Impact Behaviour Analysis of a Passive Compliant Unit for Active Space Debris Removal

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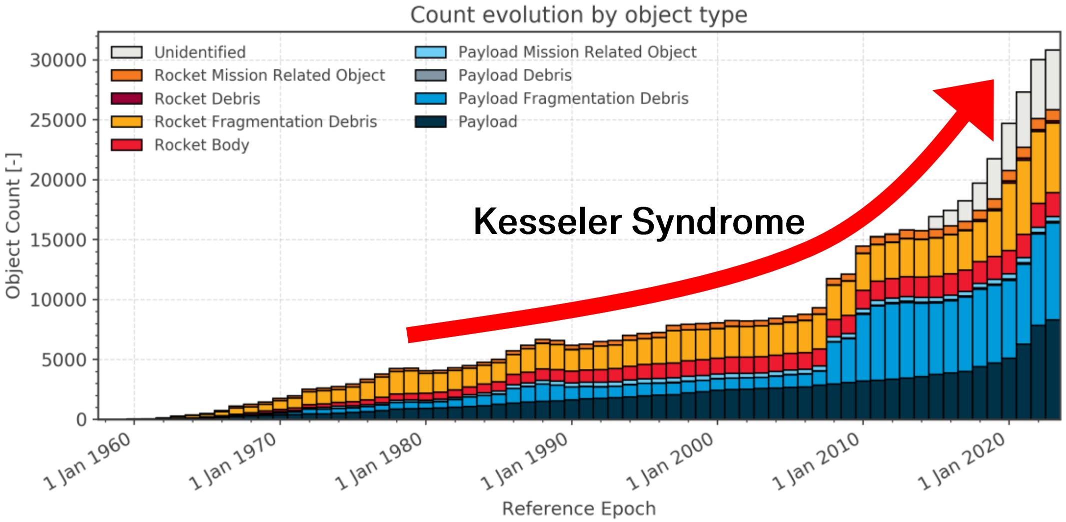
The Problem of Space Debris

- **More than 130 Million**, estimated number of debris objects, based on statistical models to be in orbit, June 2024[1]
- **The Kesseler Syndrome** denotes the **exponential increase** of space debris around Earth[2]
- **Active and Passive** Debris Removal are needed[3]



Nearly half of trackable small lobjects in LEO[1] are shaped as a box

1. *LEO less than 2000km, and less than 100kg trackable objects. ESA DISCOS Database, June 2024*

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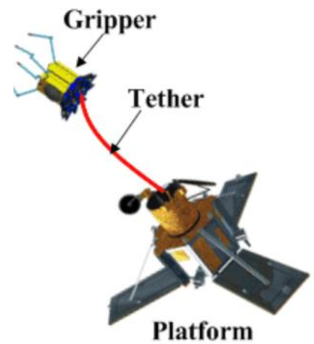
[1] ESA DISCOS, consulted in September 2022. (sdup.esoc.esa.int/discosweb/statistics/)
[2] Drmola, J. & Hubik, T. Kessler Syndrome: System Dynamics Model. In:Space Policy. pp. 29-39 (2018)
[3] Liou, J. Active Debris Removal and the Challenges for Environment
Remediation. (2012)

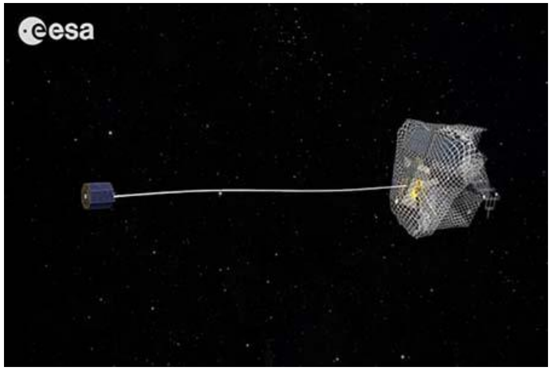
Active Debris Removal State of the Art

- Companies tend to focus on **one-to-one solutions**
- Those solutions **lack of reliability**, **compactness** and may **harm the debris**
- Capturing harmlessly a range of small satellites requires **compliance**, **reliability** and **versatility**

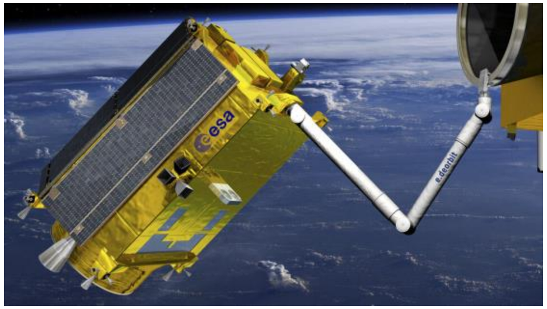
- **Critical requirements**
- Control on the first impact with a flat surface
- No damage, soft approach
- Securely attach the debris and the servicer together



