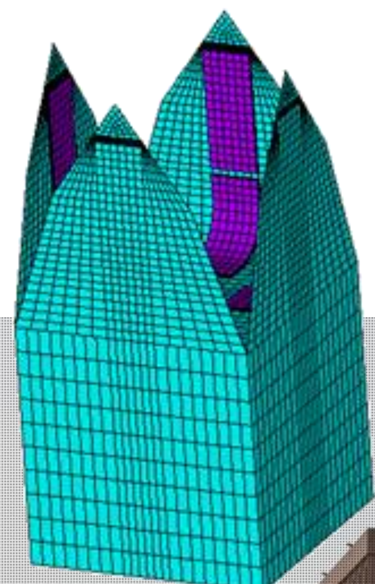
Manufacturing Technology Research Group MaTeR

S.Un.R.i.S.E. Second University of Rome in Space Experiments

e-SPADES

European SPace DEbris Suppression



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Final Presentation Slides

Project abstract

Space debris is mainly constituted by small items which cannot be de-orbited by using specific satellites launched from the Earth due to costs and difficulty in miniaturizing robotic arms or other rigid actuation systems. In a long-period vision, small cleaning satellites, with a size comparable with the debris to remove, can be manufactured in Space. Traditional robotic systems would be extremely expensive and some also would have problems in grabbing objects with undefined shape. Grabbing loads could result in debris fragmentation whereas fine tuning of the grabbing procedure would lead to not acceptable costs. Moreover robotic systems are too much complex for in-Space manufacturing. It is evident that an innovation is necessary in materials, and shape memory polymer composites (SMPC) are optimal candidates. SMPC can freeze a non-equilibrium shape (open) and recover the equilibrium shape (closed) by heating. Heaters and sensors are integrated in the SMPC structure during manufacturing. These smart structures can be easily produced in Space with a very simple structure which can be tailored on the size of debris to remove. They do not apply loads during grabbing with the result of optimal debris containment. Moreover, shape recovery rate is low, and debris approach and capture are managed with sufficient time. Also rotating debris can be captured while reducing the risk of structure damaging or debris disengaging by SMPC device re-opening. In fact, the SMPC works as a damper during recovery and becomes stiff only after freezing. This project aimed to define, for the first time, the optimal SMPC geometry for debris capture. Our laboratory experiments so far had shown the ability of SMPC structures to grab simple objects but an optimal configuration for Space debris was necessary. Numerical modelling has been made as well as laboratory prototypes, with integrated heating systems, for testing device functionalities. Results show the very good behavior of the SMPC device for grabbing small debris, damping its rotational speed during the approach.

The project evolution

WP1 - Device working conditions (M1-M6)

T1.1. Background and potential of SpaDeS

T1.2. Analysis of debris distribution and properties

T1.3. Analysis of Space environment

T1.4. Conceptual design of the grabbing mechanism

T1.5. Example of a cleaning mission

T1.6. Intermediate review meeting (D1)

WP2 - Design and modelling (M4-M9)

T2.1. Definition of the grabbing geometry

T2.2. Definition of the manufacturing procedure

T2.3. Design of the SMPC device

T2.4. Modelling the behaviour of the SMPC device.

WP3 - Validation (M7-M12)

T3.1. Manufacturing SMPC samples

T3.2. Sample characterisation

T3.3. Manufacturing SMPC devices

T3.4. Testing SMPC device functionalities

T3.5. Validating numerical models

T3.6. Final review meeting and related deliverables (D2 + D3, D4, D5, D6, D7)

Gantt

		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
WP1 - Device working conditions (M1-M6)													
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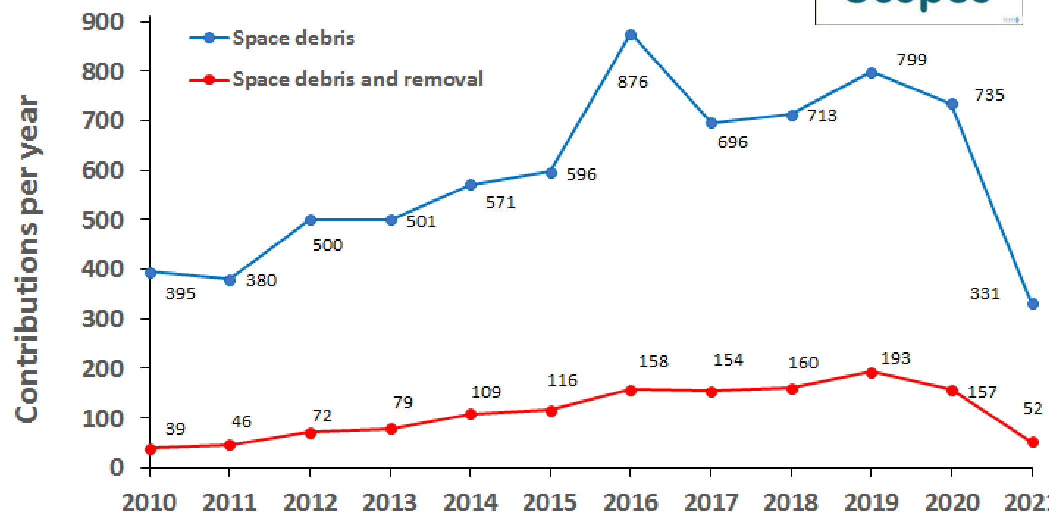
T3.5.	Validating numerical models												
T3.6.	Final review meeting and related deliverables												
				Review Meeting							Final meeting		
	01-apr-21												
	30-sep-21												
	01-apr-22												

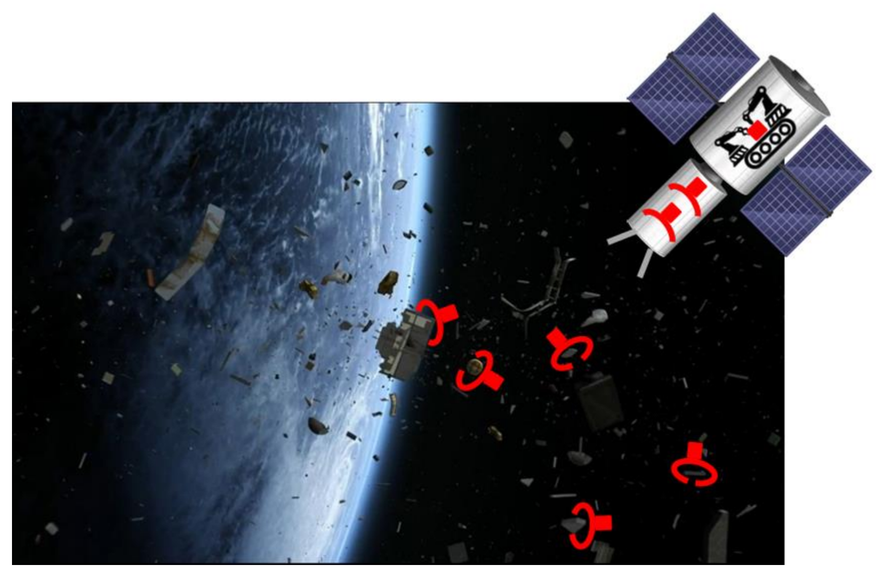
Background and potential of SpaDeS

- Scientific Literature (Agencies)
- Internal Research
- Available Data from Market

- “Space debris” AND “Removal” AND “Shape memory polymer composites”, only
    1. *Conceptual design of an experiment for the international space station about shape memory composite in space environment*, ASME 2017 12th MSEC).
    2. *Design and testing of self-deployable structures for advanced space applications*, 69th IAC 2018.

Proceedings of AVT-257 NATO Specialists Meeting on "*Best Practices for Risk Reduction for Overall Space Systems*", 26-29 September 2016, Avila, Spain)

