C20

スペースデブリ模擬構造への金属製銛撃ち込みにおける銛回転の影響評価

Effects of Rotation of a Metal Harpoon on Penetration Behavior for Capturing Space Debris

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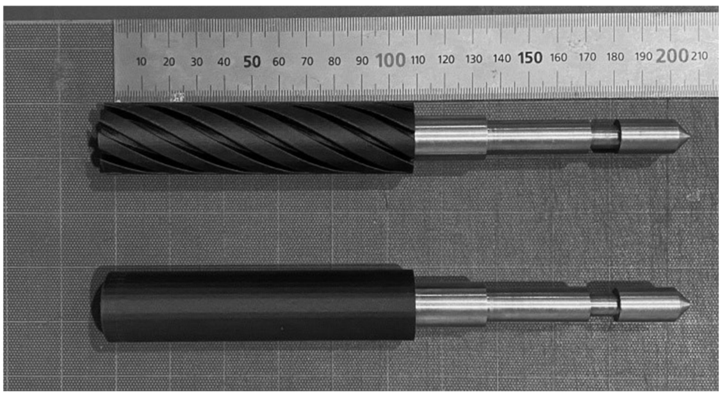
この研究では回転する銛をデブリ模擬構造へ撃ち込み，その貫入挙動を調べた．対象の傾きと先端形状が貫入挙動に大きな影響を与え，場合によっては貫入が難しくなることがあるため，銛自身に回転を加えることで安定した貫入の実現を目指した．
地上での試験のため，溝を有する銛後端部を炭素粉末入りのナイロン素材で作成し，銛に取り付け，その溝を空気が通ることで銛を回転させた．銛の回転により生じるジャイロ剛性により，銛の直進性を増加させる．回転する銛の影響評価のために，比較用として溝のない銛も用意し，0°，30°，45°で傾いた対象に対する銛の撃ち込みを行った．
実験結果から銛の回転数と撃ち込み速度にはおよそ正の相関があることが分かった．傾き角0°，30°における銛の撃ち込みでは貫入挙動に大きな差異は見られなかったが，傾き角 45°における銛の撃ち込みでは貫入速度及び貫入孔の大きさが回転しない銛に比べて小さくなった．

In this study, we shot a rotating harpoon into a structure simulating space debris and investigated its penetration behavior. The penetration behavior greatly depends on the harpoon tip shape and an oblique angle of a target. Hence, we make a harpoon rotate to stabilize the harpoon during the penetration. We installed the special part with grooves made of nylon material with carbon powder to the rear part of the harpoon to rotate the harpoon during the penetration experiments on the ground. The harpoon rotates by air passing through the grooves. The gyro effect is generated by the harpoon rotation, and it increases the stability of the harpoon. We also prepared a harpoon without the groove for comparison and shot the harpoon into the target at the oblique angle of 0, 30 and 45 degrees to evaluate the effect of the rotation of the harpoon. It was observed that there was an approximate positive correlation between the rotation speeds and the injection velocity from the experimental results. There is no difference in the penetration behavior of the harpoon at the oblique angle of 0 and 30 degrees. However, the penetration velocity and the size of the penetration hole by the rotating harpoon were smaller than those of the non-rotation harpoon at the oblique angle of 45 degrees.



Harpoon with grooves and harpoon without grooves

10 th Space Debris Workshop
10 January 2023

Effects of Rotation of a Metal Harpoon on Penetration Behavior for Capturing Space Debris

National Defense Academy of Japan

Department of Equipment and Structural Engineering

Yuto Tamaki and Hiroaki Tanaka

C20
16:45-17:00

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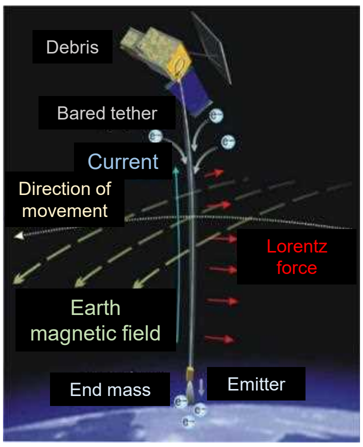
Active Debris Removal (ADR)

- ADR is a method in which a spacecraft equipped debris removal system actively approaches space debris, captures it, and deorbits it. So, orbital environment is gradually improved.

