Concept and Design of the Caging-Based Debris Gripper for PAF Capturing

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ABSTRACT

This paper presents the concept and design of a gripper intended to capture an un-cooperative object, such as a rocket body that became a debris object. The Payload Attach Fitting (PAF) is selected as the grasping point of the debris. The caging technique is used for the capturing method, and form closure is chosen as the holding method of the gripper. Wire actuation is selected for the gripper's actuation mechanism. This paper also introduces the extending mechanism and wire routing design, and the gripper is developed. The performance of the developed gripper's mechanisms are experimentally verified, and PAF capturing was demonstrated to show that the developed gripper satisfies the conceptual design.

1 INTRODUCTION

Space debris has attracted growing attention as one of the problems that must be solved for sustainable space development. Numerous debris objects larger than 10cm are now being tracked, and it is estimated that a much larger number of small debris objects less than 1cm in size also exists. Considering the velocity of such debris on orbit, small debris objects are difficult to avoid or shield against, but collisions with large debris objects must be avoided to prevent a more massive number of small debris objects from being generated. Simulations, such as [1], have shown that Active Debris Removal (ADR) is one of the key elements to prevent the generation of small debris objects and stabilize the future space environment.

As used rocket bodies account for nearly half of the total mass of debris objects existing on the Earth orbit, ADR technology used for the removal of rocket bodies is very effective. JAXA thus selected the upper stage of the H-IIA rocket as one of the candidates of the ADR mission.

Figure. 1 illustrates the brief ADR sequence on orbit.

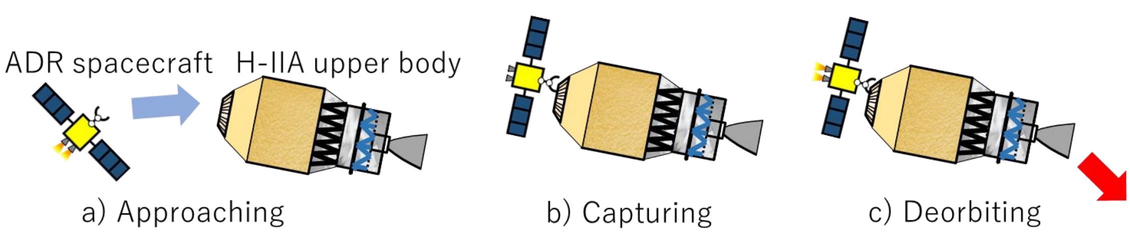


Fig. 1. Sketch of the brief ADR sequence.

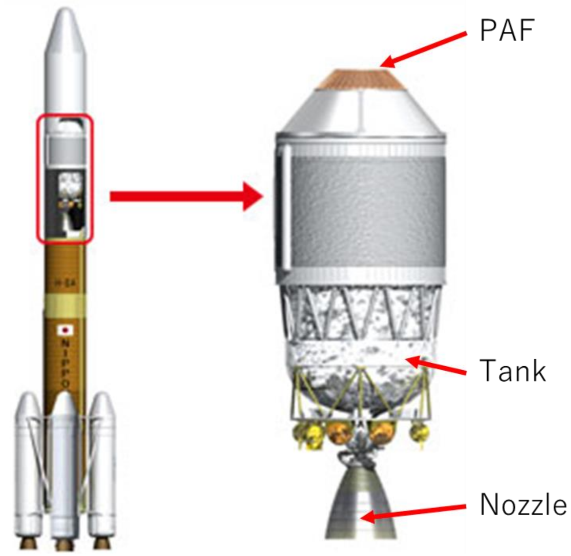
Approaching – The ADR spacecraft approaches the debris object.

Capturing – The gripper is activated to capture the target.

Deorbiting – The ADR spacecraft holds the debris object and deorbit.