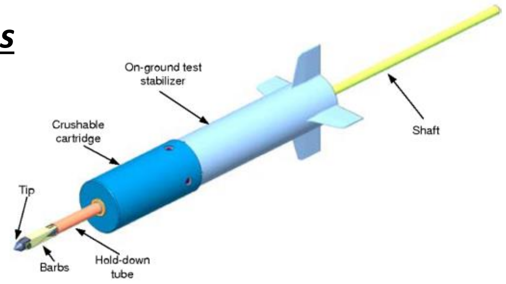
Tether



Nets

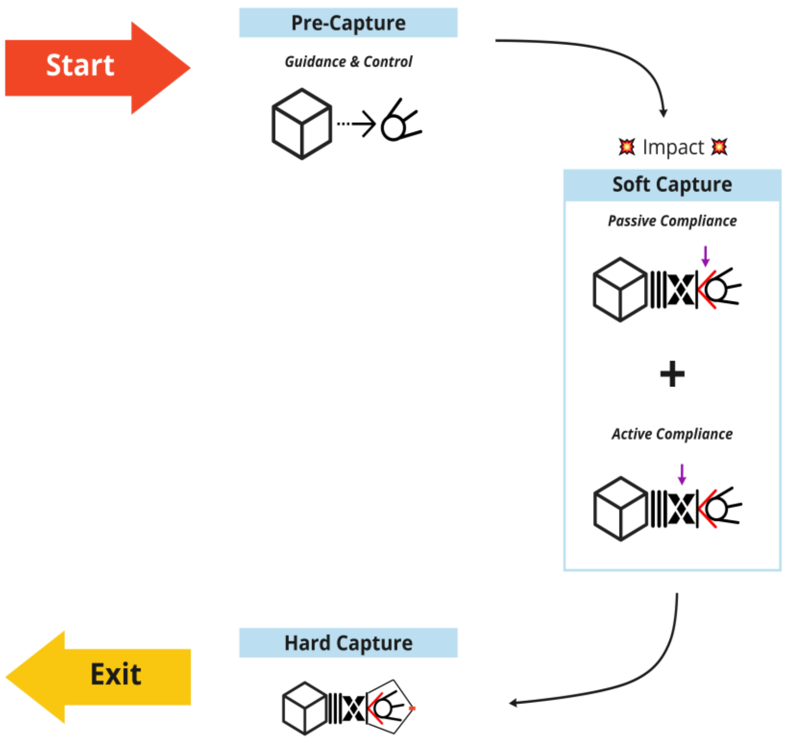


Robotic Arms



Harpoons

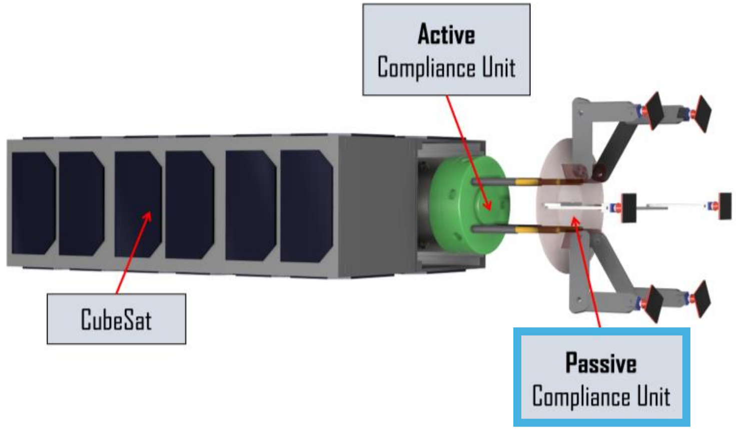
A 2-Step Hybrid Compliant System[1]



Concept of Operations

Focus on Soft Capture

- Active and Passive Compliance allow a one-to-many solution
- Target uncooperative space debris
- Approach on flat surfaces
- CubeSat integration



Early Concept Sketch

[1] Hubert Delisle, M., Christidi-Loumpasefski, O., Yalc, ın, B., Li, X., Olivares-Mendez, M. & Martinez, C. Hybrid-Compliant System for Soft Capture of Uncooperative Space Debris. Applied Sciences. 13 (2023), https://www.mdpi.com/2076-3417/13/13/7968

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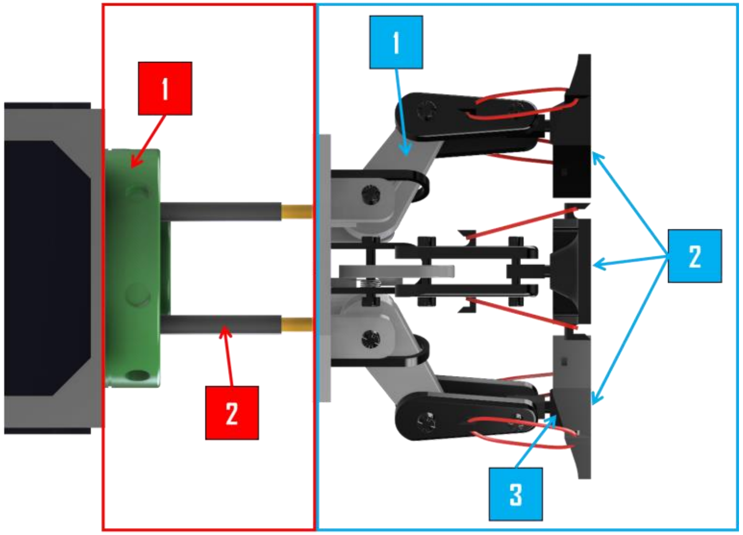
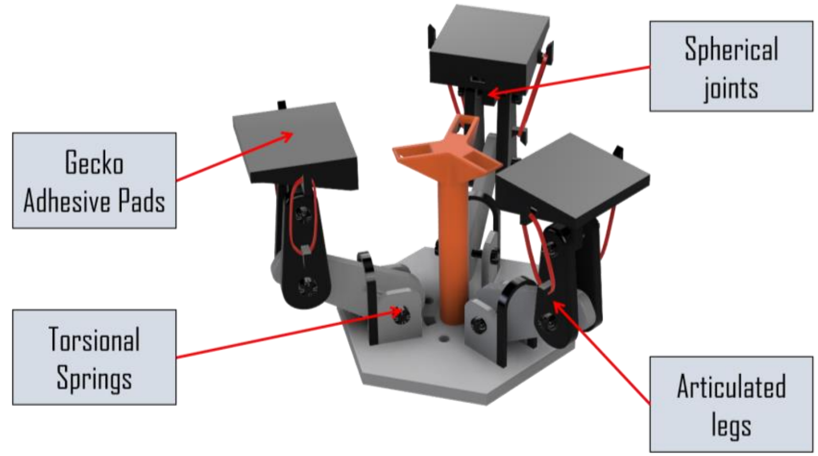
Concept Design

