# CONCEPT AND DESIGN OF ROBUSTNESS IMPROVED CAGING BASED DEBRIS GRIPPER(HKK)

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## ABSTRACT

Space debris has been recognized as a social problem. For the safety of space activities, actively removing the large sized debris is known as the effective methods to solve the problem. To realize ADR, capturing and grasping end effector is required. Authors developed Caging Based Debris Gripper (CBDG). Concept model was designed and developed, and its function and mechanism design were experimentally evaluated. However, the robustness was not discussed enough. To solve this problem, the authors developed the next conceptual model (HKK). In this paper, the concept and design of debris end effector HKK is proposed. By reconsidering the equipment configuration, this end effector managed to realize fully redundancy to the 1 failure. The mechanism design to realize this end effector is also introduced.

Keywords: ADR; Capture and Grasp; End Effector.

## 1. INTRODUCTION

As the number of space debris is increasing year by year, this problem cannot be ignored for sustainable space environment and development. A huge number of debris larger than 10 cm in size has been observed, and more debris smaller than 1 cm is expected to be exist on orbit. What is perceived as a threat here is debris of a small size. This is because that the smaller debris cannot be tracked, it is difficult to avoid or shield against due to its velocity. Since the most of the small size debris are generated by the collision of the large sized debris, simulation shown in [1] shows the ADR of large sized debris is the one of the effective method to prevent increasing of the small sized debris. When the total mass of debris objects existing on orbit is considered, nearly half of the mass is the used rocket bodies. JAXA thus selected the upper stage of the H-IIA rocket as one of the candidate of the ADR mission.

Fig. 1 is the image of the sequence of the ADR mission. As shown, ADR satellite approaches to the debris, and capture using its end effector. After the successful capture, end effector should keep grasping while the ADR satellite finish its deorbit phase. Therefore, the role of the end effector can be defined as capture and grasp.

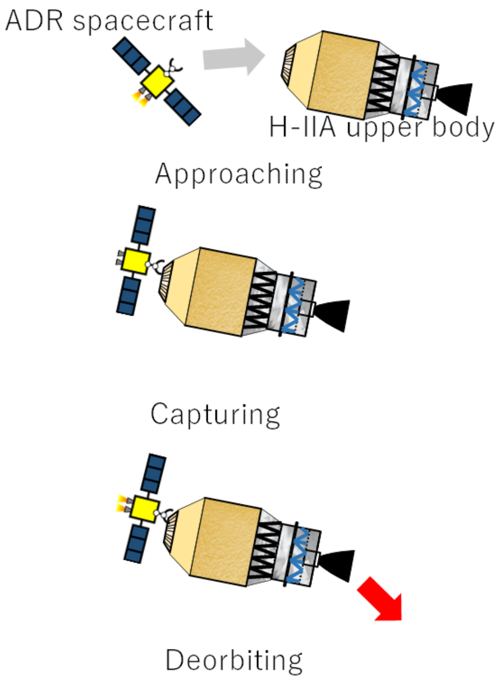


*Figure 1. Image of the ADR sequence*

Since there are no external force such as friction fore on the target that would allow it to remain in place, the risk of pushing the target away is existing. To prevent this failure, the caging technique is selected as a capturing method of the end effector. Caging technique is the capturing method that creates a geometrical enclosure around the target without contact. This means that the risk of pushing the target away can be eliminated even the contact dynamics between the debris and the end effector is unknown.

The grasping method should also be considered carefully because the end effector should keep grasping the target during deorbit phase, even the contact dynamics are unknown, as well. To meet this problem, form closure, which grasp the target by geometrical enclosing, is selected for the grasping method of the end effector.