Debris removal system

De-orbit sail ©SSC

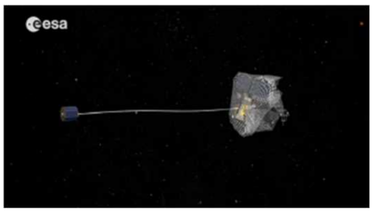
Propulsion system ©ESA



Electrodynamic tether (EDT) ©JAXA

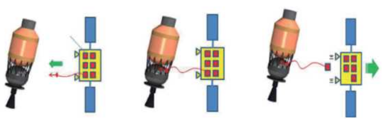
Capturing system

Robotic arm ©ESA

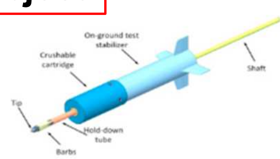


Net ©ESA

Research object



Capture concepts by JAXA

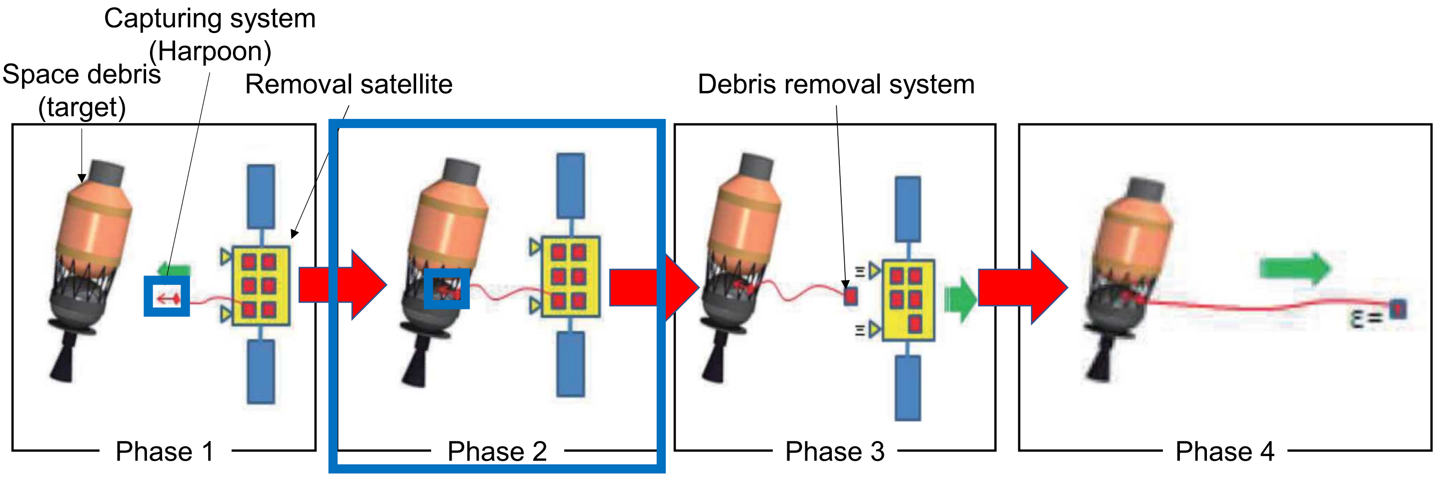


Capture concepts by ESA

Capturing space debris by shooting metal harpoon.

2

Capturing space debris by shooting a metal harpoon



Phase 1: Debris removal satellite approaches a target.

Phase 2: Debris removal satellite mutually pauses against the target, and estimates movement of it, and shoots the tethered harpoon to it.

Phase 3: Debris removal system is separated from debris removal satellite.

Phase 4: The target is deorbited by debris removal system.

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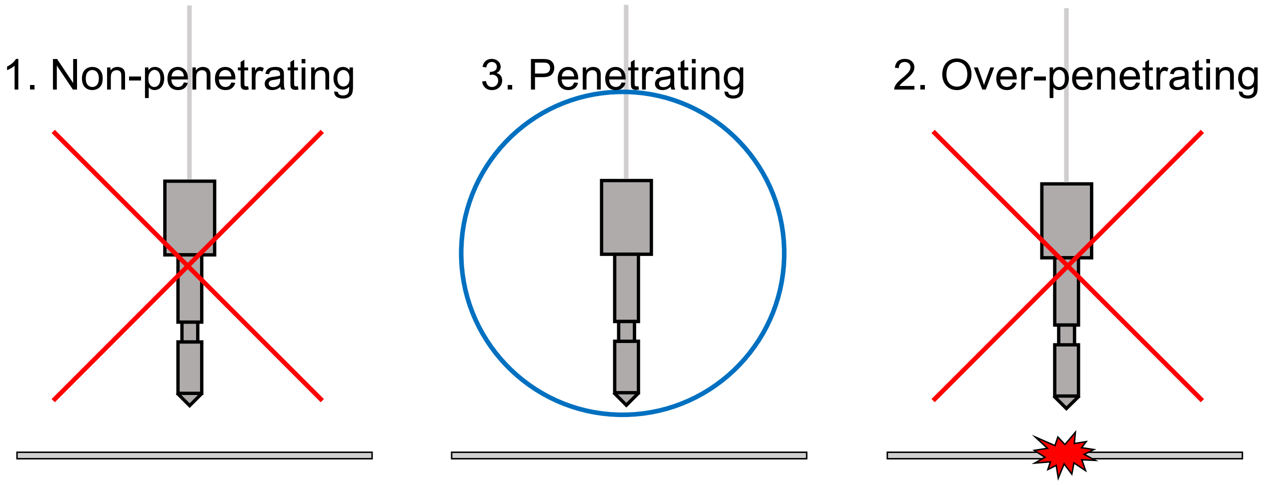
Difference in the penetration states at injection speed

Penetrating state is suitable for capturing space debris because of generating holding force by hooking a narrow section of the harpoon on penetration hole.



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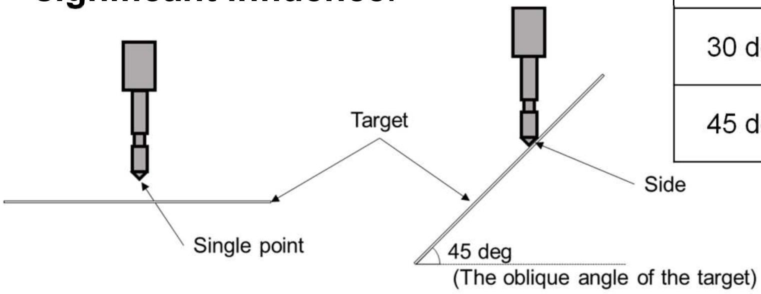
The shooting test of a metal harpoon with various tip shapes in previous study

- The penetration velocity of conical harpoon tip is comparably smaller than that of the other tips but it **increases sharply** at an oblique angle of 45 deg.

⇒The relation the tip shape and the oblique angle of the specimen has a **significant influence**.