As shown in the sequence above, capturing and holding tasks are very important for the ADR spacecraft. This means that gripper technologies that can capture and hold an object are essential. But because the target is an uncooperative object, it does not have an intentionally designed structure that can be grasped on orbit. Moreover, most space debris objects are not capable of being controlled. This makes capturing debris on orbit extremely difficult. Capturing may fail due to position and attitude errors between the ADR spacecraft and the debris object. In addition, the relative velocity and angular velocity may cause capturing failure. In case of failure, the target or the ADR spacecraft could be pushed away and potentially pose a risk of generating another debris.

The grasping point of the uncooperative debris object, which is the upper stage of H-IIA rocket in this study, should therefore be carefully decided. Figure. 2 shows the image and information of the upper stage of H-IIA rocket [2].



Information of the H-IIA upper body	
Length (m)	9.2
Diameter (m)	4.0
Mass (t) without propellant	3.1

Fig. 2. Image and information of the H-IIA upper stage.

The Payload Attach Fitting (PAF) is a mechanical interface that connects a satellite to a rocket at the top of the rocket’s upper stage. Because the PAF has sufficient strength due to its original function, and is easily approachable because there are no other obstacles such as electric components, the PAF is selected as the grasping point of the ADR spacecraft’s gripper.

Considering future ADR missions, it is more efficient to have one ADR spacecraft deorbit multiple debris objects. This means the gripper should be capable of releasing the target. And given the very high cost of launching the spacecraft, a lighter ADR spacecraft is better for cost performance, thereby requiring a simpler system for the spacecraft and a gripper to realize such a lighter ADR spacecraft.

In summarizing the information above, the requirements for the gripper can be described as follows.

- Capable of capturing the PAF, even position and attitude errors, relative velocity and angular velocity existing.
- Does not push the target away during the capture.
- Can hold the PAF while the ADR spacecraft deorbits with the target debris objects.
- Capable of retry considering capturing failure and future ADR mission.
- Simple system.

Various types of grippers have been studied and developed to address the problems of capturing uncooperative object on orbit. Although net capturing system [3] has been verified experimentally, it lacks retry capability. The concept of the Expansion Rod [4] is very unique, but this gripper requires high precision control of both position and attitude. The gecko gripper [5] has exhibited impressive performance in capturing the object, but this largely dependent on surface conditions. [6] is the gripper that has retry capability, but its acceptable position and attitude errors are small. The gripper described in the authors’ previous studies [7] and [8] can capture the PAF even in case of existing position and attitude errors, but these gripper systems are too complicated and cannot satisfy the requirements of this study.

In this paper, we propose the concept of a gripper that can satisfy the requirements for capturing the PAF of H-IIA rocket’s upper stage. Tendon actuation is selected to realize gripper extension and contraction movement with high actuation speed. The detailed mechanism of gripper actuation is also discussed. In this study, experiments were carried out to verify the functions and movements of the proposed mechanisms, in order to show that the proposed gripper satisfies the requirements.

This paper is organized as follows; Section 2 introduces the concept of the gripper. Section 3 explains the mechanisms and designs of the gripper. Section 4 describes the developed gripper in detail and the experimental verifications results, as well as a demonstration of the gripper in capturing the PAF. Section 5 summarizes the contribution of this study.

2 GRIPPER CONCEPT

As mentioned in Section 1, the gripper's main function is to capture a debris objects and then hold it as the ADR spacecraft deorbits. The methods for both capturing and holding are discussed and decided in this section. The concept of the gripper that realizes these capturing and holding methods is proposed at the end of this section.

2.1 Capturing Method

The function of the gripper requires that it capture the H-IIA upper stage's PAF even in case of position and attitude errors existing, as well as relative velocity and angular velocity. The gripper should also avoid pushing the target away, even in case of the contact dynamics between the target and the gripper is unknown. A technique called "caging" is very effective for avoiding those problems. Caging refers to creating a geometrical enclosure around the target without contact, as shown in Fig. 3. This means that larger position and attitude errors are acceptable, and because the gripper geometrically encloses the object without contact, the potential risk of pushing the target away can be eliminated. Therefore, we decided to use the "caging" technique for our gripper.