Active Compliance Unit (ACU):
1. F/T Sensor
2. EM Linear Actuators

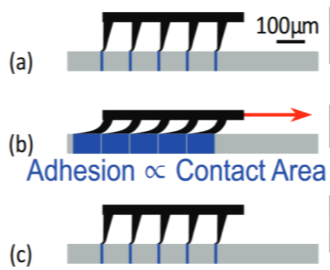
Passive Compliance Unit (PCU):
1. Articulated Legs
2. Gecko Adhesive Pads
3. Spherical Joints



Soft Capture Unit Composition



Passive Compliant Unit Composition



Gecko-inspired Dry Adhesive [1]

- **Reliability** - Use a bio-inspired dry adhesive to prevent motion-reaction
- **Robustness** - Constant stiffness coefficient with torsional springs to prevent hard shocks
- **Versatility** - Tunable stiffness coefficient with EM linear actuators to change the overall equivalent stiffness

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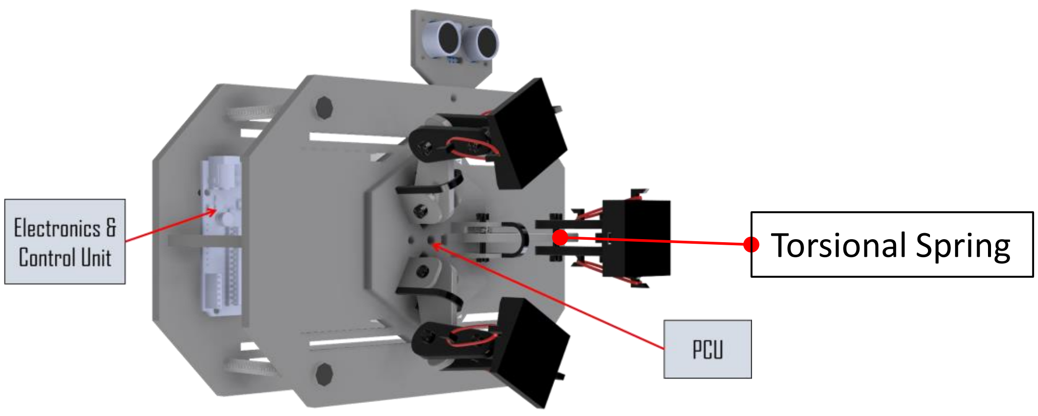
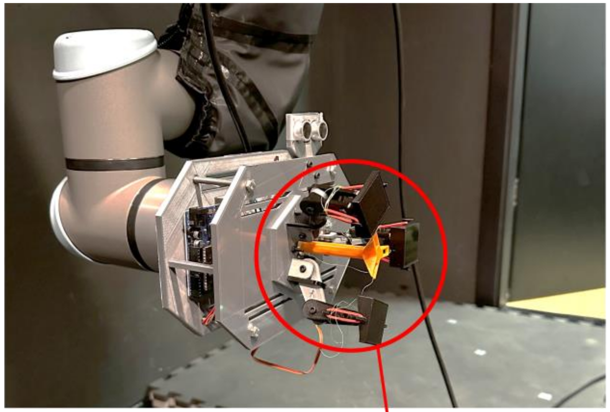
[1] Hawkes, E., Jiang, H. & Cutkosky, M. Three-dimensional dynamic surface grasping with dry adhesion. The International Journal Of Robotics Research. pp. 1-16 (2015)

Early Stage Prototype



CAD Model

3D Printing & Assembly



Torsional Spring Specifications

Sign	Value	Description
D_m	6.0×10^{-3} m	Mean Coil Diameter
d	0.8×10^{-3} m	Wire Diameter
E	200×10^{9} Pa	Young's Modulus
N_a	4	Number of Active Turns

$$k_T = \frac{d^4 E}{64 D_m N_a}$$ [1]

$$k_T = 0.053\,\mathrm{N\,m\,rad^{-1}}$$

[1] Borchia, D. Torsion Spring Calculator., https://www.omnicalculator.com/physics/torsional-spring.

