hockman, M. R. Cutkosky, and M. Pavone, Robust Capture and Deorbit of Rocket Body Debris Using Controllable Dry Adhesion, in *Proc. IEEE Aerospace Conf.*, Big Sky, MT, US, 2017, pp. 1–8.

[10] M. A. Estrada, H. Jiang, B. Noll, E. W. Hawkes, M. Pavone, and M. R. Cutkosky, Force and Moment Constraints of a Curved Surface Gripper and Wrist for Assistive Free Flyers, in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA)*, Singapore, 2017, pp. 2824–2830.

[11] H. Jiang, E. W. Hawkes, C. Fuller, M. A. Estrada, S. A. Suresh, N. Abcouwer, A. K. Han, S. Wang, C. J. Ploch, A. Parness, and M. R. Cutkosky, A Robotic Device using Gecko-Inspired Adhesives Can Grasp and Manipulate Large Objects in Microgravity, *Science Robotics*, Vol. 2, Issue 7, 2017, pp. 1–11.

[12] A. Parness, T. Hilgendorf, P. Daniel, M. Frost, V. White, and B. Kennedy, Controllable On-Off Adhesion for Earth Orbit Grappling Applications, in *Proc. IEEE Aerospace Conf.*, Big Sky, MT, US, 2013, pp. 1–11.

[13] M. Henrey, J. Tellez, K. Wormnes, L. Pambaguian, and C. Menon, Sticking in Space: Manufacturing Dry Adhesives and Testing Their Performance in Space Environments, in *12th Symp. on Adv. Space Technologies in Robotics and Automation*, 2013.

[14] A. Parness, Testing Gecko-Like Adhesives Aboard the International Space Station, in *Proc. AIAA SPACE and Astronautics Forum and Exposition*, Orlando, FL, US, pp. 1–7.

[15] T. G. Chen, A. Cauligi, S. A. Suresh, M. Pavone, and M. R. Cutkosky Testing Gecko-Inspired Adhesives with Astrobee Aboard the International Space Station, *IEEE Robotics and Automation Mag.*, Vol. 29, No. 3, 2022, pp. 24–33.

[16] M. P. Murphy, B. Aksak, and M. Sitti, Gecko-Inspired Directional and Controllable Adhesion, *Small*, Vol. 5, 2008, pp. 17–175.

[17] A. Parness, D. Soto, N. Esparza, N. Gravish, M. Wilkinson, K. Autumn, and M. R. Cutkosky, A microfabricated wedge-shaped adhesive array displaying gecko-like dynamic adhesion, directionality and long lifetime, *K. R. Soc. Interface*, Vol. 6, Issue 41, 2009, pp. 1223–1232.

[18] D. Hirano, N. Tanishima, A. Bylard and T. G. Chen, Underactuated Gecko Adhesive Gripper for Simple and Versatile Grasp, in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA)*, Paris, France, 2020, pp. 8964–8969.

[19] T. Smith, J. Barlow, M. Bualat, T. Fong, C. Provencher, H. Sanchez, and E. Smith, Astrobee: A new platform for free-flying robotics on the international space station, in *Proc. Int. Symp. on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS)*, Beijing, China, 2016.

[20] V. Schrödera, R. Regeleb, J. Sommera, T. Eisenbergc, and C. Karraschd, GNC System Design for the Crew Interactive MObile Companion (CIMON), in *Proc. 69th Int. Astronautical Congress (IAC)*, Bremen, Germany, 2018, IAC-18-B3,6-A5.3,2.

[21] S. Mitani, M. Goto, R. Konomura, Y. Shoji, K. Hagiwara, S. Shigeto and N. Tanishima, Int-Ball: Crew-supportive Autonomous Mobile Camera Robot on ISS / JEM, in *Proc. IEEE Aerospace Conf.*, Big Sky, MT, US, 2019, pp. 1–15.

[22] A. Cauligi, T. G. Chen, S. A. Suresh, M. Dille, R. G. Ruiz, A. M. Vargas, M. Pavone, and M. R. Cutkosky, Design and Development of a Gecko-Adhesive Gripper for the Astrobee Free-Flying Robot, in *Proc. Int. Symp. on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS)*, Pasadena, CA, USA, 2020.

[23] T. G. Chen, K. A. W. Hoffmann, J. E. Low, K. Nagami, D. Lentink, and M. R. Cutkosky, Aerial Grasping and the Velocity Sufficiency Region, *IEEE Robotics and Automation Lett.*, Vol. 7, Issue. 4, 2022, pp. 10009–10016.