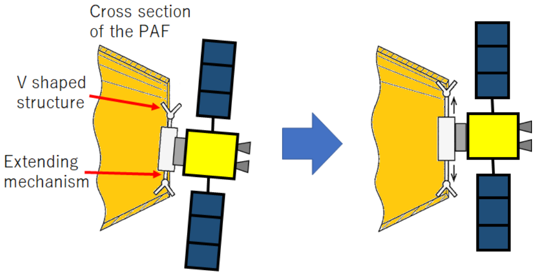


*Figure 2. Image of the ADR concept*

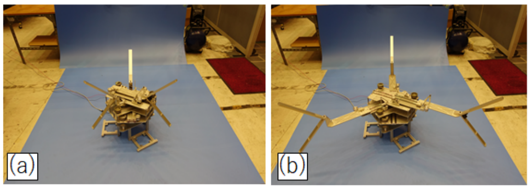


*Figure 3. Image of the developed CBDG-BBM1.*
*(a) Launching configuration (b) Grasping configuration*

PAF, Payload Attachment Fitting, is selected as the capturing and grasping point of the target debris. Fig. 2 shows the concept image of the ADR system with end effector that captures PAF with caging technique and grasp it by form closure. As shown in figure, V shaped structure is attached at the end of the extending mechanism. ADR control itself and insert the end effector inside the PAF. When the end effector is inserted, the extending mechanism will be actuated. Eventually, the caging configuration will be satisfied by the V shaped structure, and form closure will also be satisfied when the extending keep extending until V shaped structure hits the PAF and stop.

Authors developed the end effector named Caging Based Debris Gripper (CBDG), that realizes the described concept of the end effector. Fig. 3 is the image of the CBDG that has been developed [2]. Wire actuation is selected as the extending mechanism, because of its actuation speed, mass and mechanical strength.

Initial experiment of capturing PAF is conducted as shown in Fig. 4. The validity of the capturing, grasping method and concept of the end effector is evaluated by this demonstrative experiment.

However, the experiment also revealed the technical issues that should be solved to use as end effector of the ADR mission, that are

- Fault tolerance design for system safety and more reliable mission success.
- Modification of the actuation mechanism to realize long time grasping without power supply.

Since the end effector system does not designed 1 failure tolerant, any failure of the end effector will lead to the