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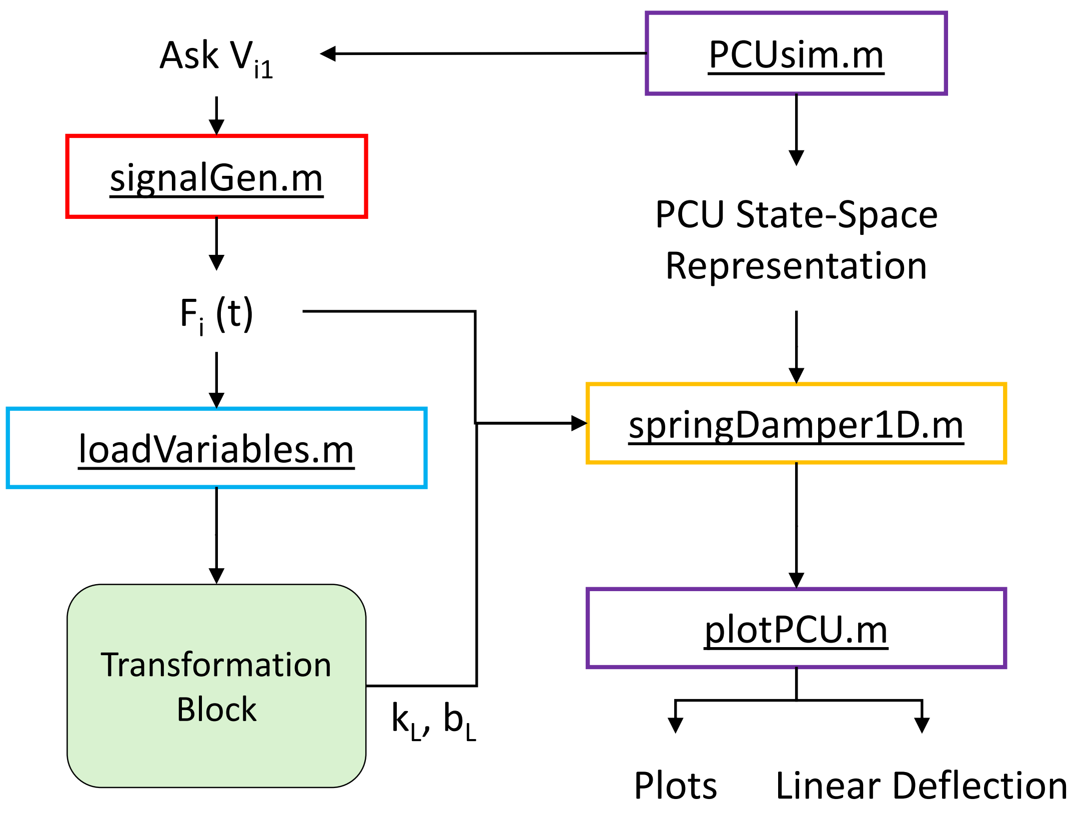
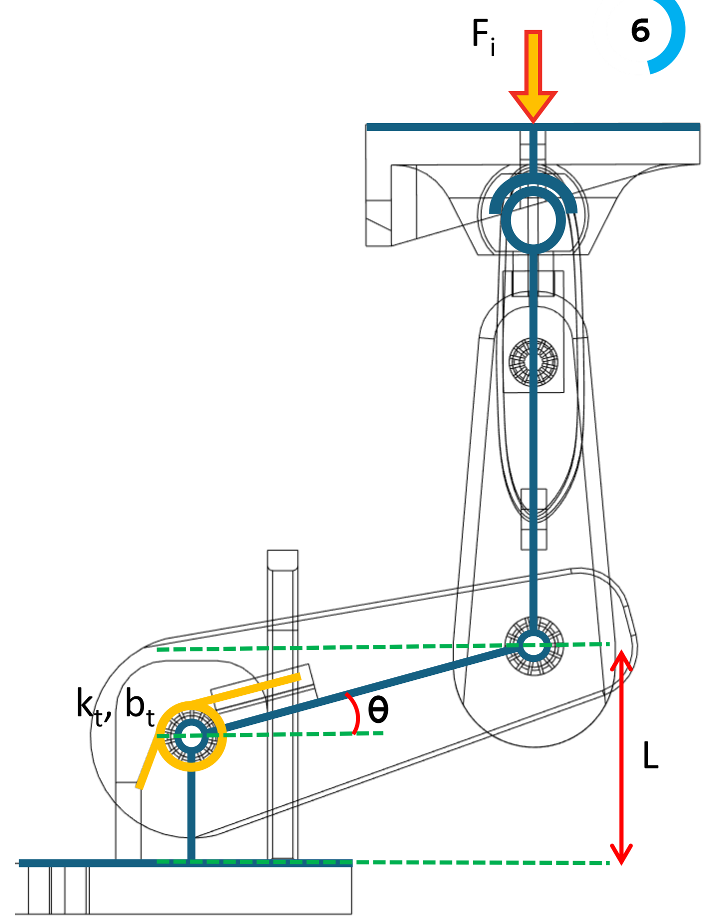
Goals



Model Wrokflow



Sketch of 1 Articulated Leg

- Assess the system's safety by measuring the longitudinal deflection L
- Get knowledge on the proposed concept

State-Space Model

Dynamic Equation

$$m_{PCU}\ddot{y}(t) = u(t) - b_{eq,PCU}\dot{y}(t) - k_{eq,PCU}\,y(t)$$

↓

State-Space Model

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = A\begin{bmatrix}x_1\\ x_2\end{bmatrix} + B\begin{bmatrix}u\end{bmatrix}$$

$$\begin{bmatrix}y\end{bmatrix} = C\begin{bmatrix}x_1\\ x_2\end{bmatrix}$$

,

$$A = \begin{bmatrix}0 & 1\\ -\frac{k_{\text{eq,PCU}}}{m_{\text{PCU}}} & -\frac{b_{\text{eq,PCU}}}{m_{\text{PCU}}}\end{bmatrix}$$