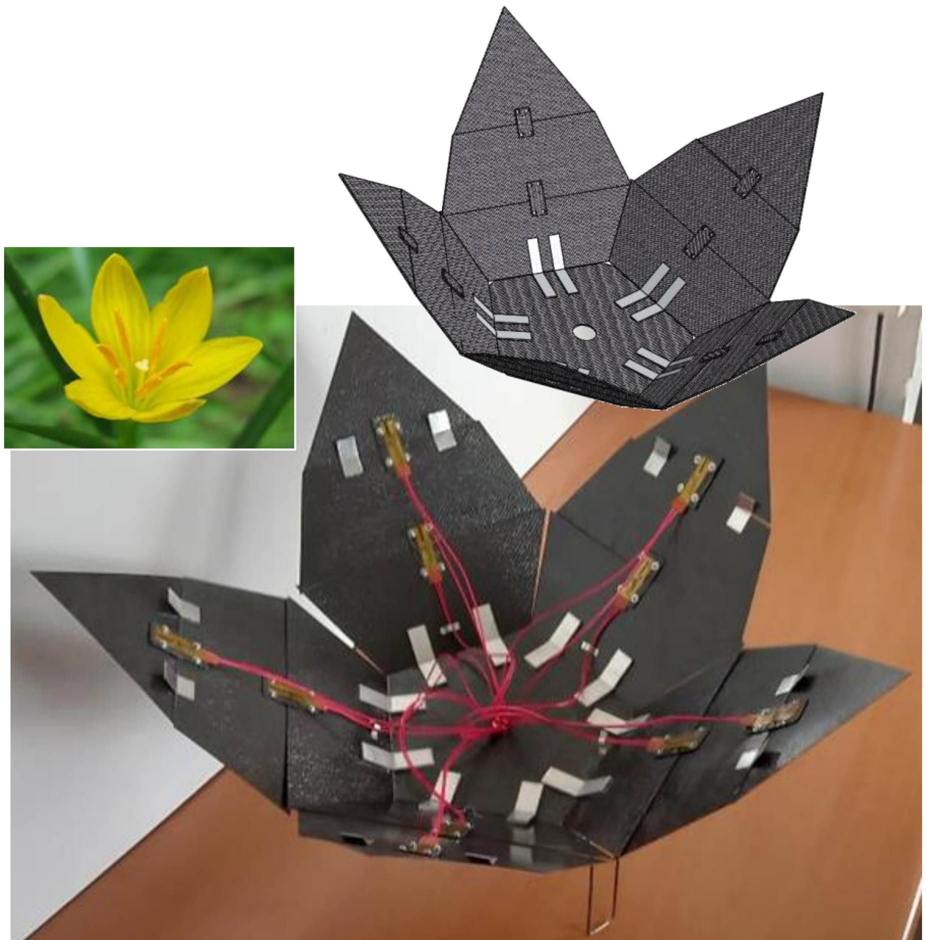


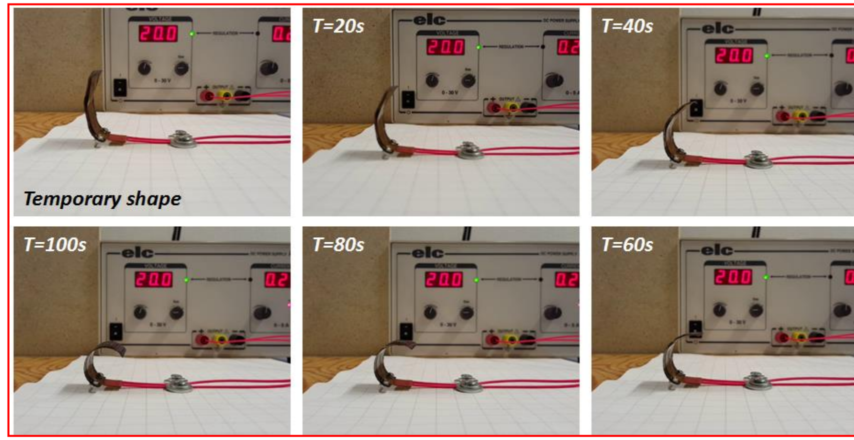


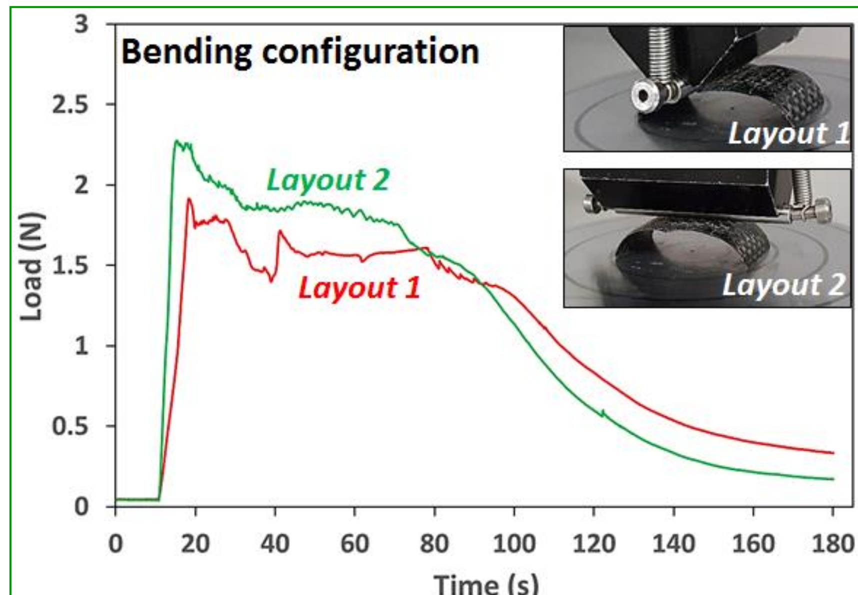
Background: Internal Studies

Designing the smart composite hand

- Prototyping of smart hinges
- Testing smart hinges
- Measuring recovery loads



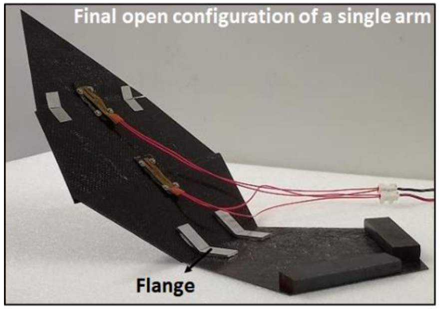


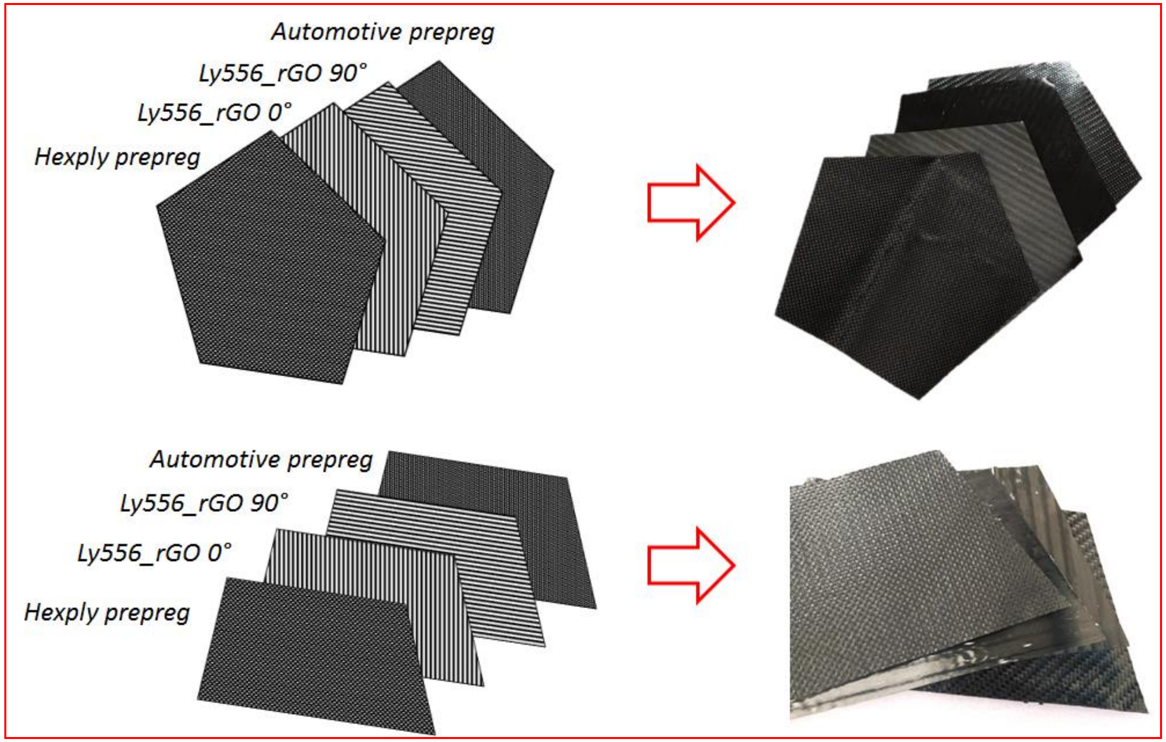


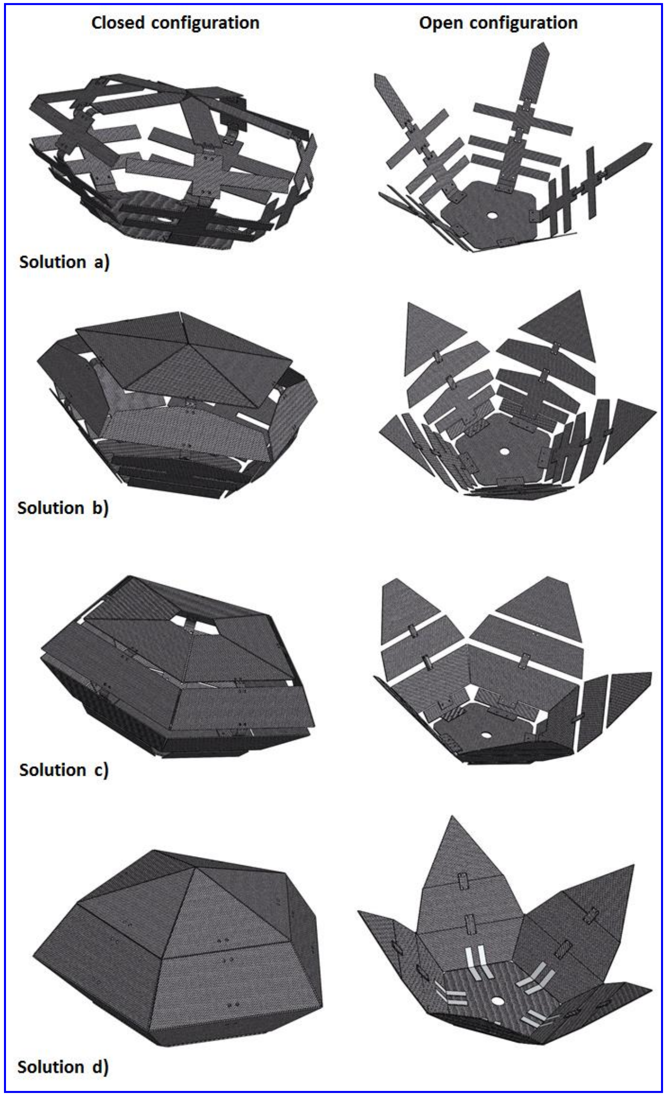
Background: Internal Studies

Designing the smart composite hand

- Structure modelling
- Prepreg cutting
- Laminate molding
- Structure assembly



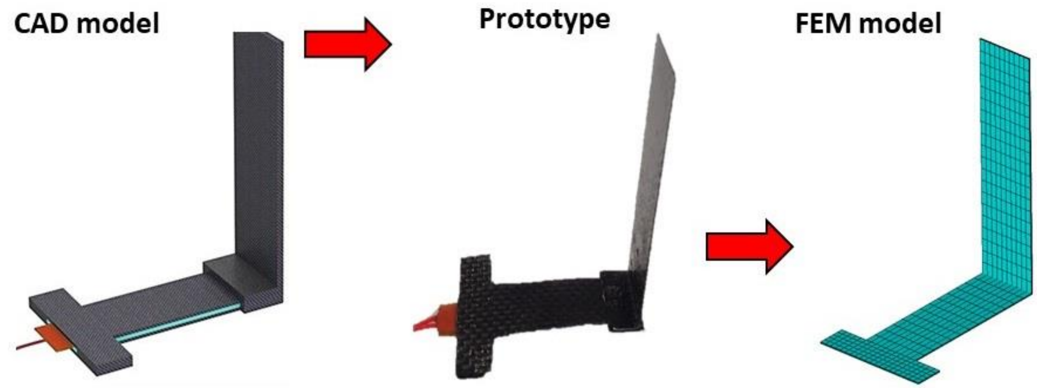


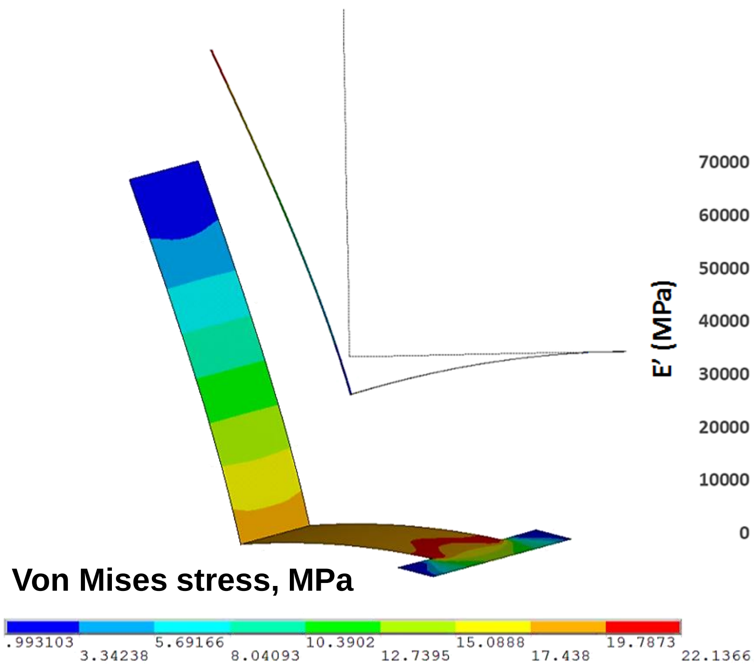


Background: Internal Studies