The collision of the harpoon with conical tip shape

The minimum penetration velocity of each harpoon (m/s)

Angle	Conical 	Spherical 	Flat 	Double-bladed 
0 deg	16.8	22.7	23.6	15.6 (15.0)
30 deg	17.5	23.3 (22.5)	13.9	15.4
45 deg	**35.2**	44.6*	30.9	17.3

* : Velocity of passing through

※ The velocity in parentheses is the average velocity of the difference between the maximum non-penetration velocity and minimum penetration velocity when the difference is greater than 1m/s.

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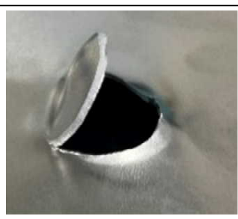
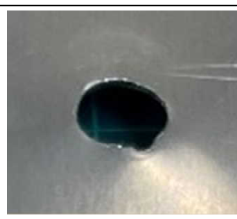
Penetration hole by various tip shapes

Tip shapes	**Conical**	**Spherical**	**Flat**	**Double-bladed**
Penetration hole				
Characteristics	The penetration hole is petaling and pullout resistance is big after penetrating.	The penetration hole is round hole and pullout resistance is not expected after penetrating.	The penetration hole is round hole and pullout resistance is not expected after penetrating.	The penetration hole is round hole and new additional debris is generated.  New additional debris

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Research objective about rotation of the harpoon

The problem of the previous study

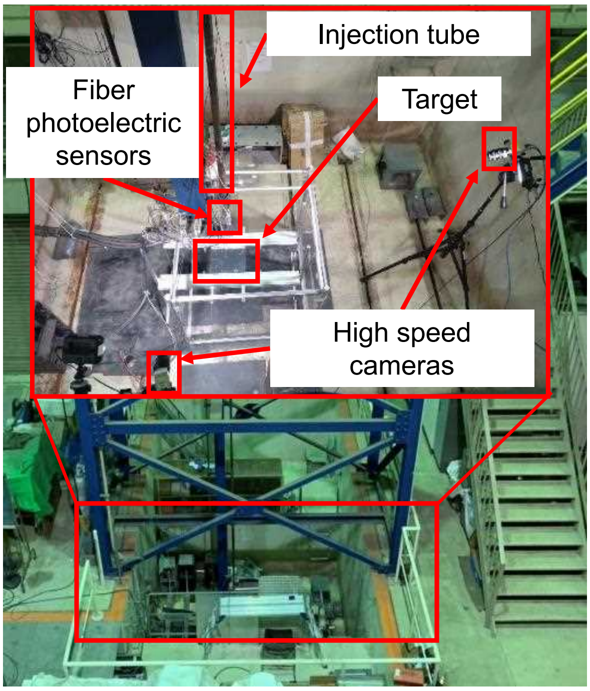
The conical harpoon tip shape is suitable for capturing space debris.
However, its penetration behavior was greatly changed at the oblique angle of 45 deg.

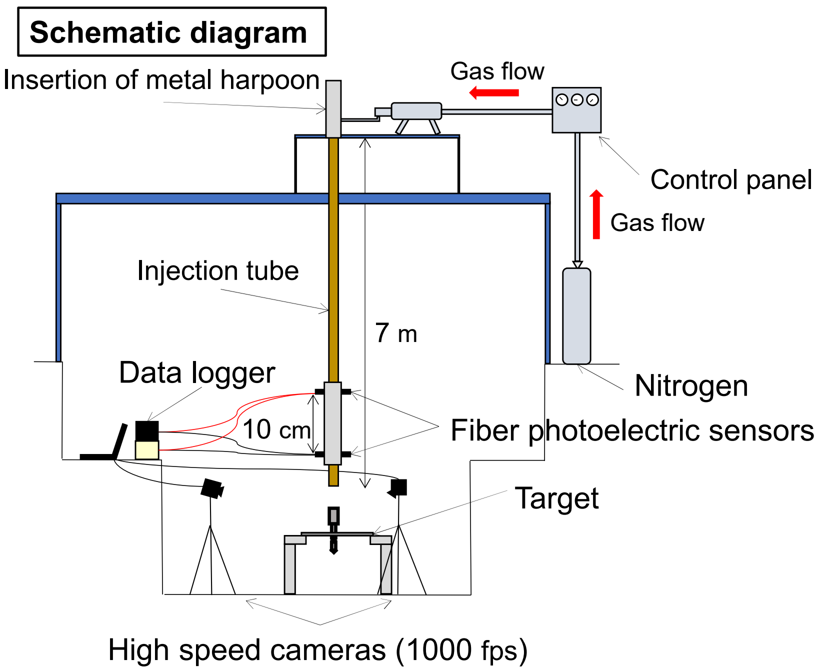
Rotating the harpoon increases its straightness, which is thought to be effective when shooting the target with the oblique angle.

Research objective

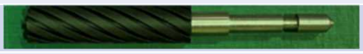
・We develop the system for rotating harpoon for ground test.
・We evaluate the effects during shooting the harpoon by rotating it.

Experimental equipment in National Defense Academy of Japan

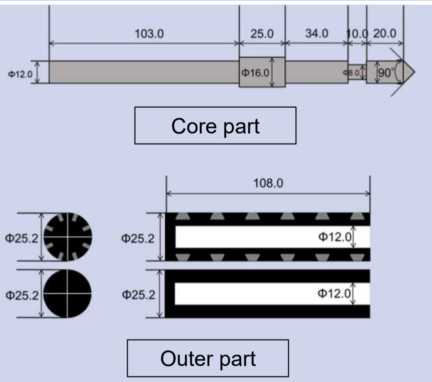




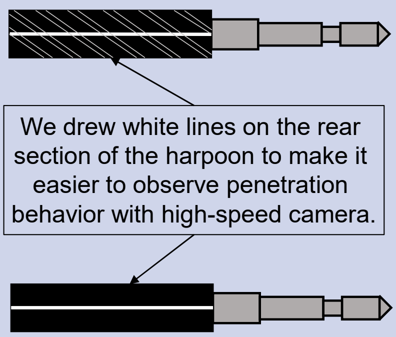
The appearance of a metal harpoon and the structure of the rear part