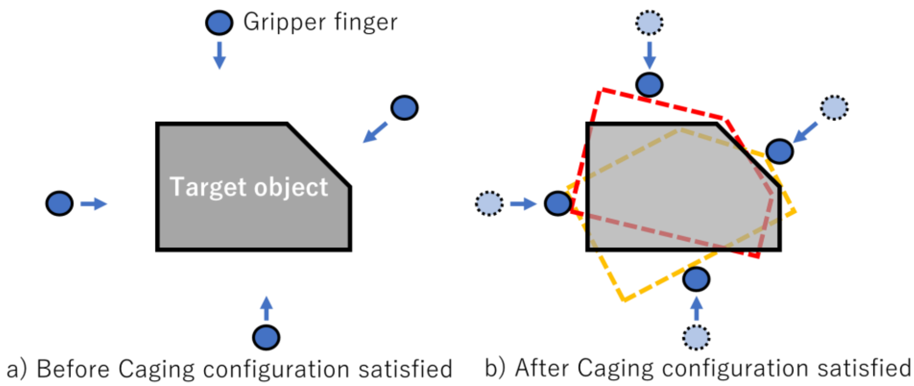


Fig. 3. Gripper fingers moving to satisfy the caging configuration. The target object is geometrically enclosed and cannot move out after the caging configuration is satisfied.

2.2 Holding Method

In general, holding method with physical contact can be classified into two types of method, that are "Force Closure" and "Form Closure". Force closure is the holding method using the equilibrium of forces. In this case, the contact forces used to satisfy the force closure configuration. Form closure is the holding method that geometrically surrounds the object and restrict the object to move and rotate. Figure. 4 illustrates both types of holding methods. As the form closure configuration is not affected by contact dynamics such as friction and restitution, form closure is selected for use as our gripper's holding method.

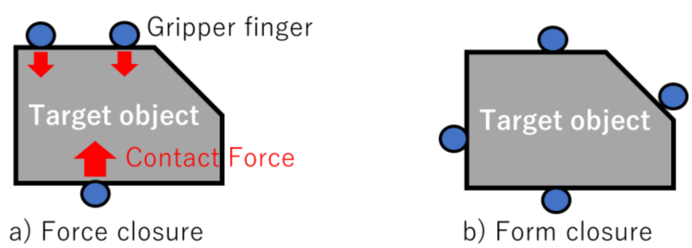


Fig. 4. Force closured configuration and form closured configuration

2.3 *Conceptual Design of the Gripper*

The caging technique is selected for the gripper's capturing method, and form closure is selected for its holding method. As form closure can be satisfied continuously from the caging configuration, both methods have good compatibility. This is because both methods have a common feature of the gripper enclosing the object. However, since the H-IIA is very large object as shown in Fig. 2, the gripper should be larger to satisfy the geometrical enclosure, which is not realistic. As mentioned in Section 1, the gripper's grasping point is the PAF. And considering the geometrical shape of the PAF, capturing from its inner side could realize the capturing and holding methods described in this section, with a smaller size when considering use on orbit. The brief capturing sequence is shown in Fig. 5. The gripper has two or more extending mechanisms, and a V shaped structure is attached at the end of each extending mechanism. The gripper is inserted inside the PAF, and activates the extending mechanism. During the extending mechanism operation, the caging configuration is satisfied. Continuous actuation of the extending mechanism ends with form closure of the PAF.