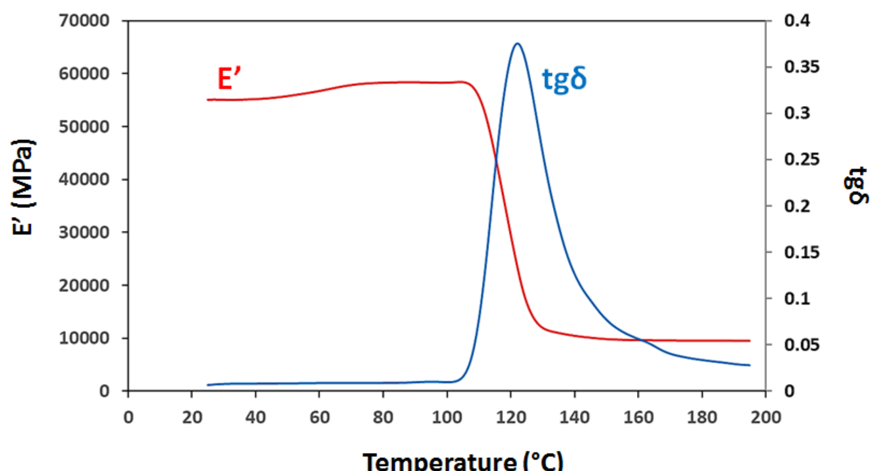
Modelling

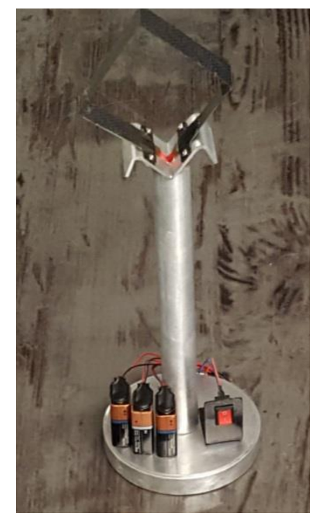
- Modelling shape memory behavior
- Applying to the SMPC finger
- Simulating SMPC actuation
- Development of FE models





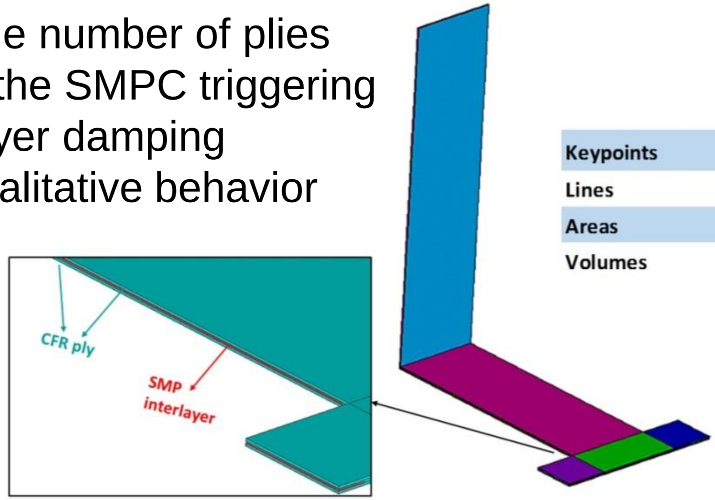
Von Mises stress, MPa



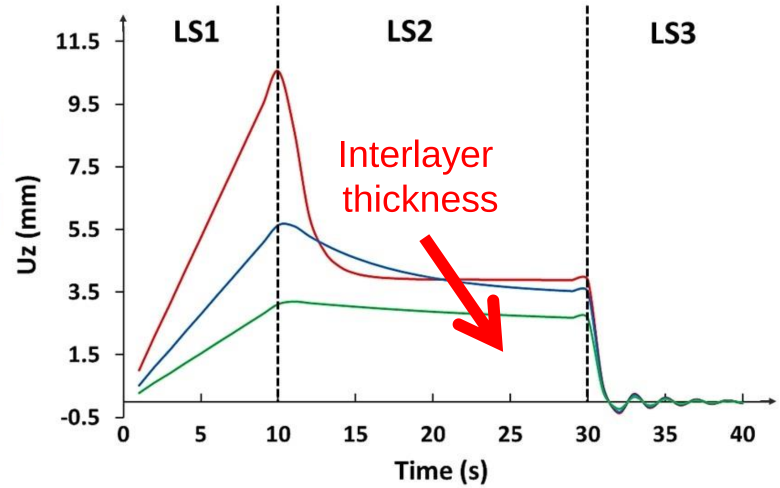


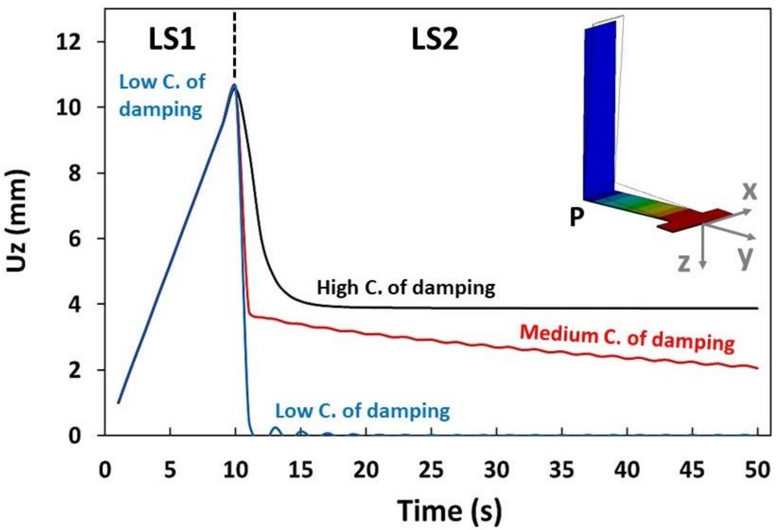
Background: Internal Studies

- Effect of the number of plies
- Modelling the SMPC triggering
- SM interlayer damping
- Correct qualitative behavior

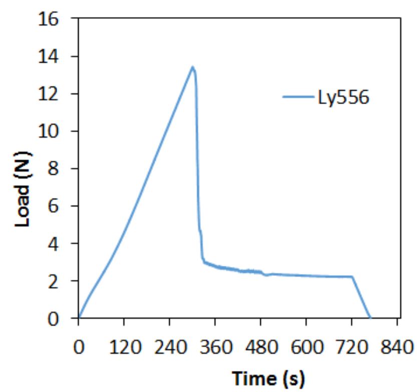


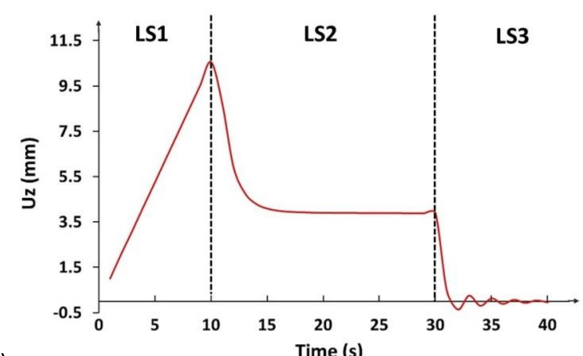
Keypoints	52
Lines	108
Areas	73
Volumes	16





(a)