		Rotation harpoon	Non-rotation harpoon
Material	Core part	Made from SS400	
	Outer part	Made from Onyx (Carbon fiber)	
Appearance			
Mass		200 g	213 g
Inertia momentum		7071.5 $g \cdot mm^2$	8520.9 $g \cdot mm^2$

The size of each component



Schematic diagram after configuration



※ Basic study as ground tests

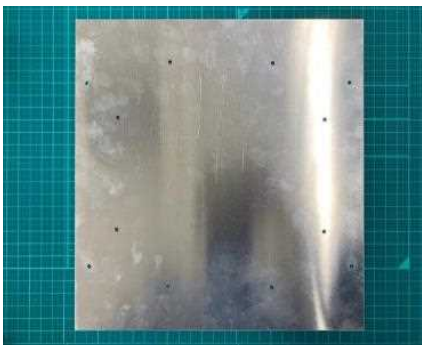
The harpoon rotates by the air flowing through the grooves.

In the experiment, rotation speed is between approximately 700 and 2000 rpm.

Specification of a target and experimental method

Specification of the target

Material	Al2024-T3
Size (mm)	250 × 250 × 1
Density (kg/m^3)	2770

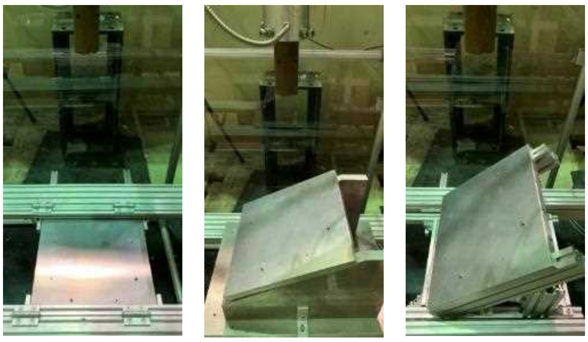


Al2024-T3

Material of space debris is various, but aluminium alloy is commonly used for satellite.

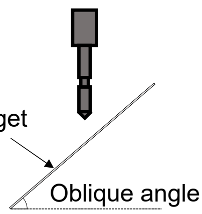
(The target shape is simple because of basic study about shooting the metal harpoon.)

Experimental equipment

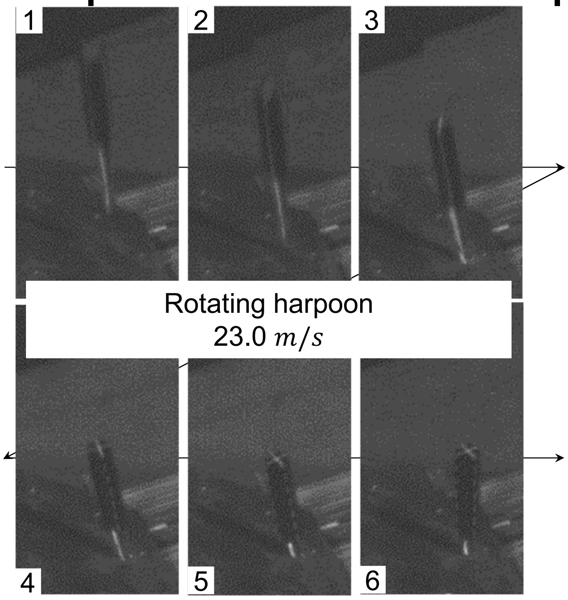


0 deg 30 deg 45 deg

We evaluate penetration characteristics of the harpoon while oblique angle of fixed target was changed.



Shooting tests of rotating and non-rotating harpoons at the oblique angle of 45 deg (1/2)



Rotation of the harpoon generates gyro effect and rotating harpoon penetrates the target stably. On the other hand, non-rotating harpoon is not stable.

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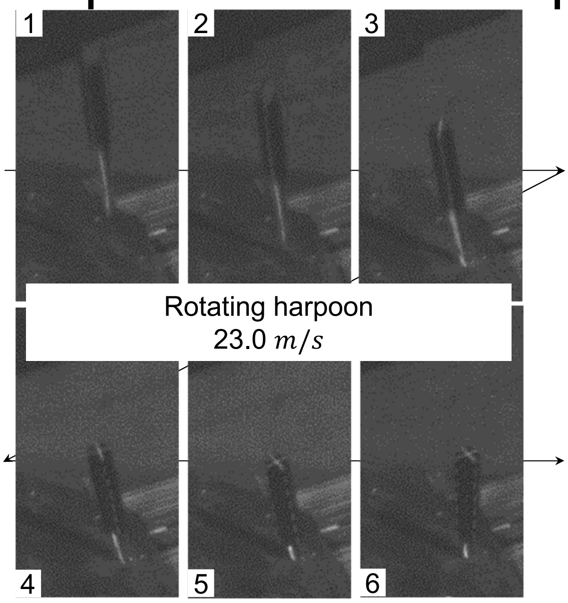
Shooting tests of rotating and non-rotating harpoons at the oblique angle of 45 deg (2/2)



The fact that the non-rotating harpoon is non-penetrating despite its high injection velocity means that the rotation of the harpoon has a significant effect on penetration.