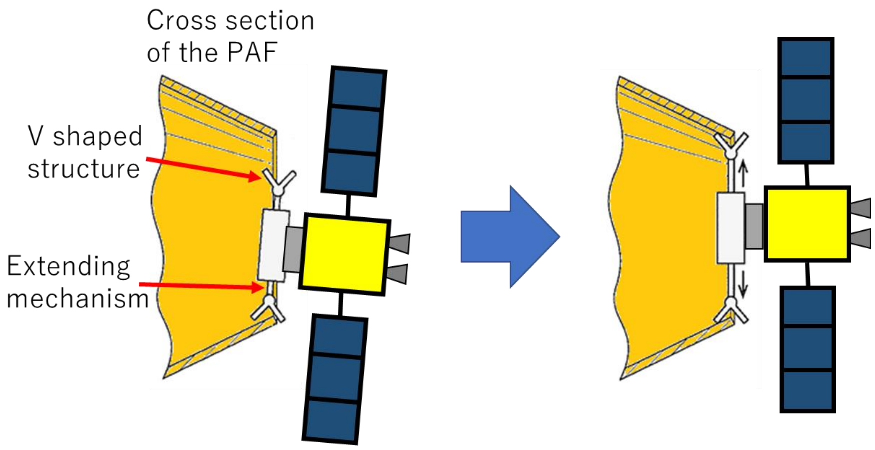


Fig. 5. The brief sequence of the gripper capturing and ends up with form closuring configuration.

The extending ratio of the extending mechanism, and the shape of the V shaped structure determine acceptable position and attitude errors. A larger V shaped structure would accept larger errors, but since the diameter of the PAF is constant, it requires longer extending ratio. Acceptable relative velocity and angular velocity are affected by the extending speed of the extending mechanism. A higher speed of extending mechanism actuation allows for higher relative velocity and angular velocity between the ADR spacecraft and the debris object.

3 MECHANISM DESIGN

3.1 *Gripper and mechanism requirement*

As mentioned in Section 2, the extending ratio of the extending mechanism and the V shaped structure determine the acceptable position and attitude errors. And the extending speed affects the acceptable relative velocity and angular velocity errors.

Table. 1 below lists the target value for the acceptable position and attitude errors, considering the GNC system of the ADR spacecraft.

Table. 1. Target value of the acceptable position and attitude error.

Position error of PAF in-plane direction	±120mm
Position error of PAF out-of-plane direction	160mm
Attitude error	±5deg

To satisfy the target value listed in Tab. 1, the extending length required for the extending mechanism is calculated to be 410mm, with the shortest length being 300mm, and the longest length being 710mm. Considering the acceptable velocity and angular velocity, the extending mechanism's actuation speed is set to less than 1sec.

3.2 Actuation mechanism

There are many candidates for this gripper's extending mechanism. However, not many could be used for spacecraft, and even fewer when considering the requirements for this gripper. Table. 2 below lists the tradeoff results of possible actuation mechanisms for the gripper. To realize a simple system gripper, extending mechanisms that can actuate with a single actuator, without any sensors, are selected.

Table. 2. Tradeoff results of actuation mechanisms.

	Extending ratio	Actuation speed	Retry capability	Weight	Use in space environment
Pantograph	High	Fast	Yes	Heavy	Possible
Rack and pinion	Low	Fast	Yes	Middle	Possible
Worm screw	Low	Slow	Yes	Heavy	Possible
Spring	High	Fast	No	Light	Possible
Belt actuation	High	Fast	Yes	Middle	Impossible
Wire actuation	High	Fast	Yes	Middle	Possible

From the above tradeoff results, wire actuation is selected for the gripper's extending mechanism.

3.3 Design of the wire actuation mechanism

As the extending ratio requirement is set to more than 200%, wire actuation should have more than two stages configuration. Figure. 6 shows a brief sketch of wire actuation to realize the required extending mechanism.