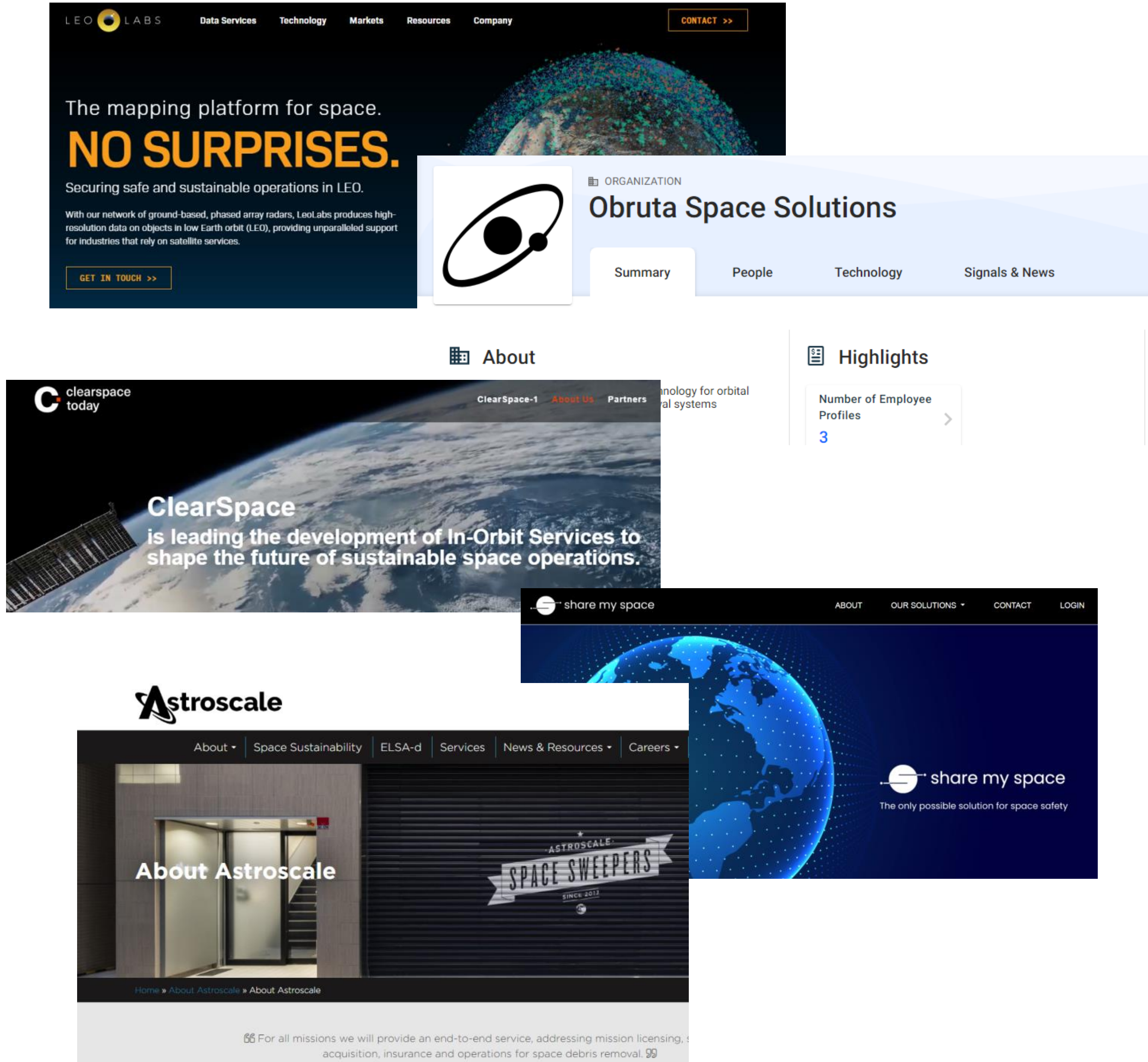




(b)

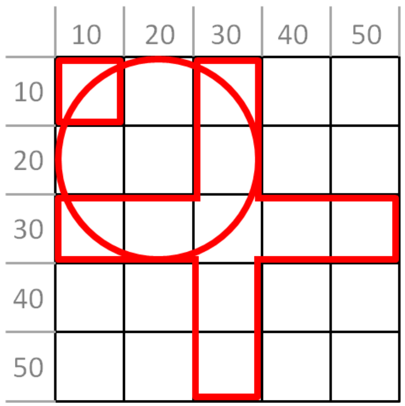
Background: Stakeholders

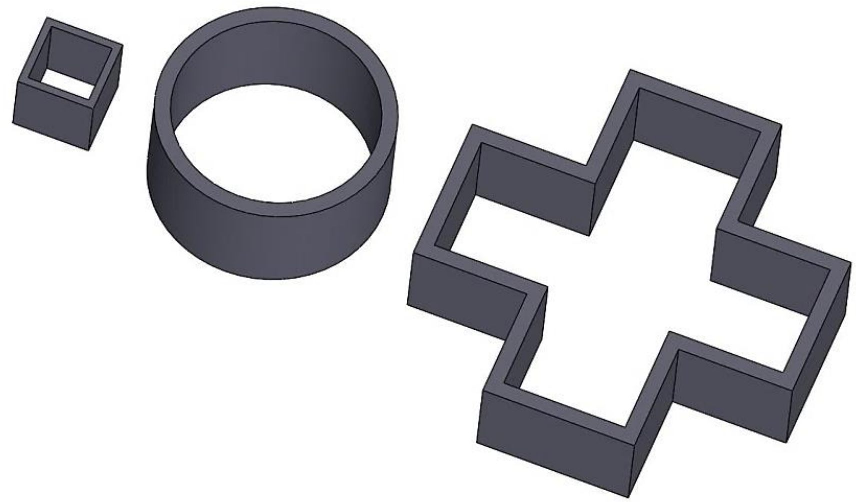
- Market size
- Agencies and big manufacturers

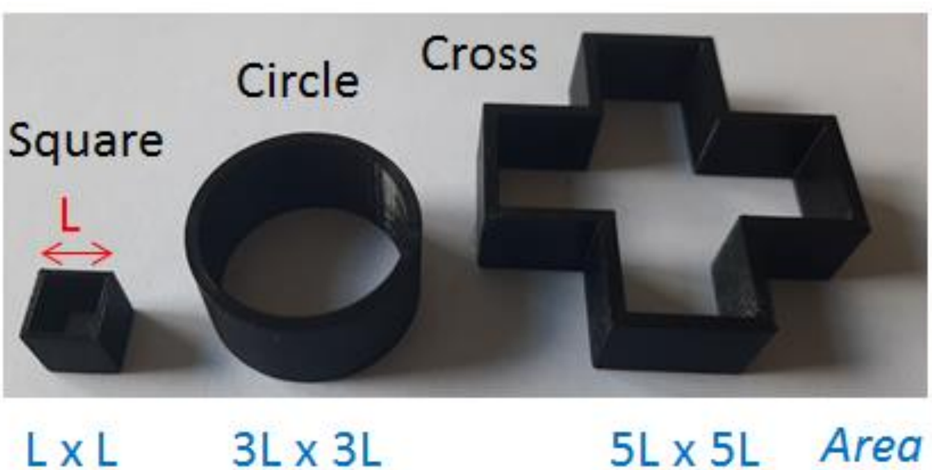


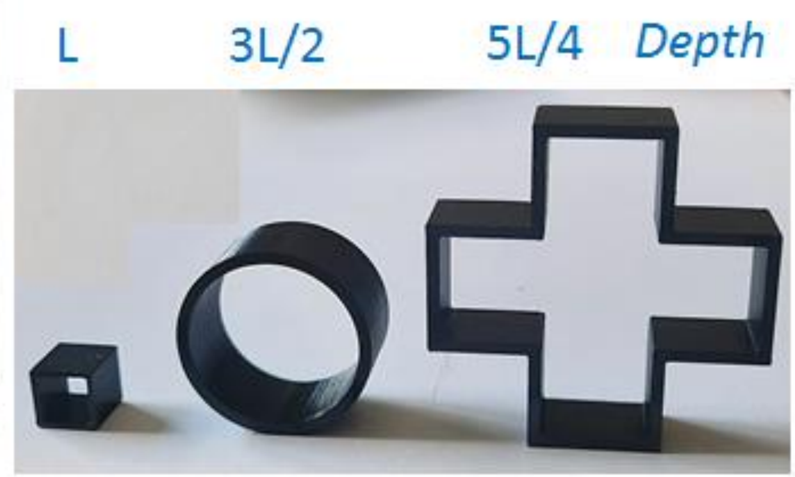
Background: Functional and performance requirements

- 1-10 cm: 1, 3, 5 cm (with the same architecture)
- 10x10, 30x30, and 50x50 with l, l/2, and l/4 shape ratio
- Altitude of 800 km
- Possibility of different weights
- Rotational speed
- From large debris fragmentation