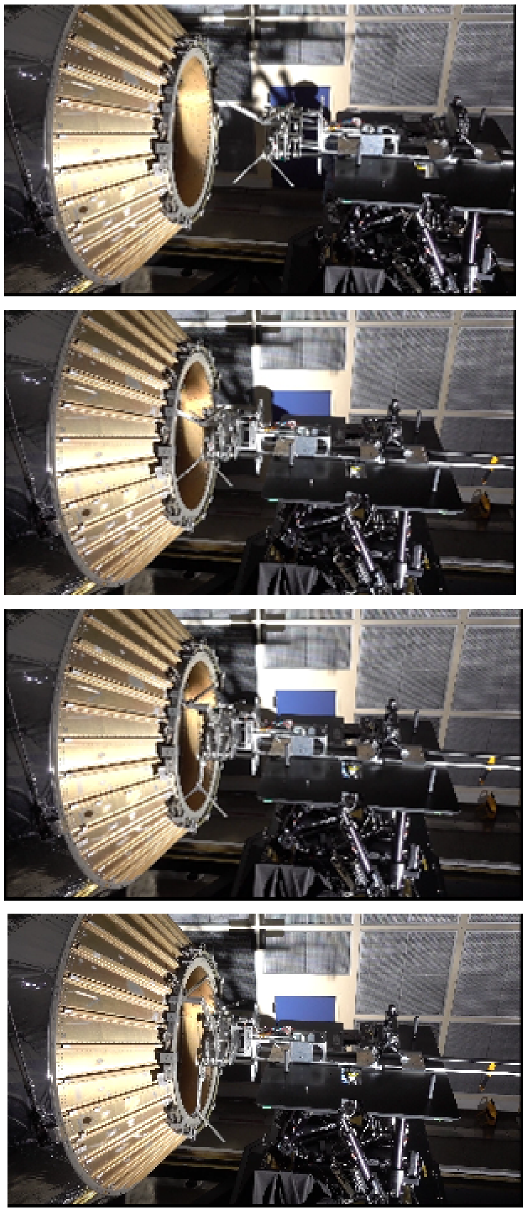

*Figure 4. Initial experiment of BBM1 capturing PAF*

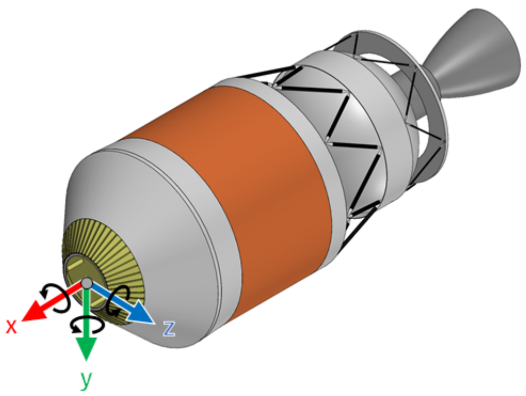


*Figure 5. Coordinate definition. Origin is at the center of PAF.*

mission failure. As for the actuation mechanism, we have confirmed that a form closure is useful, but that is based on the assumption that the extension mechanism is always keep its length. Since CBDG-BBM1 is actuated by the geared motor, unless the braking system is attached, continuous grasping would requires power supply all the way through the long deorbit phase.

In this paper, a new concept of CBDG that solves the technical issues identified above, under the new name of HKK, is proposed. By reviewing the equipment configuration, HKK is designed to be able to tolerate one failure and has improved reliability. The design of the actuation mechanism was also improved, to realize eliminating the need for power supply during the deorbit phase.

Section 1 describes the introduction of this paper and introduces the previous study, CBDG. Section 2 proposes the redesigned end effector, named HKK, to realize 1FO. Actuation mechanism of HKK is discussed in Section 3, and Section 4 summarizes and introduces the future work of this end effector.

## 2. CONCEPT OF HKK

As described in Section 1, initial experimental verification confirmed that CBDG's capturing and grasping functions have sufficient potential to capture PAF. However, fault tolerance design is not designed enough and should be modified considering to use in space. Since the main design concept, caging capture and form closure grasp do not to be changed, the equipment configuration should needs to be changed. In CBDG's case, the number of extending mechanism with V shape structure should be re-considered to satisfy the 1FO requirement.

At first, the successful condition of capturing and grasping should be defined. Fig. 5 shows the coordinate with the PAF center as the origin.

Since the target PAF is a ring shape, capturing and grasping of 5 DoF, except roll direction, are considered in this

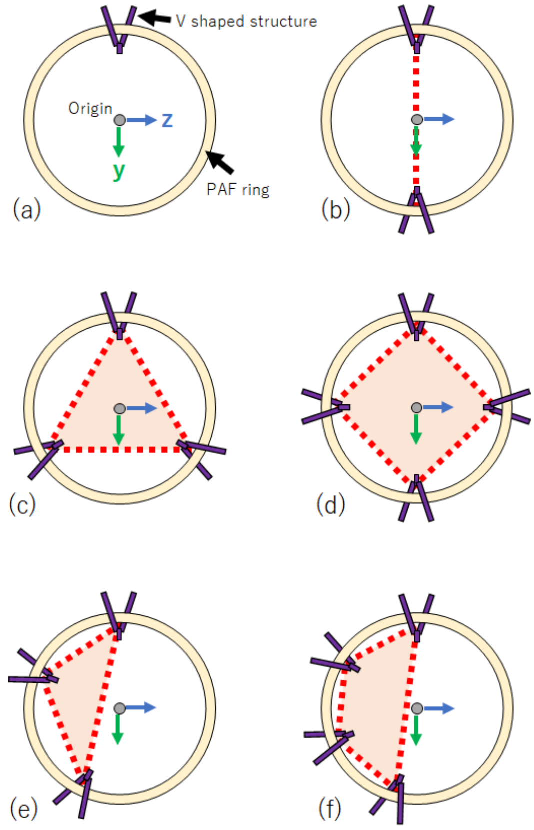


*Figure 6. Configuration of the PAF capturing by 1 to 4 V shaped structure.*

section.