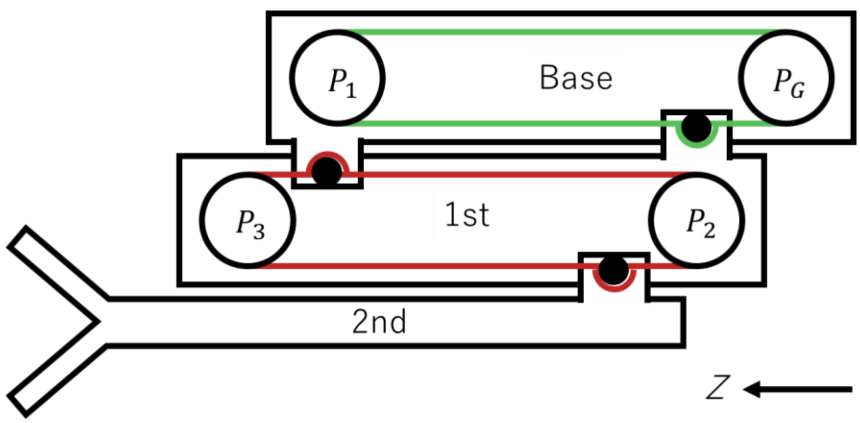


Fig. 6. Brief sketch of the extending mechanism. P_G, P_1, P_2 and P_3 indicated the pulley, red and green line indicate the wire.

As shown in Fig. 6, the extending mechanism consists of three stages. P_G, which is the drive pulley to be rotationally driven by the geared motor, and P_1 is set at the Base Stage of this mechanism. P_1 is connected to the P_G via a wire, and driven by P_G. The 1st Stage is connected to the Base Stage by a slider rail along the extensional direction. P_2 and P_3 are set in this 1st Stage. The 2nd Stage with the V shaped structure at the end is also connected to the 1st Stage by the slider rail. There are no pulleys set in this 2nd Stage. When the P_G is rotated in the CW direction, the green wire in the figure rotates in the same direction as well. Because the 1st Stage is connected to this wire at the bottom side, this stage moves in the extending direction, which is +Z direction in figure, at the same speed. In addition, the red wire is set between P_2 and P_3, and connected to the Base Stage. Because the 1st Stage moves in the extending direction but the red wire cannot move as it is connected to the Base Stage at the top side, 2nd Stage which is connected at the bottom side of the red wire moves in the extending direction, at double the speed of 1st Stage movement.

Therefore, the extending speed and extending force could be described as follows;

$$r\,\omega = v_1 \qquad (1)$$

$$v_2 = 2v_1 \qquad (2)$$

where r is the radius of the P_G, v_1 is the extending speed of the *1st Stage*, and v_2 is the extending speed of *2nd Stage*.

3.4 Configuration of the Extending Mechanisms and Synchronized Actuation

Wire actuation is selected for the extending mechanism, and its design was described above. However, as shown in Fig. 5, this griper requires more than two extending mechanisms. When considering the capture of a free flying object, three extending mechanisms with a V shaped structure at the end would be the minimum configuration for this gripper. To minimize the size of the gripper in the shortest configuration, arranging the each extending mechanism to the out-of-plane direction of the PAF to configurate three layers would be the best design. Figure. 7 shows a brief sketch of the gripper configured with three extending mechanisms. The wire actuation mechanism is used to connect the P_G of each extending mechanism, in order to actuate the gripper with one single motor and realize a simpler system. Figure. 8 shows the brief sketch of the wire routing of each P_G.

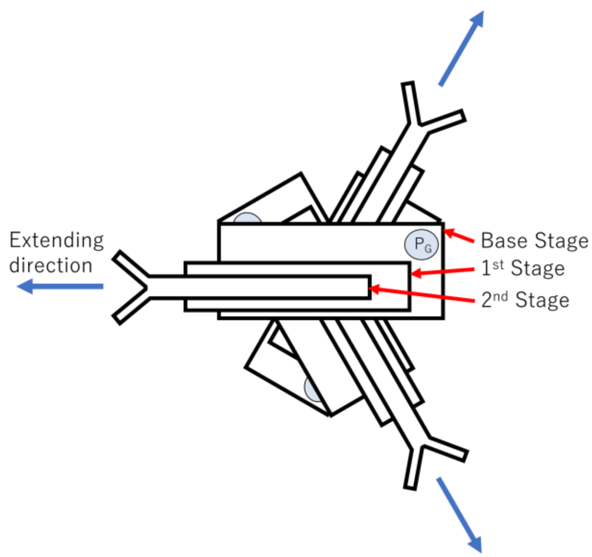


Fig. 7. The brief design of the gripper configurated with 3 extending mechanisms.