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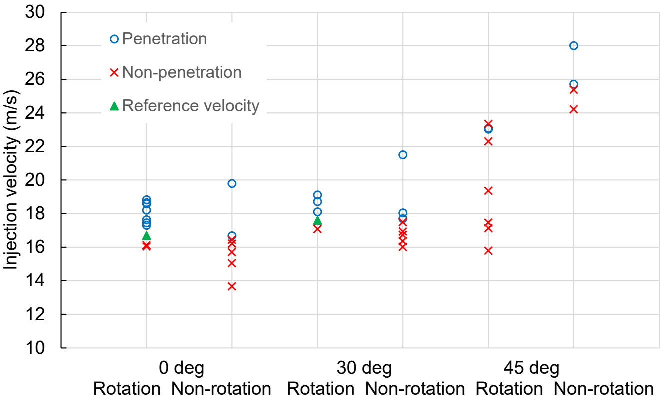
The injection velocity and penetration behavior of each harpoon



The minimum penetration velocity of each harpoon type (m/s)

Angle	Rotating harpoon	Non-rotating harpoon
0 deg	17.3 (16.7)	16.7
30 deg	18.1 (17.6)	17.7
45 deg	23.0	25.7

※ The velocity in parentheses is the average velocity of the difference between the maximum non-penetration velocity and minimum penetration velocity when the difference is greater than 1m/s.

Oblique angle of 0 deg ➡ No difference in the penetration behavior is observed regardless of whether rotation exists.

Oblique angle of 30 deg ➡ Little slippage of the harpoon with the grooves was observed.

Oblique angle of 45 deg ➡ The difference of the penetration velocity is 2 m/s and harpoon rotation has effects on the penetration behavior.

The effect of penetrating was improved by using harpoon rotation.

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Size of penetration hole for each harpoon type

Penetration hole by **rotating harpoon**

Penetration hole by **non-rotating harpoon**

➡ We think penetration hole of non-rotating harpoon is **bigger** than that of rotating harpoon because the posture of non-rotating harpoon is not stable after penetrating.

The narrow section of the harpoon hooks on the penetration hole during pulling out the harpoon. Therefore, rotating harpoon is expected to increase pullout resistance.

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Conclusion

・We developed the system for rotating the harpoon for ground test.

・The rotating harpoon penetrates stably due to the gyro effect.
⇒The penetration hole and penetration velocity of the rotating harpoon are smaller than that of the non-rotating harpoon.

↓

The rotation of the harpoon is effective for improving penetration behavior.

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Thank you for your kind attention.
Please let me know if you have any question.

Mail: ed22003@nda.ac.jp

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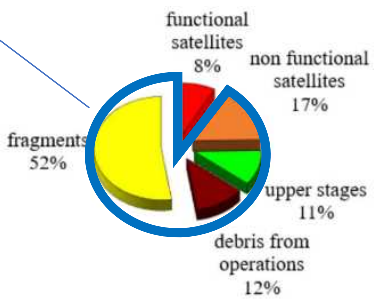
Artificial objects in earth orbits

- Since space development has been rapidly progressed, there are many problems of space debris because the objects orbiting the earth have not been properly disposed of in the past.

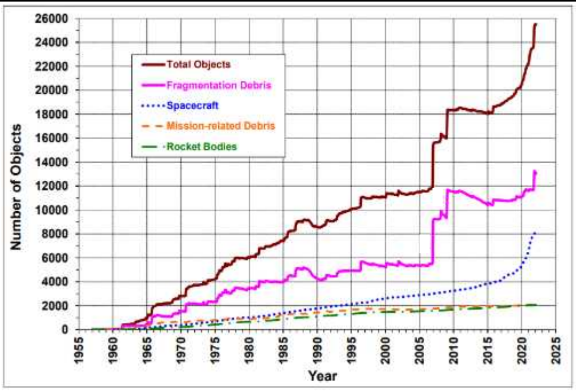
Space debris is mainly

① Fragmentation	③ Mission-related Debris
② Spacecraft that have completed their mission	④ Rocket body

92 % of the objects orbiting the earth is space debris.



Source：Committee on the Peaceful Uses of Outer Space, Scientific and Technical Subcommittee, February 2019

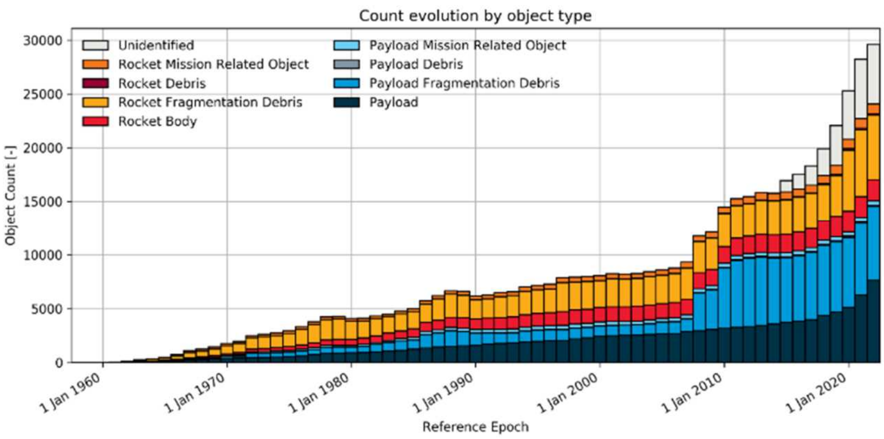


Catalogued debris (more than 10 cm)

Source : NASA Orbital Debris Quarterly News, Volume 26, Issue 1, March 2022

Space debris orbits at high speed. When it collides with spacecrafts, they will be greatly damaged. 17

The number of space debris



The number of observing objects
About 23,000 objects

Rocket Mission Related Object + Payload Mission Related Object + Rocket Debris + Payload Debris	6%
Rocket Fragmentation Debris + Payload Fragmentation Debris	56 %
Rocket Body	9%
Pay load	29 %