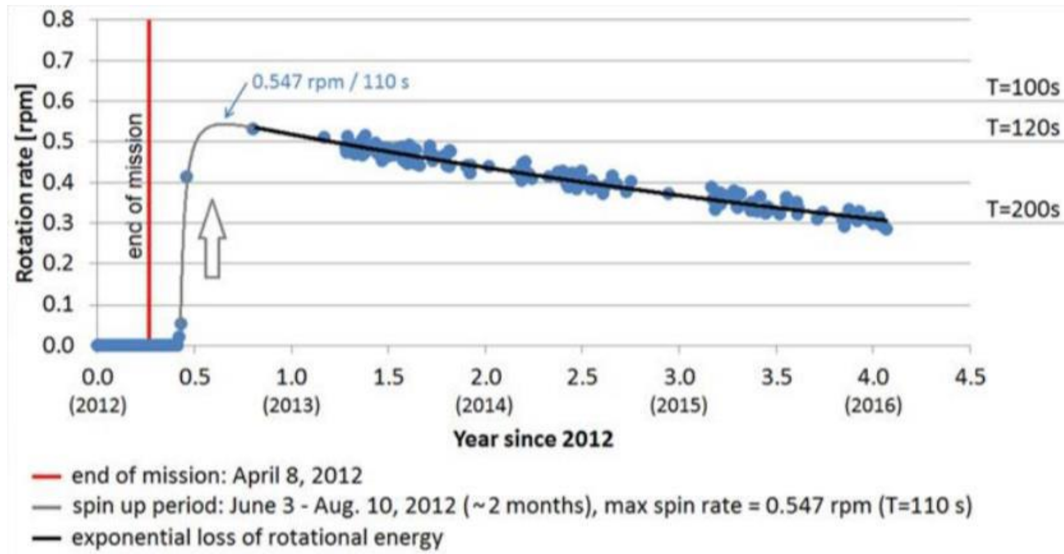






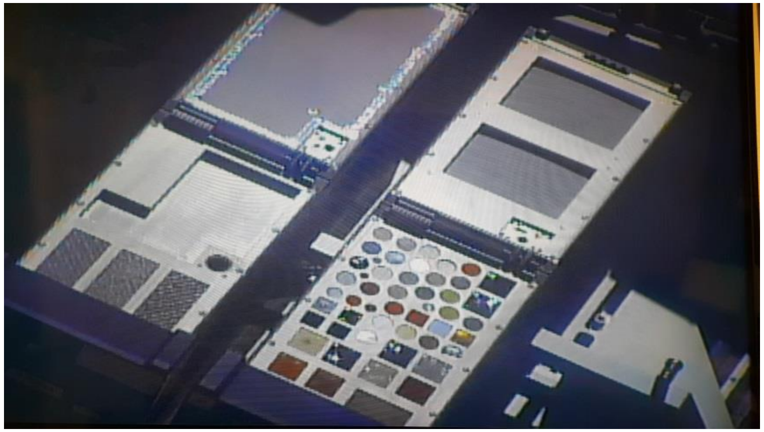
Analysis of debris distribution and properties

- Data from ESA
- *Existing Space object catalogues are typically limited to objects larger than 5 - 10 cm at low altitudes (LEO)*
- Focus of large debris
- ENVISAT spin < 1 rpm

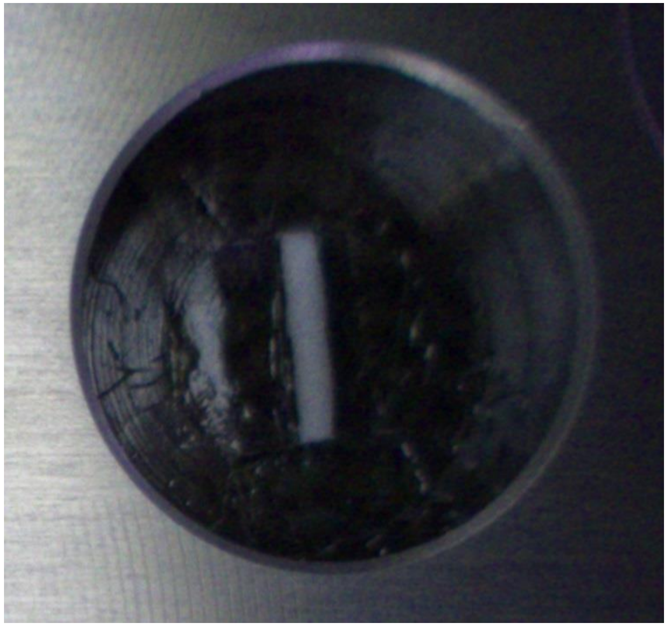


It has been observed that "*the chaser satellite and the space-debris will have a relative speed with respect to each other. Assuming the chaser can find and reach the debris, there will still be some residual error which is typically compensated by the capture mechanism. For large chasers that synchronize their motion with the debris this is typically in the order of up to 0.5 deg/s and 10 mm/s for speed and up to 5 deg and 70 mm in position*". The suggestion is that "*an analogous assumption would also be needed for the design of e-Spades*".

Analysis of Space environment



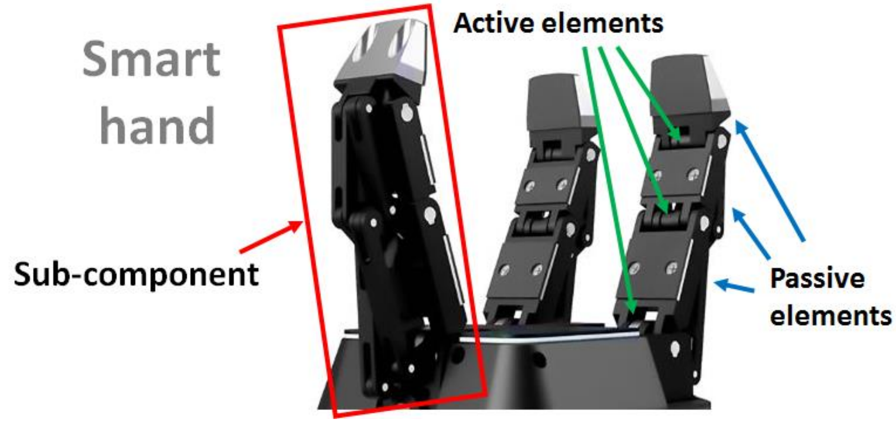
- Data from ISS
- MISSE 9, 10, 12, 13 with NASA
- Complex environment
  - Vacuum: outgassing
  - Atomic oxygen
  - Ultraviolet radiation
  - Particulate or ionizing radiation
  - Plasma
  - Temperature extremes and thermal cycling: -120°C to 120°C
  - Micrometeoroid and orbital debris impact: from 10 to 60 km/s

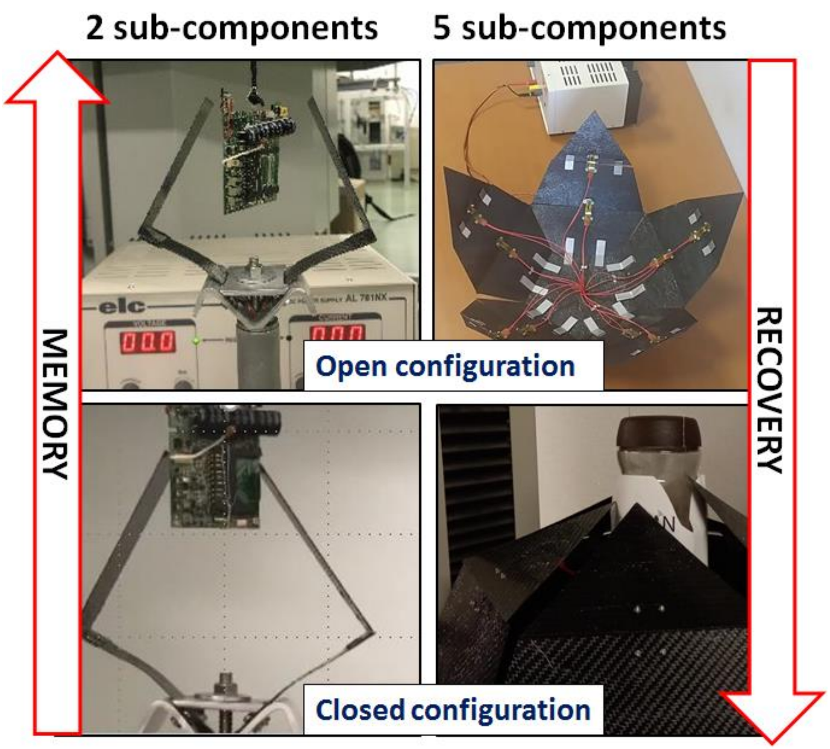


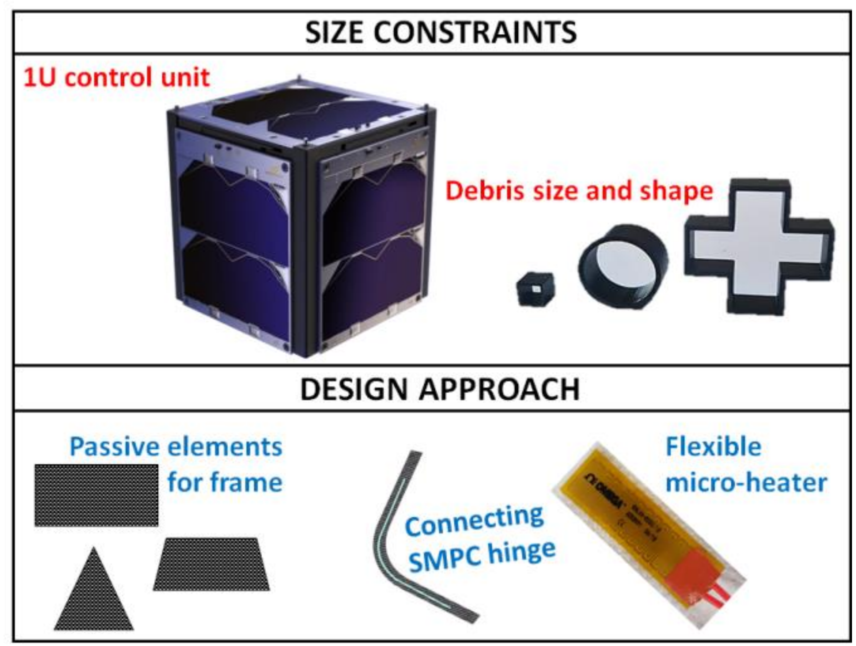
M.in.o.S.
Materials in Open Space

Conceptual design of the grabbing mechanism

- Modular design
- Constraints (1 U)