$$B = \begin{bmatrix}0\\ \frac{1}{m_{\text{PCU}}}\end{bmatrix},$$

$$C = \begin{bmatrix}1 & 0\end{bmatrix}$$

$$k_{eq,PCU} = k_{1,PCU} + k_{2,PCU} + k_{3,PCU}$$

,

$$b_{eq,PCU} = b_{1,PCU} + b_{2,PCU} + b_{3,PCU}$$

↓

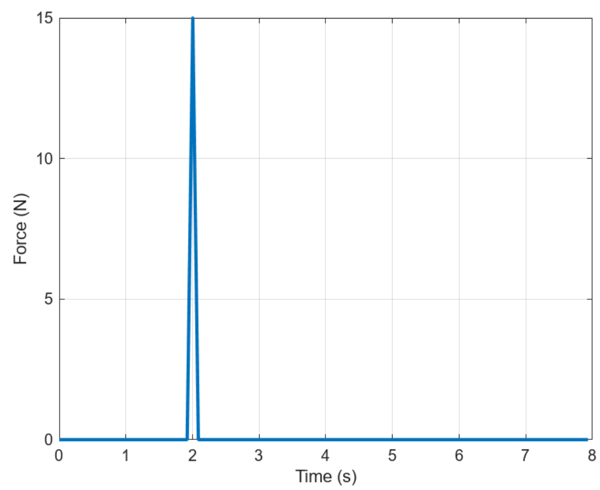
Computing $\hat{L}$ over time

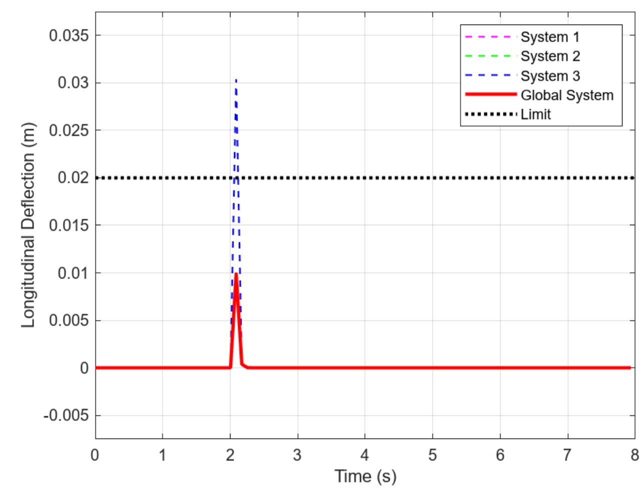
↓

Plotting the results

↓

Assessing the results





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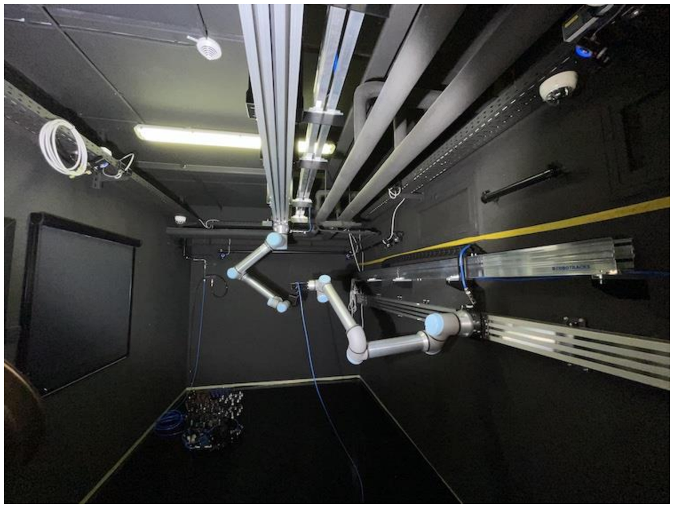
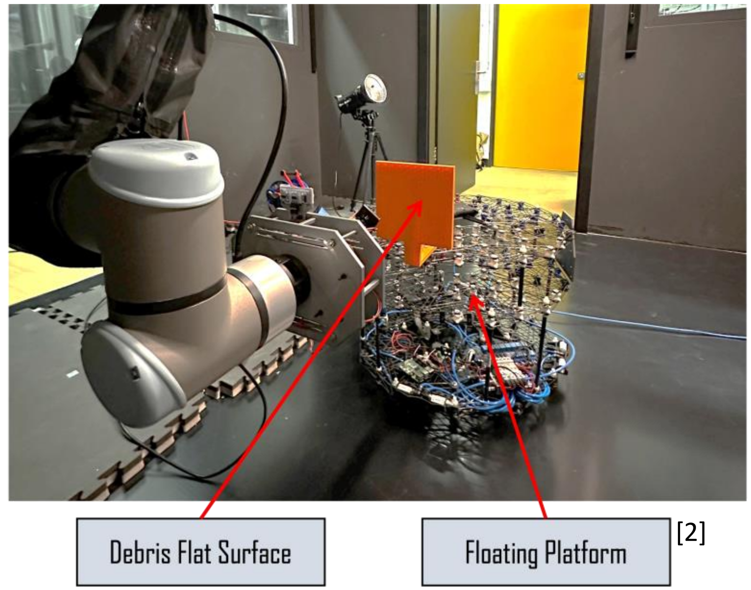
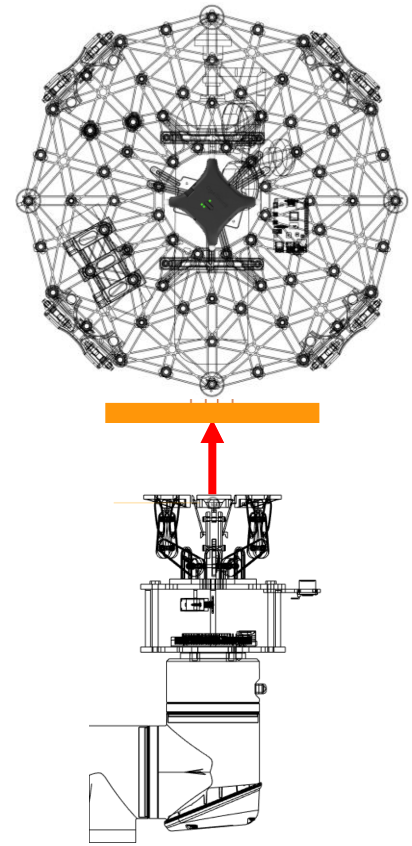
ZeroG Lab – Set-up



Zero-G Lab[1]