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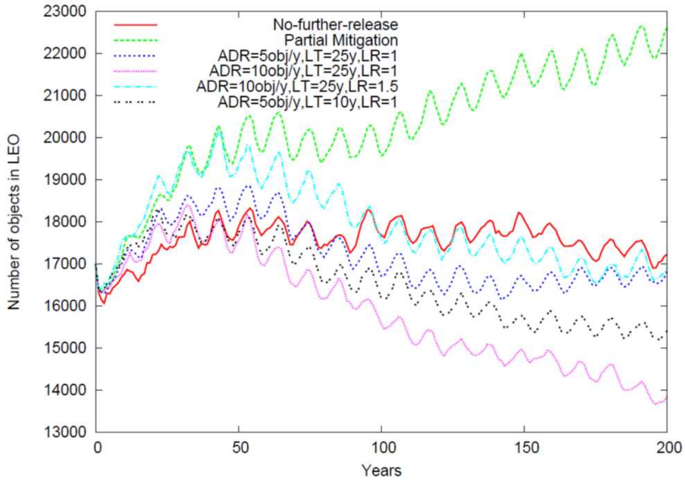
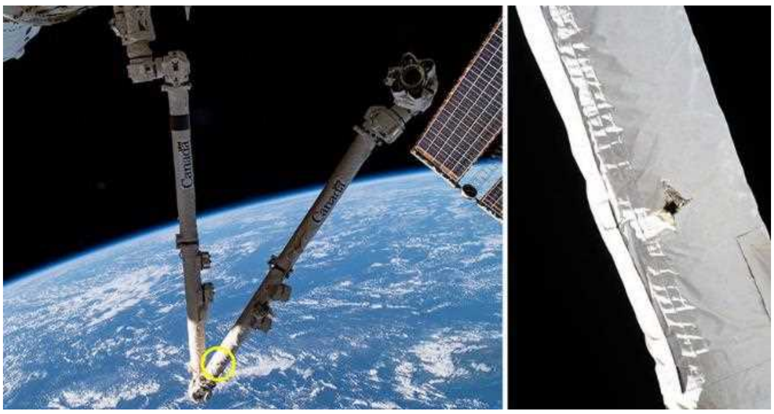
Projected change in total debris count due to debris removal



It is possible to be stable space environment by removing space debris from LEO per 5 or 10 objects.

Space debris scar

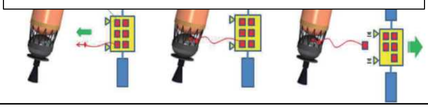


Space debris scar found in the Canadaarm2 ©CSA

The function of the robotic arm was not affected.

Risk reduction measure against a spacecraft

Removement of orbiting debris

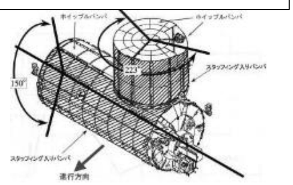


Reduction of debris

Avoidance operation of a spacecraft for preventing it from colliding with debris

There are four countermeasures

Protective measure by the debris bumper like a “KIBO”



No more debris

SSA system ©JAXA

Debris bumper of the Japanese experiment module “KIBO” ©JAXA

Prevention of occuring component with launching a satellite

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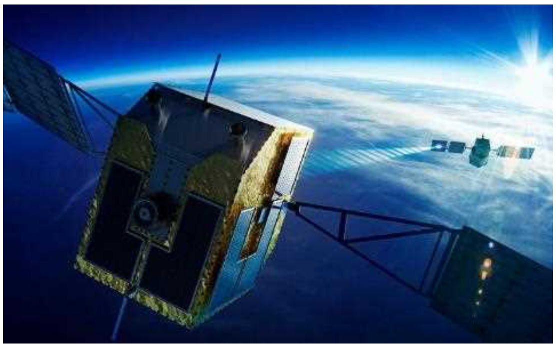
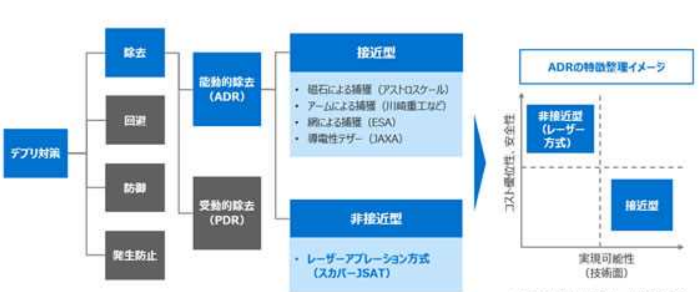
Space debris removal method





【図表1】スペースデブリ除去の手法

- スペースデブリの対策には大きく「除去」、「回避」、「防御」、「発生防止」の四つの手段がある。
- その中でも「除去」の手法には大きく能動的デブリ除去（ADR：Active Debris Removal）と受動的デブリ除去（Passive Debris Removal）があるが、現存するデブリに素早く対処していくにはADRが必要となると考えられる。
  - ADRの中でも「非接近型」のものがレーザーアブレーション方式の手法である。

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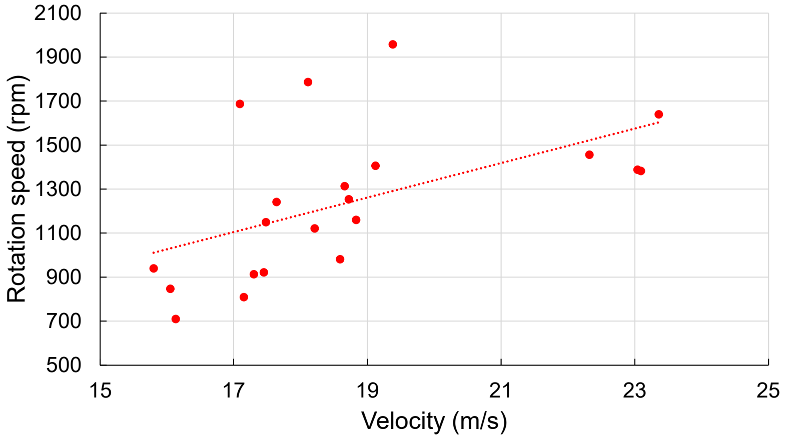
The relation between injection velocity and rotation speed of each harpoon



The relation between the velocity of each harpoon and rotation speed.