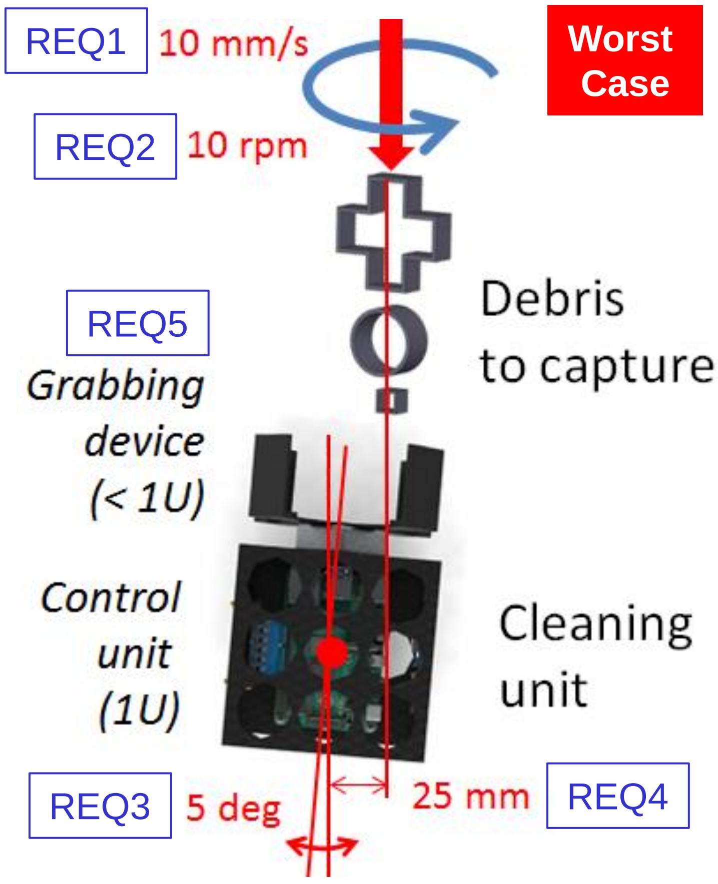


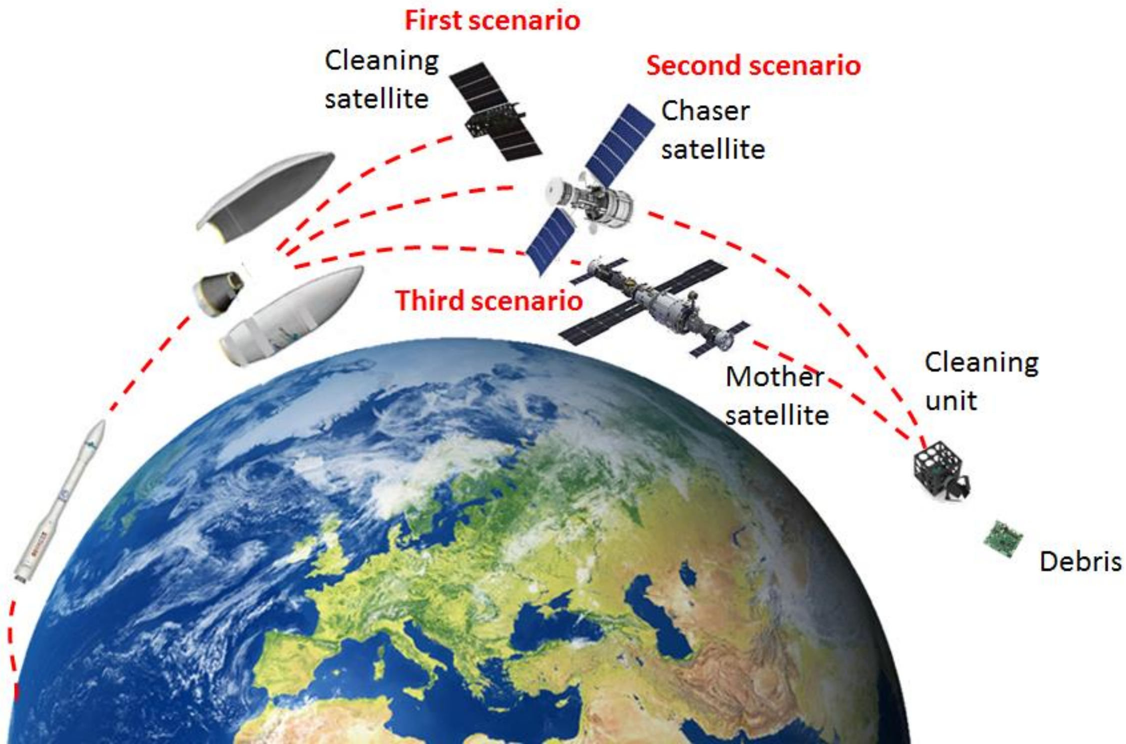




Example of a cleaning mission

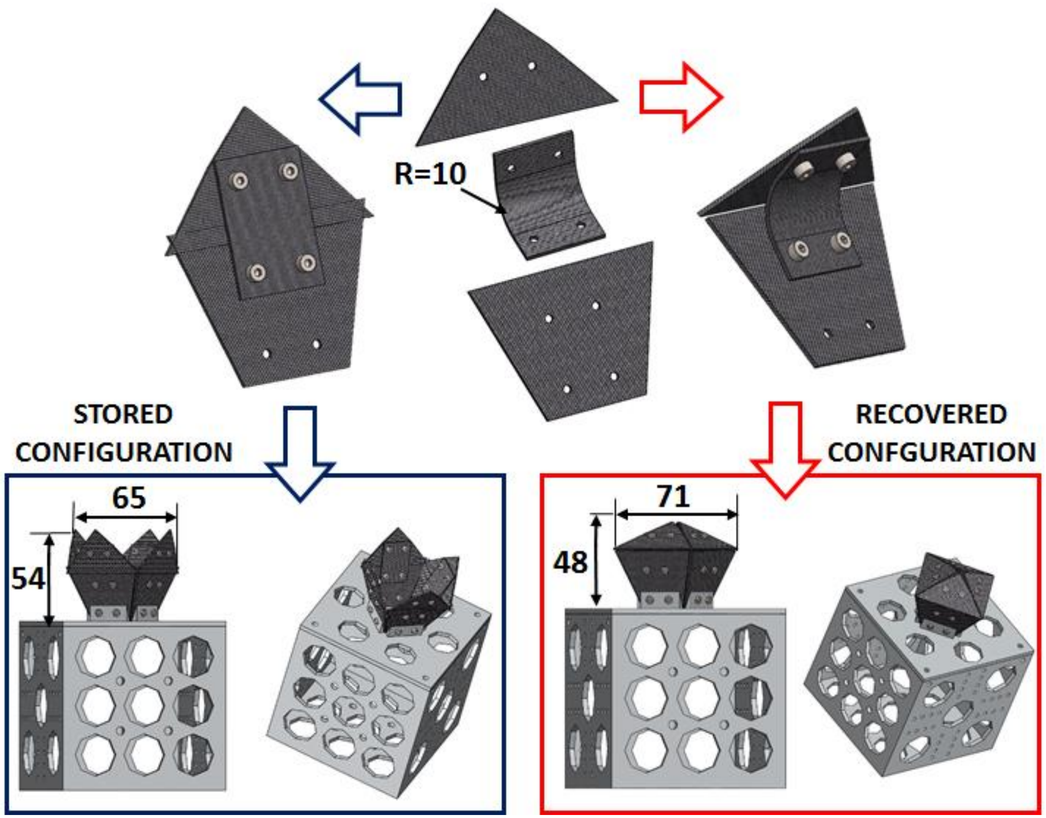
- Different scenarios
- Requirements and worst cases

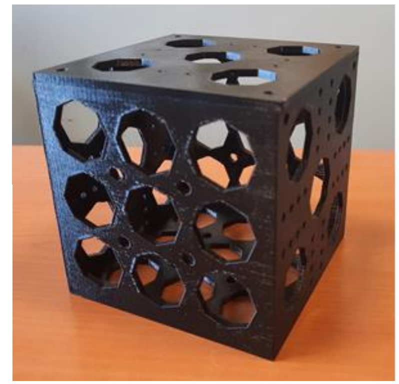


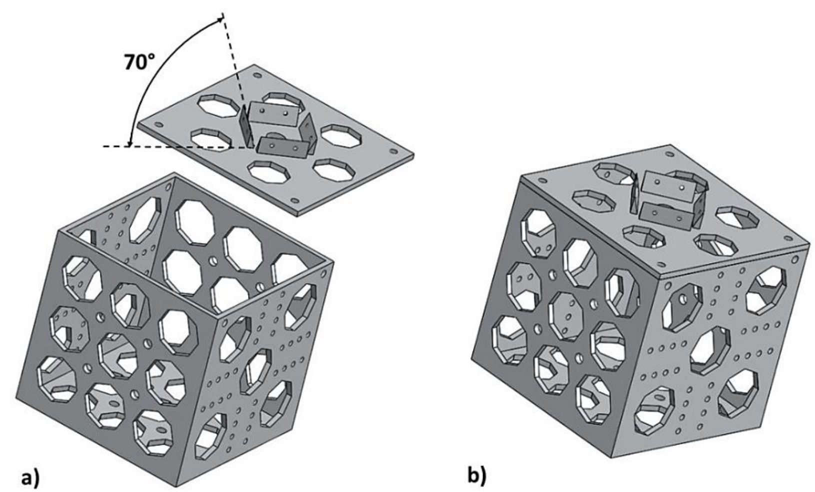


Definition of the grabbing geometry

- α-DREAM (Debris Removal by the European Autonomous Module)
- 1U reference module by FDM
- Only 1 level of hinges