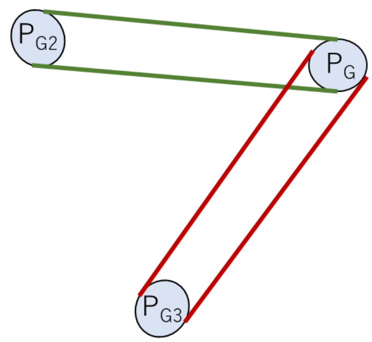


Fig. 8. The brief sketch of the wire routing. The motor connected to P_G drives the P_{G2} and P_{G3} by wire transmission.

4 EXPERIMENTAL VERIFICATION

4.1 Prototype Gripper

Figure. 9 is the image of developed gripper. Since three extending mechanisms are arranged to configurate three layers, V shaped structures were deviated as well to realize the same extending plane in each extending mechanism. A single motor is set to realize the wire routing as shown in Fig. 8, which is 24 W (Maxon Motor).

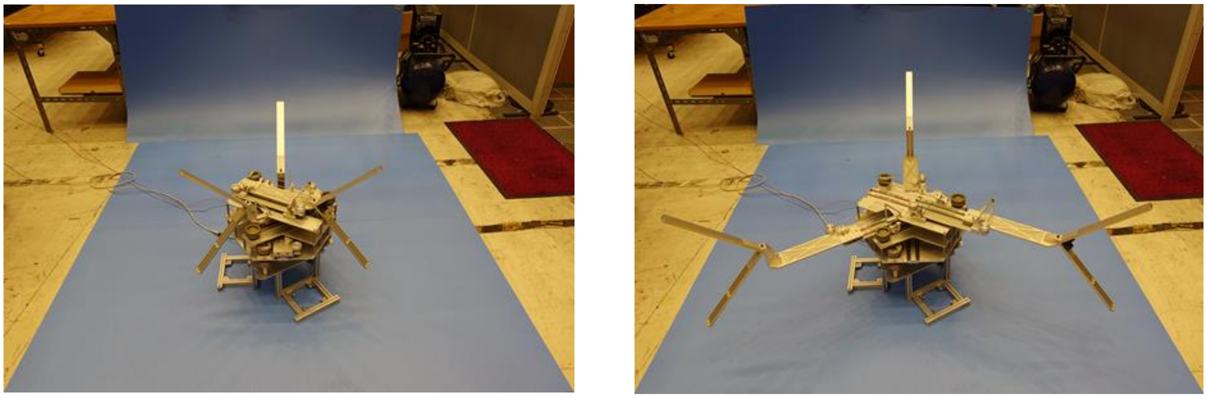


Fig. 9. The image of developed gripper, the shortest (left) and extended (right) configuration.

4.2 Experimental Results of Extending Movement

The experiments were conducted to verify the movement of the gripper prototype. Pulley radius are designed and manufactured to be 30mm, and motor angular velocity is measured by the encoder. The extending speed of 1st and 2nd Stages are measured using motion tracking systems. The result of each mechanisms' extending movement is shown in Fig. 10. As shown in the figure, each extending mechanisms realized an extending length of 410mm, with the same extending movement with a single motor. This figure also shows that the actuation speed was realized in less than 1sec from the shortest configuration to the extended configuration. Figure. 11 shows a comparison of the tracked movement and estimated movement from the motor's encoder of the 1st and 2nd Stage using Eqs. (1) and (2). The result shows that the mechanism moves as designed. However, a slight deviation of estimated and tracked movement can be seen. This is thought to be caused by the motor slipping, resulting in full torque not being transmitted to P_G.