The relation between the velocity of each harpoon and rotation speed is positive correlation.

We guess injection velocity and rotation speed depends on air pressure.

Demonstration of shooting the harpoon in the space

Shooting a deployable harpoon into a structure simulating space debris

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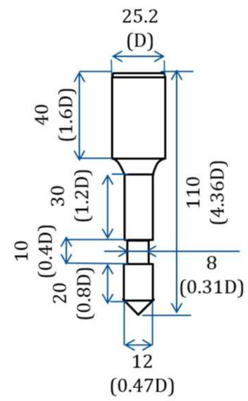
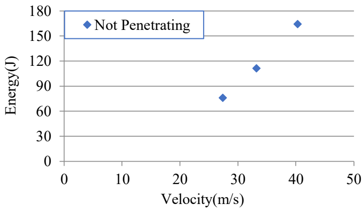
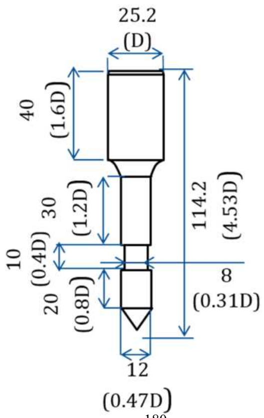
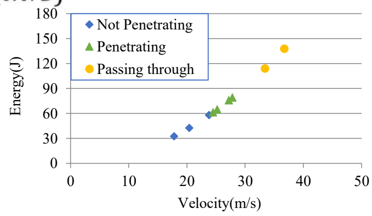
The conical tip shape harpoon with various tip angle









L. B. T. Nguyen, H. Tanaka and H. Hata,
"Evaluation of the effect of the point angle and angle of incidence of a metal anchor on its docking state in a satellite structure for space debris mitigation,"
Mechanical Engineering Journal, Vol.5, Issue.1, pp.17-00087, 2018.

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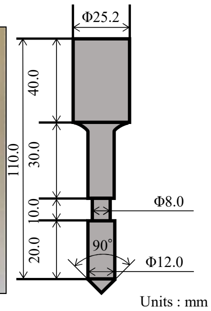
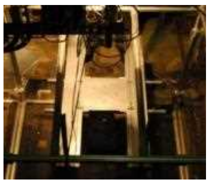
The shooting previous study of the metal harpoon in National Defense Academy of Japan



Conical tip shape

Pullout resistance test



Shooting the harpoon into fixed target

Shooting the harpoon into free fall target

Assumption

Citation：Thanh Long NGUYEN, Hiroaki TANAKA, Hidehiro HATA, Fundamental study on lodgeing an anchor on satellite structure for space debris mitigation system, Transaction of the JSME, 2017 (in Japanese).

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Penetration velocity of the harpoon when gravity acceleration is taken into account

$$v^2 - {v_0}^2 = 2gy$$
$$v = \sqrt{{v_0}^2 + 2gy}$$
$$= \sqrt{15^2 + 2 * 9.8 * 0.59}$$
$$= 15.38 \ldots\ [m/s]$$

← About 2% increase

Penetration velocity of the harpoon when gravity acceleration is taken into account (m/s)

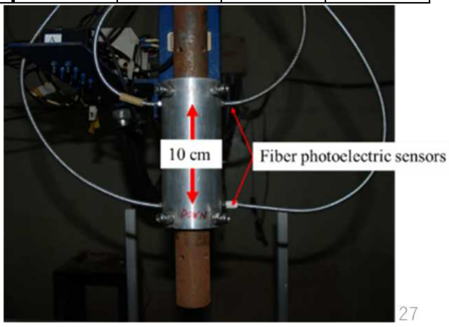
Angle	Conical	Spherical	Flat	Double-bladed
0 deg	17.3	22.9	23.9	16.0 (15.3)
30 deg	17.9	23.5 (22.7)	14.3	15.7
45 deg	35.4	44.8*	31.0	17.7

v: The harpoon velocity before impact $[m/s]$

v_0: The harpoon speed when passing lower sensor (Assume 15 $[m/s]$)

g: Gravity acceleration $[m/s^2]$

y: The distance from lower sensor to the specimen $[m]$



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計測誤差

$$V_m = V + V_e = \frac{L + L_e}{T + T_e} = \frac{L}{T}\left(\frac{1 + \frac{L_e}{L}}{1 + \frac{T_e}{T}}\right) \fallingdotseq \frac{L}{T}\left(1 + \frac{L_e}{L}\right)\left(1 - \frac{T_e}{T}\right)$$
$$\fallingdotseq \frac{L}{T}\left(1 + \frac{L_e}{L} - \frac{T_e}{T}\right) = V\left(1 + \frac{L_e}{L} - \frac{T_e}{L/V}\right)$$
$$V_e = V\left|\frac{L_e}{L}\right| + V^2\left|\frac{T_e}{L}\right| \fallingdotseq V_m\left|\frac{L_e}{L}\right| + {V_m}^2\left|\frac{T_e}{L}\right|$$

V_m：計測された銛の速度 $[m/s]$
V: 銛の真の速度 $[m/s]$
V_e：銛の真の速度との誤差 $[m/s]$
L：光スイッチの間隔 $[m]$ (10 cm =0.1 m)
L_e：光スイッチ間隔の誤差 $[m]$ (機械加工誤差が支配的)
T：計測時間 $[s]$
T_e：光スイッチによる計測時間誤差$[s]$