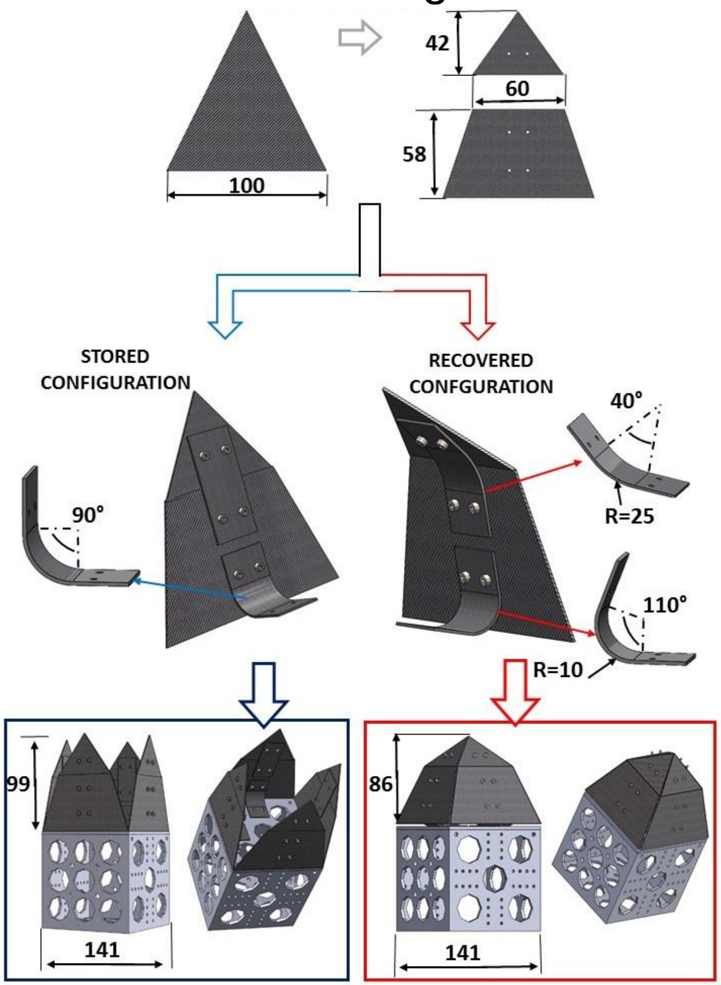


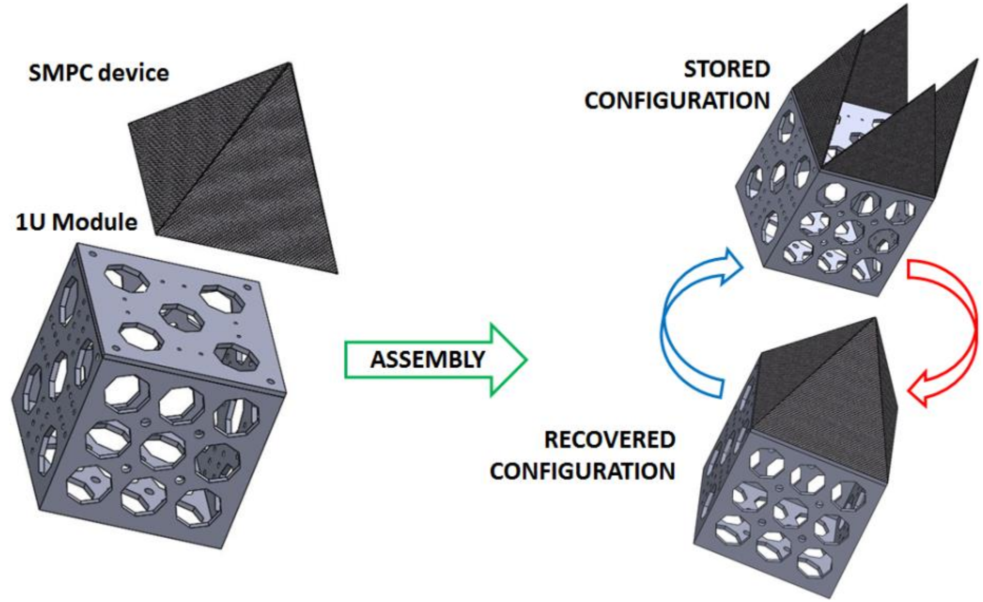


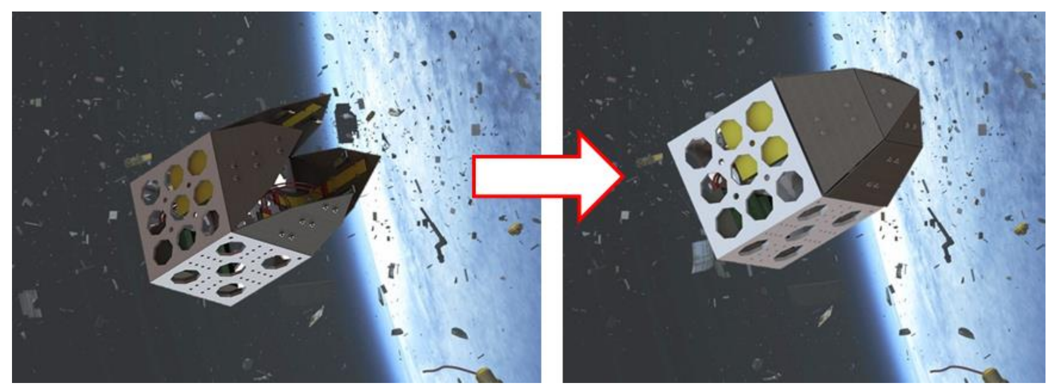


Definition of the grabbing geometry

- β-DREAM
- Increasing the volume
  - Using the 1U edge
  - 2 levels of hinges

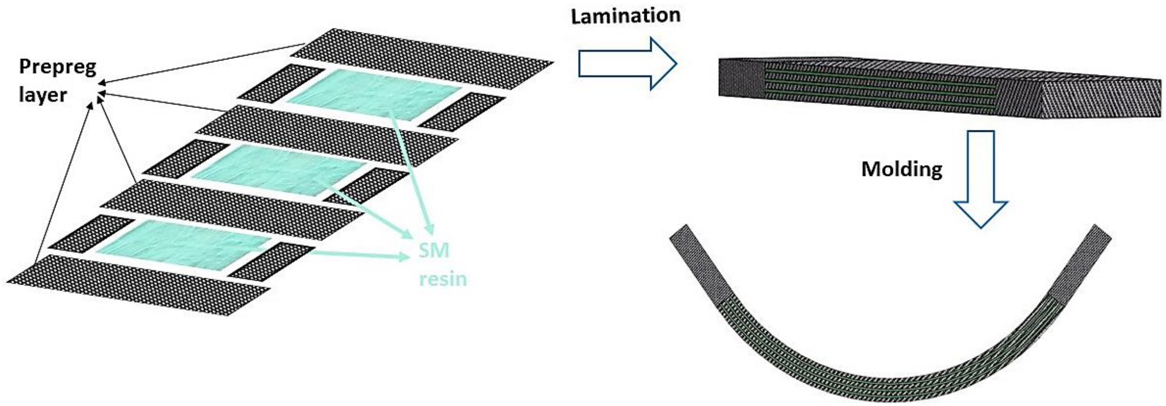


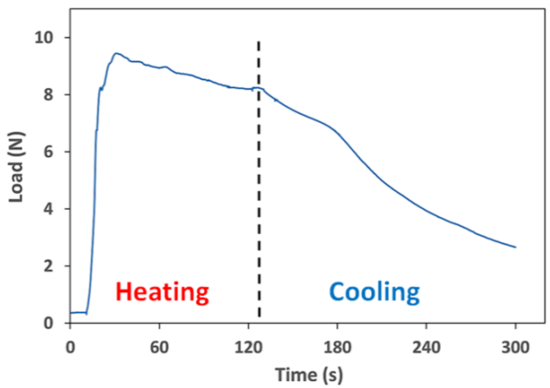


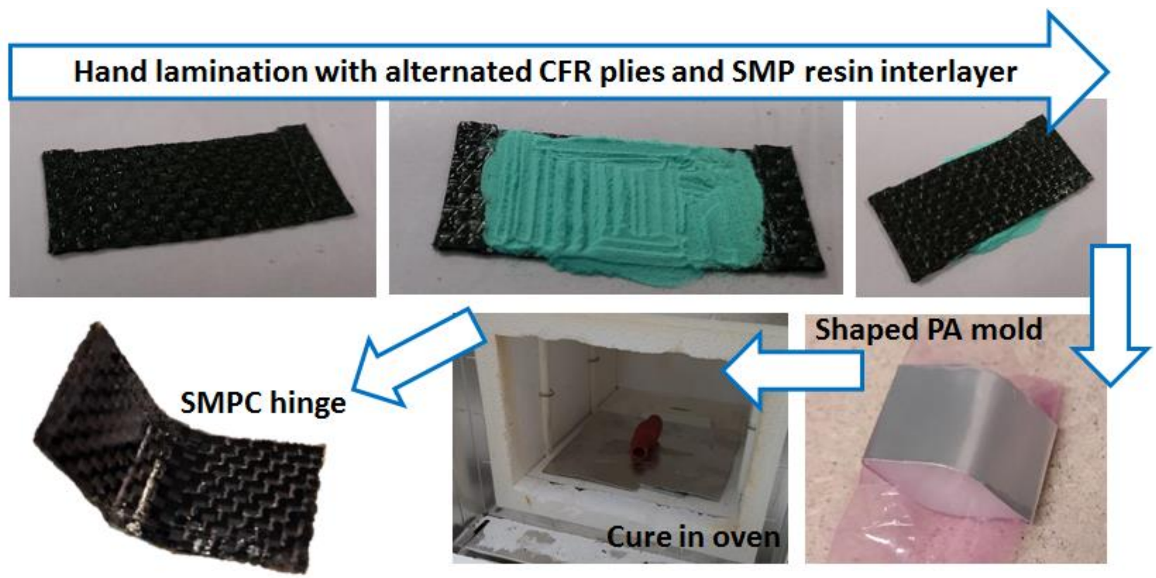


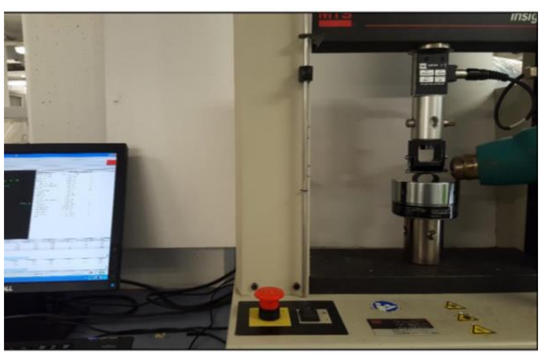
Definition of the manufacturing procedure