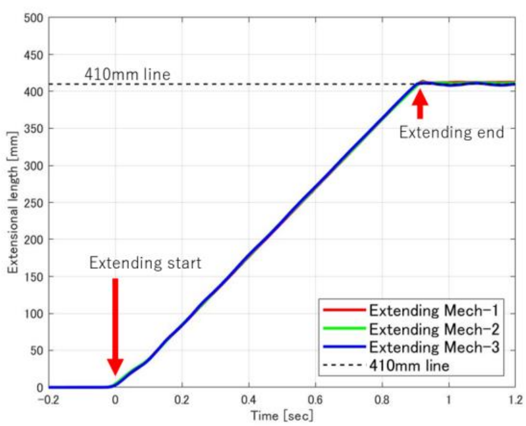


Fig. 10. Result of the tracked 2nd Stage movement of each extending mechanism.

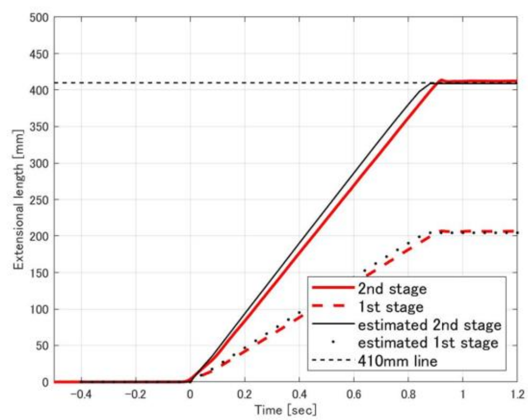


Fig. 11. Comparison of the estimated and tracked 1st and 2nd Stage movement of a single extending mechanism.

4.3 Demonstration

We tested the developed gripper by capturing the PAF, which type No. 1194. For this demonstration, the PAF was fixed to the wall, and the gripper was set on a 6-axis position and attitude controllable table. Figure. 12 shows images of the demonstration. The gripper succeeded in extending the length to capture the PAF, and V shaped structure fits the edge of the PAF, meaning that the developed gripper successfully satisfied the core concept of capturing with "caging-based technique", and holding it by form closure.

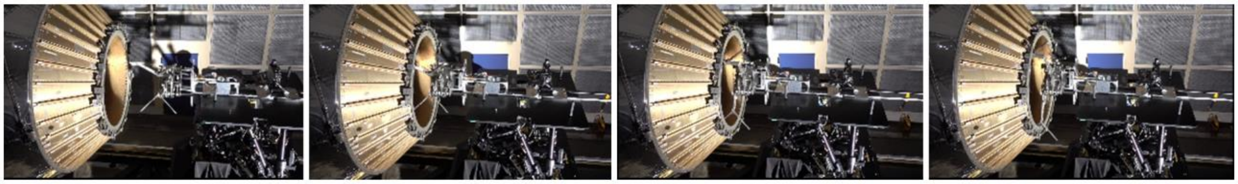


Fig. 12. Images of gripper demonstration capturing the PAF.

5 SUMMARY

This paper introduced concept and design of the gripper to capture the PAF. Since capturing un-cooperative object on orbit is extremely difficult task, the gripper should satisfy the various requirements. Caging based technique and form closure were selected for capturing and holding method of this gripper. These techniques enabled the gripper to capture the PAF without pushing target away even position and attitude errors existing, and also holds the PAF even the contact dynamics are unknown. Wire actuation is selected for actuation mechanism, considering the actuation speed, total mass, and use in space environment. The wire routing design is described and the gripper realizing those mechanisms is developed. The experimental results showed that the extending length, ratio and speed satisfied the requirements. The demonstration of capturing PAF showed that the developed gripper can capture and hold the PAF as designed.

However, since the gripper is manufactured to verify the performance of the gripper, several tasks should be solved to produce the Flight Model, especially the structural design to endure the launch vibration, and thermal design to survive on orbit. In addition, since the PAF is circular shaped, rotational axis cannot be hold by form closuring. These tasks are recognized as our future works of this study.

6 REFERENCES

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