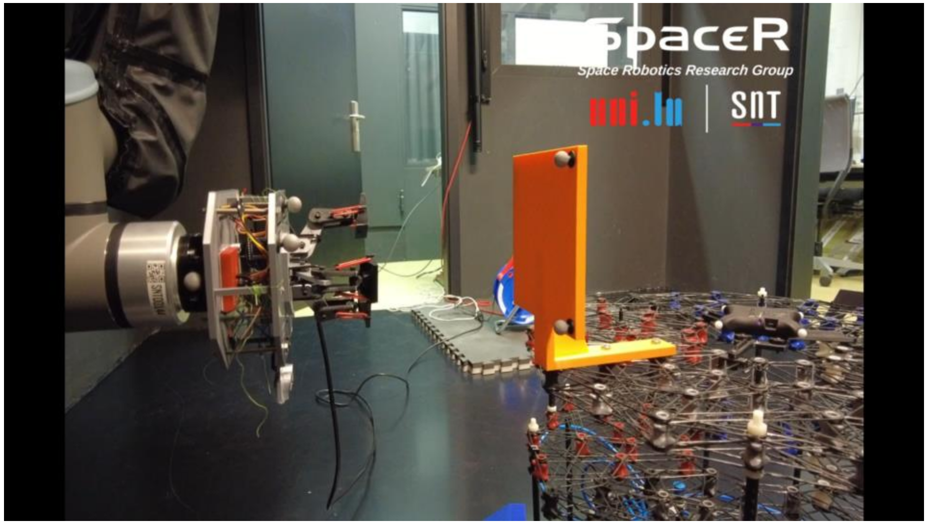
Test Set-Up



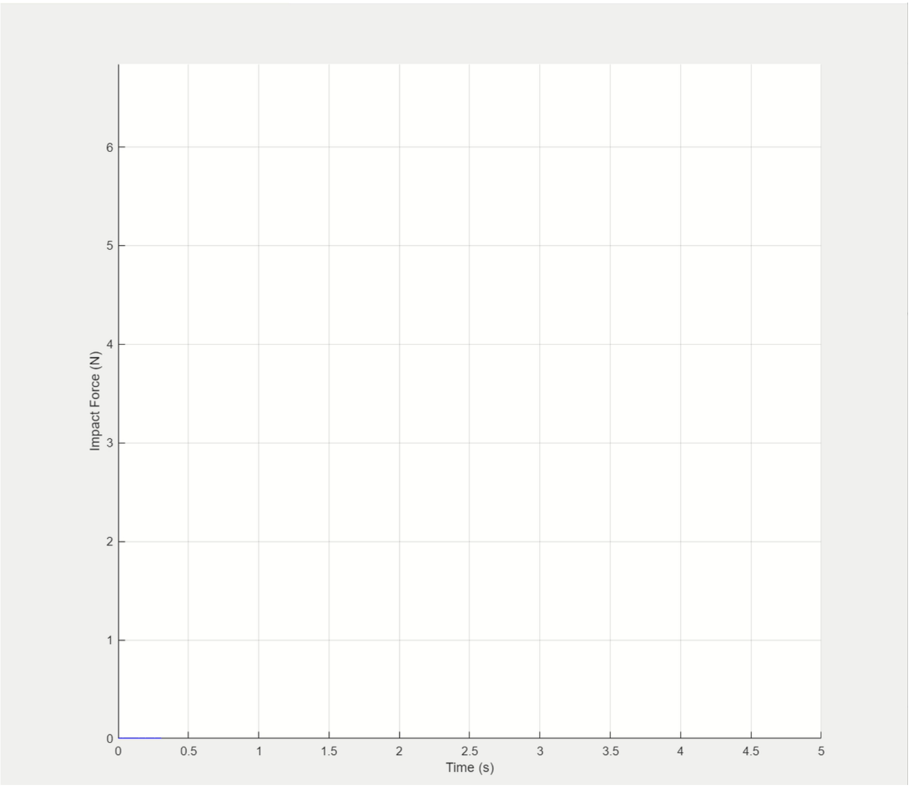
Test Procedure

[1] Al, M. Zero-G Lab: A multi-purpose facility for emulating space operations. Journal Of Space Safety Engineering. pp. 509 - 521 (2023)
[2] Al., B. Lightweight Floating Platform for Ground-Based Emulation of On-Orbit Scenarios. IEEE Access. pp. 94575 - 94588 (2023)

ZeroG Lab – Tests



Test Video Example



Impact Force Profile

Video link:
https://drive.google.com/file/d/1mqD3aHUhTSBcY6L2q3NYvQAEmXD1Ryjy/view?pli=1

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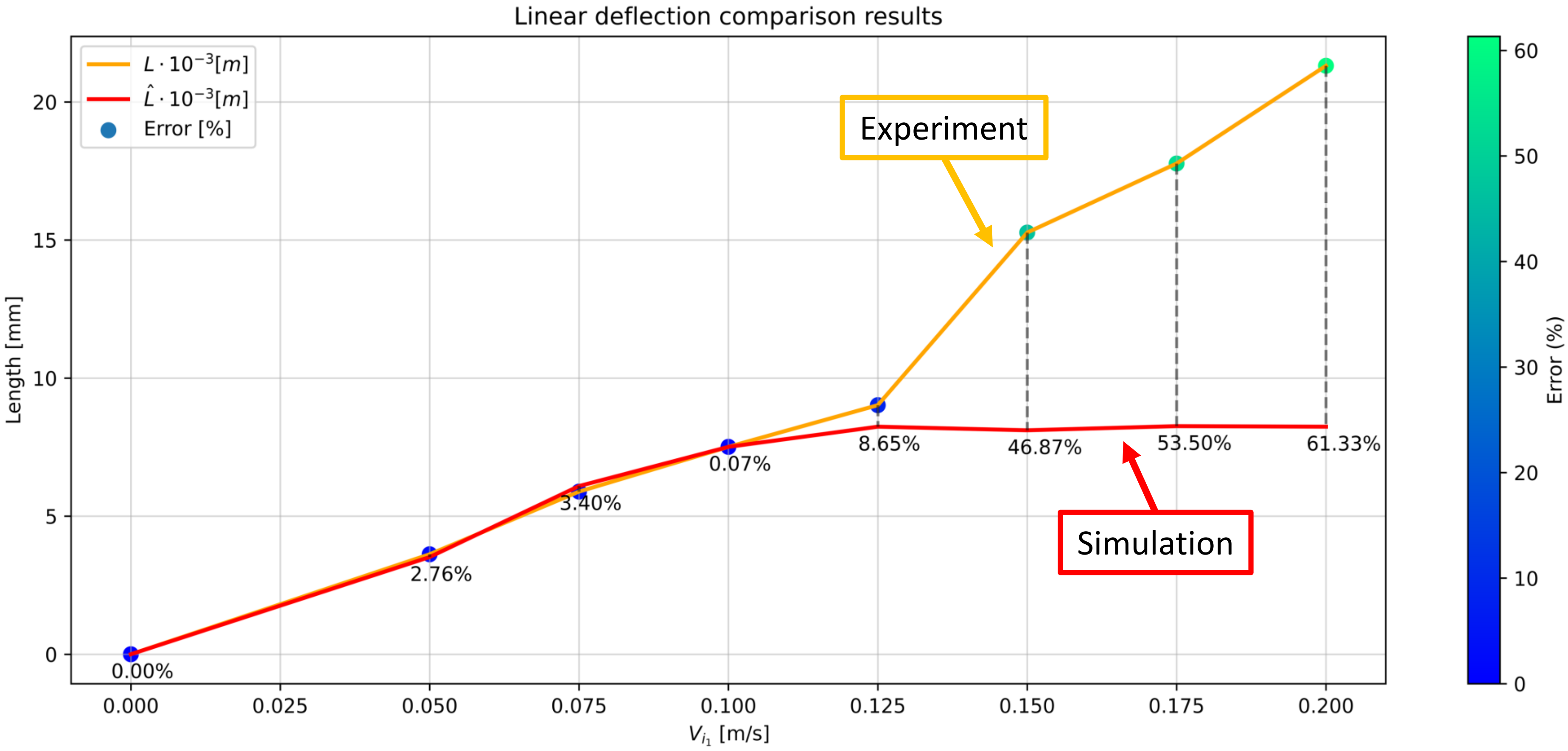
Table of Results