銛の速度を10 m/s とすると(機械加工誤差：1.0×10^{-4} m,
サンプリング周期10 μs及び人為的計測誤差も含めて30 μsとする．)

$$V_e = 10 \times \left|\frac{1.0\times10^{-4}}{0.1}\right| + 10^2\left|\frac{30\times10^{-6}}{0.1}\right| = 4.0 \times 10^{-2}[m/s]$$

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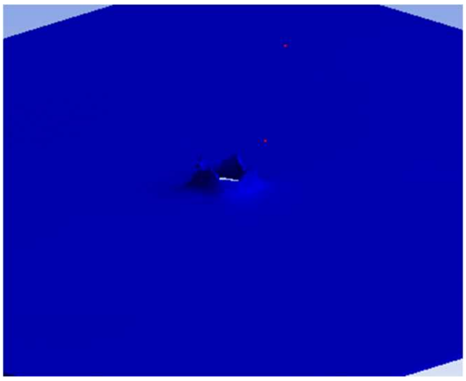
The shape of the penetration hole(Conical tip shape harpoon)



Numerical simulation indicates similar shape.

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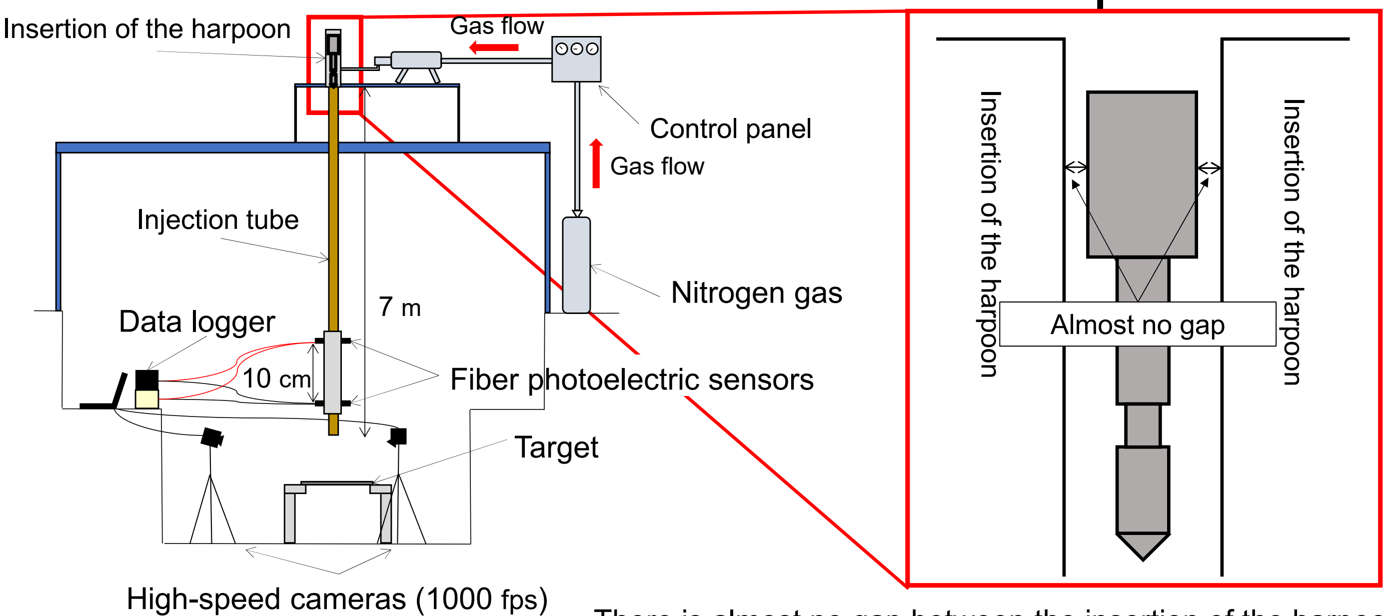
The width of insertion of the harpoon



There is almost no gap between the insertion of the harpoon and the harpoon. We consider the harpoon itself is not tilted.

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Precision error of the fixed stand

Oblique angle of 0°

Oblique angle of 30°

Oblique angle of 45°

Mechanical accuracy error is less than 1 deg in the fixed target.

質 問

1. 球先端形状は45°以上で貫通するのか.
→実際には実験していないが，傾き角が大きくなるにつれ貫入速度が必要になる.
　貫入速度が上がると運動エネルギーも上がるため
　貫入することなく，貫通すると思われる.
　銛が供試板と衝突し，滑ったとしても捕獲には適さない.

2. 解析上でも貫入孔の形状は同じか.
→同じである.

質 問

1. 銛の回転はしているのか.
→回転していない.
　現在の研究は銛に回転機構を取り付けて回転させている．摩擦のみが実験とシミュレーションの誤差ではないと思うが，今後定量的な誤差についても追求する.

質 問

1. 固定台の計測精度について

2. なぜ15°をしなかったのか.
→銛の先端形状にもよるが，平以外の先端形状に関しては傾き角が大きくなるにつれ貫入速度も上がる．15°も0°に比べて貫入速度は大きくなると予想される.
傾き角45°の時，円錐先端形状や球先端形状について特異な挙動を示した．円錐先端形状については先端形状の側面で衝突し，滑った.
球先端形状は貫入することなく，貫通した.
したがって，傾き角45°よりも例えば傾き角40°等滑りの影響や先端形状に影響がない角度については今後考察の余地がある.

3. 銛自体の傾きはないのか.
→挿入口と銛の隙間はほとんどない．銛挿入時には銛自体の傾きはないものと考えられる.