Fig. 6 (a) and (b) show the configuration when PAF ring is captured and grasped by only one, and 2 V shaped structure. Assuming that one V shaped structure can fix the ring in the X-direction, 1 V shaped structure, as shown in Fig. 6(a), this can only grasp and fix X-direction, and the other 4 DoF, Z,Y-direction, Pitch and Yaw is not fixed. Same as in Fig. 6(b) since the grasping point of 2 V shaped structure covers the origin, it fixes the Y, Z-direction and Yaw as well. However, since Pitch is not fixed and can move freely, this does not satisfy the condition of successful capture and grasp.

On the other hand, configuration shown in Fig. 6 (c) and (d) are the successful capture and grasp. In both case, ring cannot move to any DoF (except roll). CBDG-BBM1 uses 3 set of V shaped structure and extending mechanism, which is same as shown in Fig. 6 (c). However, configuration of Fig. 6 (e) and (f) does not satisfy the successful capture and grasp, because the ring can move in YZ plane. This is because the center of the ring, which is the origin, is out of the area shaded in red. This red shaded area is created by connecting the gripping points of each V shaped structure.

From this geometric consideration, the successful capture and grasp of the ring by V shaped structure can be defined

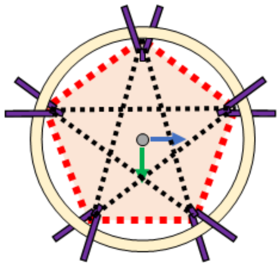

*Figure 7. Configuration of the PAF capturing by 5 V shaped structure. Black line describes the connection of gripping point when 1 set has failed.*

as follows;

- More than 3 set of V shaped structure and extending mechanism.
- Area created by connecting the gripping points of each V shaped structure should cover the center of the PAF ring.

After the successful capture and grasp configuration is defined, CBDG-BBM1's equipments configuration should be redesigned to satisfy 1FO. Since CBDG-BBM1 uses only 3 set of V shape structure and extending mechanism, 1 set of failure results only 2 set of V shaped structure and extending mechanism, which does not satisfy the definition. When 4 set of V shape structure and extending mechanism is considered, one failure may still satisfies the definition of required minimum set of 3, but it does not satisfy the other definition, meaning 4 set is not still enough for 1FO realized design. So, the minimum design that satisfies 1FO would be 5 set of V shape structure and extending mechanism. However, the shape of area created by 5 gripping point should form regular pentagon, as shown in Fig. 7.

However, since the actuation mechanism of CBDG-BBM1 uses only 1 motor to actuate 3 extending mechanism, 5 set of V shaped structure is not enough for 1FO because this motor's failure causes all extending mechanisms to be failure. To avoid this situation, end effector requires more than 2 motors, and 6 set of V shaped structure and extending mechanism. This may cause simply doubles the size and mass of CBDG-BBM1. To minimize the system, the equipment configuration should be considered.

When 4 set configuration is re-considered, as Fig. 7, the shaded area's shape does not have to be square, rectangular would be enough as shown in Fig. 8 (a).