V_{i_1} [m s^{-1}]	$F_{i,Peak}$ [N]	t_c [s]	Deflection *Experiment* $L \cdot 10^{-3}$[m]	Deflection *Simulation* $\hat{L} \cdot 10^{-3}$ [m]	ϵ [%]
0.050	3.83	0.320	3.62	3.52	2.76
0.075	4.65	0.302	5.89	6.09	3.40
0.100	6.11	0.327	7.51	7.51	0.07
0.125	6.84	0.380	9.02	8.24	8.65
0.150	6.69	0.393	15.27	8.11	46.87
0.175	6.87	0.373	17.77	8.26	53.50
0.200	6.85	0.367	21.31	8.24	61.33

Good Correlation between Simulations and Experimental Tests

Wrong Correlation between Simulations and Experimental Tests

Comparison Graph



Similar Impact Force Profile

Average of 3.72% error

Different Impact Force Profile

Average of 42.59% error

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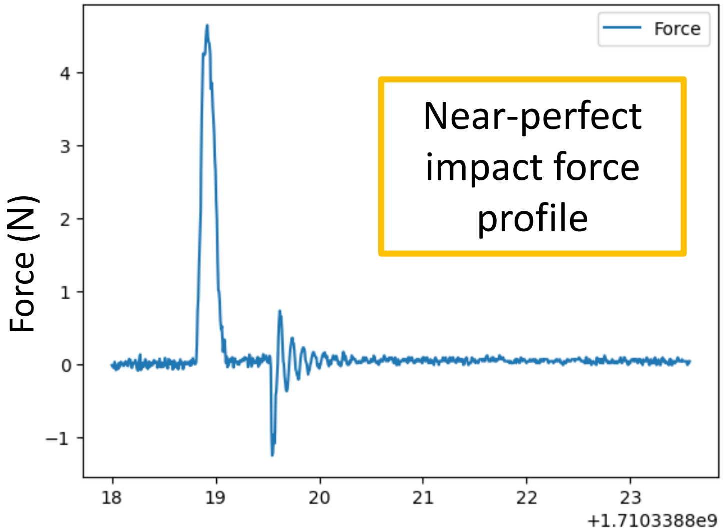
Conclusions

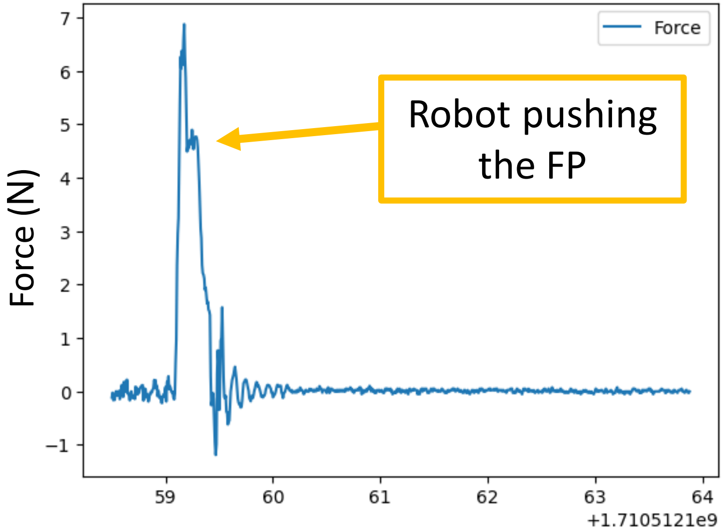
<u>What's been proposed:</u> The mechanical behaviour of the PCU has been translated mathematically in MATLAB to simulate it under different impact force profiles

<u>What's the goal:</u> Simulate its behaviour under different impact force profiles based on its mechanical properties, bringing further the knowledge on the system to safely target a range of flat-surfaced debris

<u>Core Work:</u> Code the simulation in MATLAB environment ; Prototyping the PCU and making it undergo a series of tests in the Zero-G Lab of the University of Luxembourg

<u>Main remarks:</u> The model built recreates nicely the dynamic properties of the PCU when the impact force profile matches the constructed pulse of the model ; However, for higher velocities of approach, the robotic arm pushes the FP by continuing on its programmed path, making the impact force profile too different to the one in the model.