This still not satisfy 1FO design, as well. However, this rectangular area's configuration can be realized by only 2 extending mechanism, as shown in Fig. 8 (b). By integrating 2 configuration of Fig. 8 (b) as shown in Fig. 9 (a), 1FO design can be satisfied with only 4 extending mechanism. Since the same motor can be used to

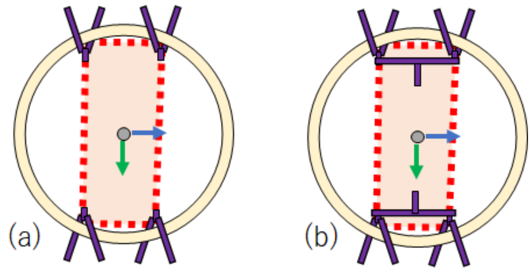


*Figure 8. Configuration of the PAF capturing by 4 V shaped structure.*
*(a) 4 extending mechanism (b) 2 extending mechanism.*

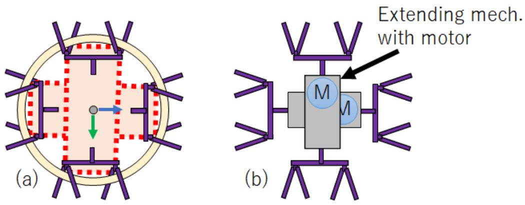


*Figure 9. Configuration of (a) 1FO satisfying V shaped structure, and (b) its equipment configuration.*

operate the extension mechanism in opposite directions, the equipment configuration can be designed as shown in Fig. 9 (b), which satisfies 1FO design.

This is the concept design of next model of CBDG-BBM1. At the same time, the name of this end effector has also reviewed and was named **HKK** by taking the initial letter of the Japanese word for capturing and grasping mechanism.

Fig. 10 is the CAD image of HKK, and Fig. 11 is developed HKK test model. Instead of using 2 V shaped structure at one gripping point as shown in Fig. 8 (b), the thicknes of each V shape structure is increased to satisfy the 4 gripping point with 2 extending mechanism.

## 3. ACTUATION MECHANISM

Since the CBDG-BBM1 is generated by geared motor, this end effector requires continuous power supply to the motor to keep grasping the deorbit phase. However, considering long time deorbit phase, keep supplying the power to the motor is not feasible from the view of ADR satellite's system design. This means that actuation mechanism should contain function that does not back drive even there are no power supply.

Several method can be the candidate to realize this requirement. Such as Motor brake, no back driving gear as [3] and worm gear system [5].

Since the material for the disk of motor brake should be considered and function test should be conducted, motor

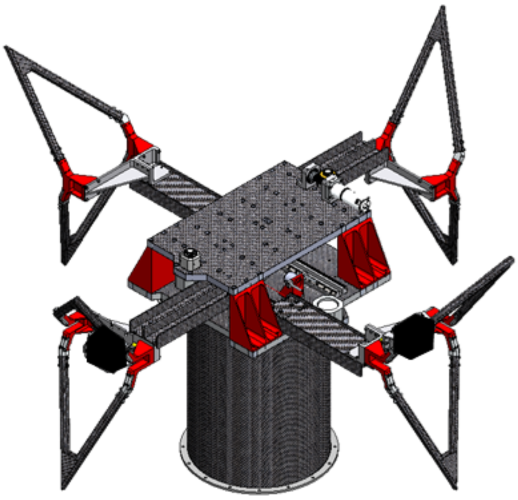

*Figure 10. CAD image of HKK*

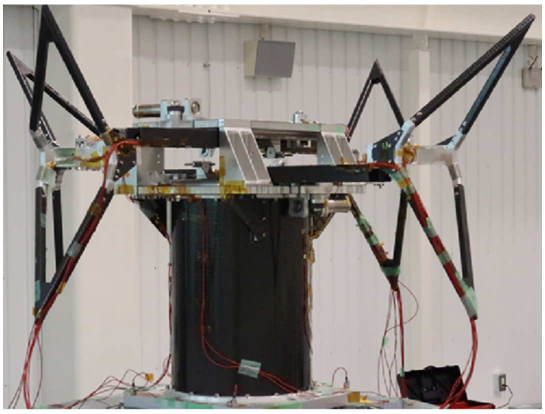

*Figure 11. image of developed HKK*

brake requires several tasks to practical use on orbit environment. Harmonic gear has been used in space [4], but the gear ratio would be large to satisfy the anti-back drive of the system. Since the capturing and grasping target is uncooperative, it is easy to imagine that relative velocity and relative angular velocity between the end effector and the target is large. This means that slow actuation may cause the ADR satellite and end effector move out of capturing range and may cause failure of the mission.

To satisfy the anti-back drive and actuation speed, worm gear system is selected for the actuation mechanism of HKK. When initial back driving efficiency according to Eqs.1 is 0 or smaller, the self lock configuration of the worm gear system is satisfied and worm gear cannot be driven from output shaft.

$$n'_A = (2 - \frac{100}{n_A}) * 100 \tag{1}$$

$n_A$ is the initial driving efficiency, and $n'_A$ is the initial back driving efficiency.

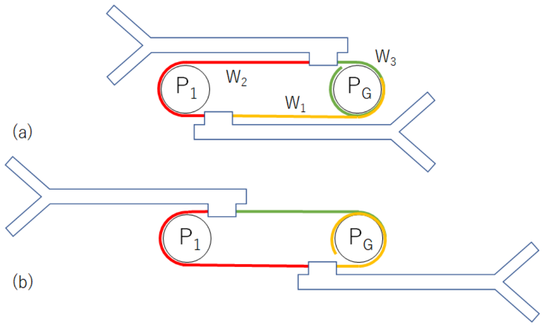



*Figure 12. Wire routing design (a) contractile state (b) extending state*

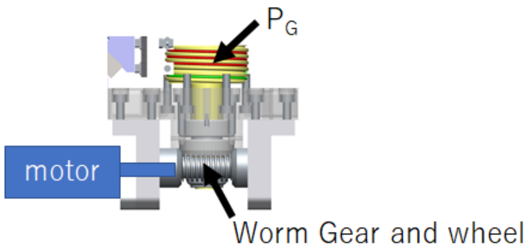



*Figure 13. Cross section of the motor, Pullev $P_G$, and worm gear.*

in this case, $n_A$ can be decided by the tooth lead angle, and minimum gear ration of worm gear system that satisfy $n'_A$ is 0 or smaller, was 40.

Fig. 12 shows the wire routing design of extending mechanism, in each contractile and extending state.

$P_G$ is the actuation pulley, and $P_1$ is the idler pulley. When $P_G$ rotate to CCW direction, $W_1$ will be rolled up by $P_G$ and actuate the bottom side of the boom with V shaped structure to the right direction of the figure. At the same time, $W_2$ pulls the top side of the boom to the left direction of the figure, because this wire connects bottom and top side's boom through $P_1$. $W_3$ will be unrolled same length from $P_G$ as $W_1$ rolled up, meaning the total length of the $W_1$, $W_2$ and $W_3$ do not change. Eventually, the booms movements are mechanically stopped by reaching at the end as in Fig. 12 (b), and this is the end of the extensional movement. This system realizes the same motor operates the extension mechanism in opposite directions, meaning this satisfies the concept design of HKK described in Section 2.

Worm gear is set at $P_G$ as shown in Fig. 13, transmitting the torque and rotational movement of the motor to $P_G$. Since $P_G$ is connected to the worm gear system and cannot be rotated by tension of wire caused by external force, extending length may stays at the same length. This means that continuous grasping can be realized with this design.

## 4. SUMMARY AND FUTURE WORK

In this paper, the needs of end effector for large size ADR is described and previous work of CBDG-BBM1 is introduced. The technical issues that should be solved to ensure the mission is discussed, and new concept of end effector named HKK is proposed. By redesigning the equipment configuration, HKK realized 1FO design. Actuation mechanism design is also reconsidered as well to realize 1FO design of HKK, and worm gear system is selected to satisfy the requirement of power supply during deorbit phase. With the above, Technology Readiness Levels (TRL) of end effector is increased. However, this development status is not enough considering to use in space. Our future work will be to continue improving TRL of this end effector. The design should be considered and applied to pass the mechanical environmental test.

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