Future Studies

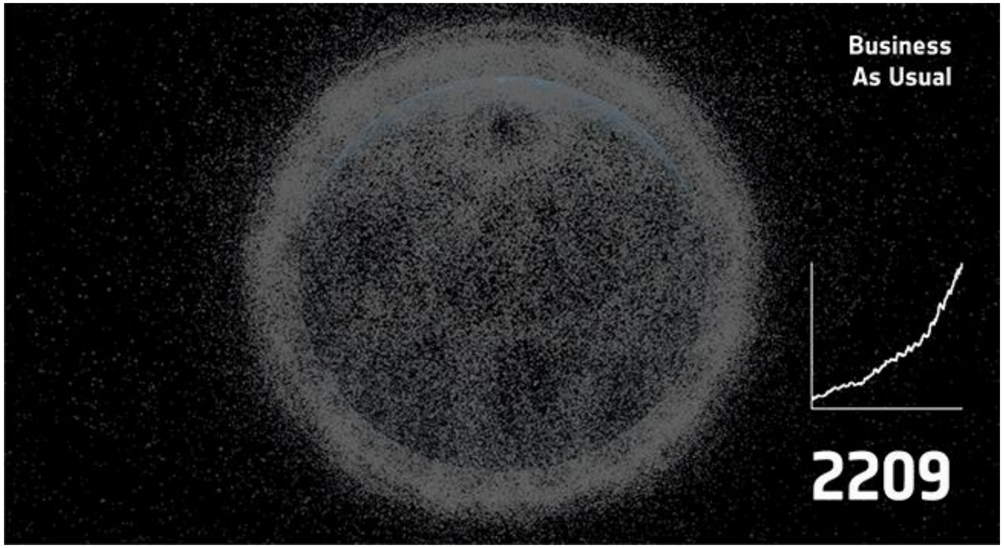
- Model improvements and upgrades to recreate the proposed design of the ADR Hybrid-Compliant system with the addition of the ACU.
- The Coefficient Of Restitution between the two entities can be investigated. The coefficients of the ACU could be fine-tuned to reduce the COR.
- Finally, an experimental validation of the SCU prototype with the dry adhesive is planned in the Zero-G Lab of the University of Luxembourg.

Better knowledge on the impact behaviour and the novel concept for ADR makes research come closer to autonomously capture a range of small debris in orbit

Let's keep Earth <u>AND</u> Space clean!

Thank you!

Q&A Session



Let's keep in touch!

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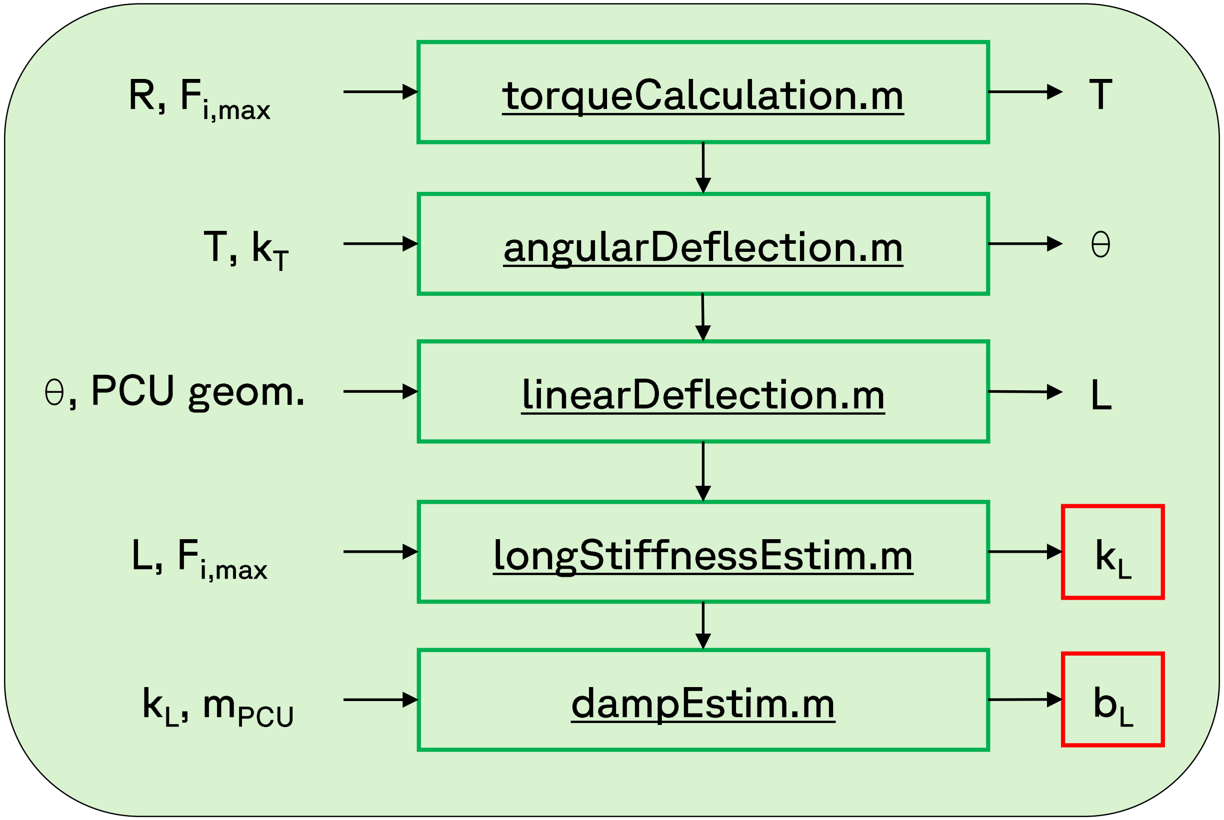
R, $F_{i,max}$
torqueCalculation.m
T
T, k_T
angularDeflection.m
θ
θ, PCU geom.
linearDeflection.m
L
L, $F_{i,max}$
longStiffnessEstim.m
k_L
k_L, m_{PCU}
dampEstim.m
b_L