- Manufacturing of SMPC hinges and structural CFRP laminates
- Procedures
- Hinge weight = 2 g
- Testing



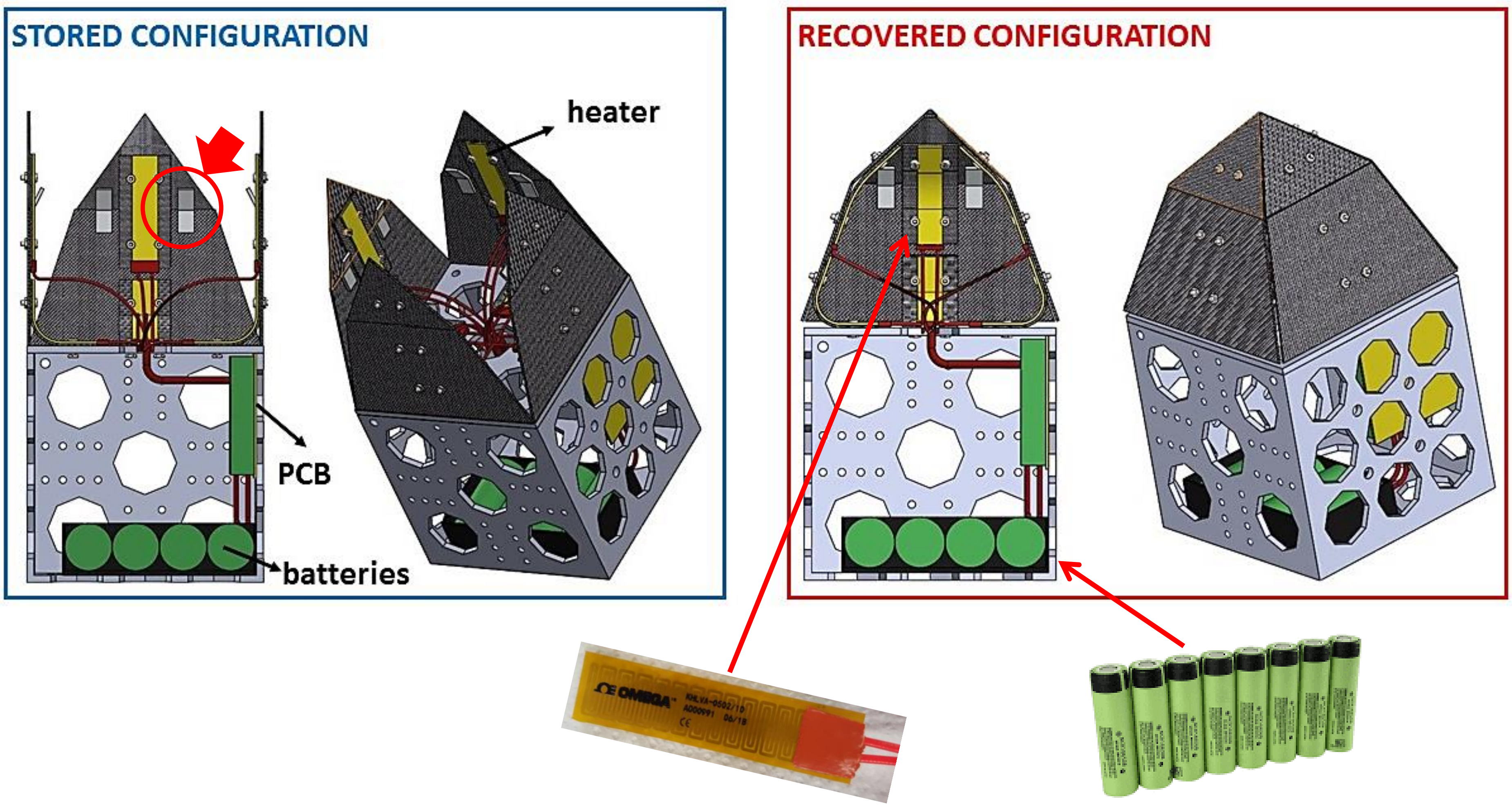






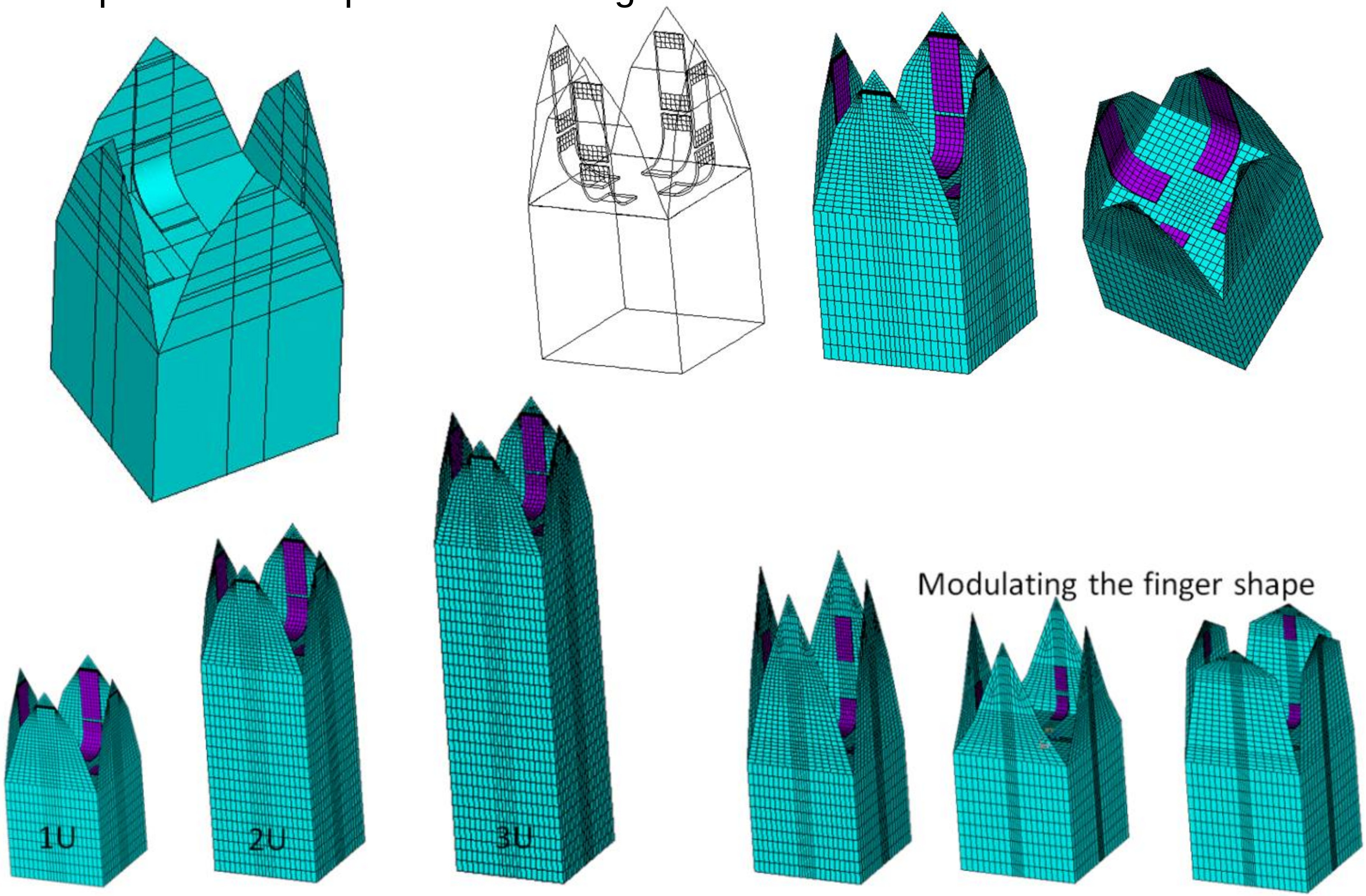
Design of the SMPC device

- β-DREAM design



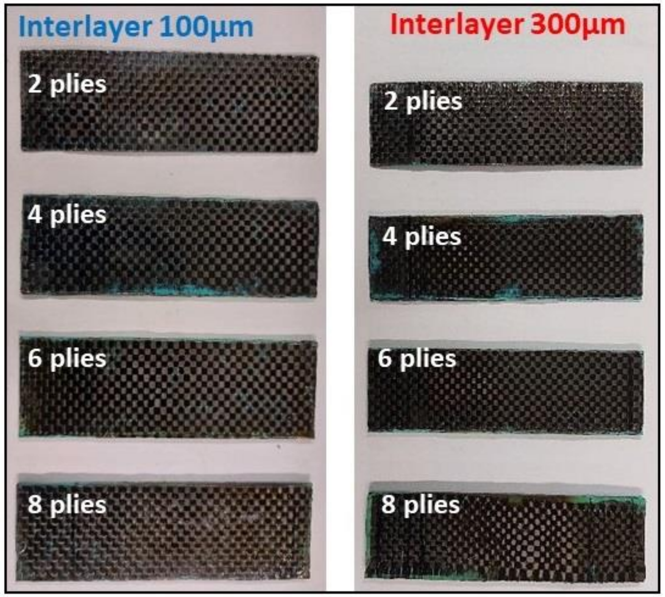
Modelling the behavior of the SMPC device

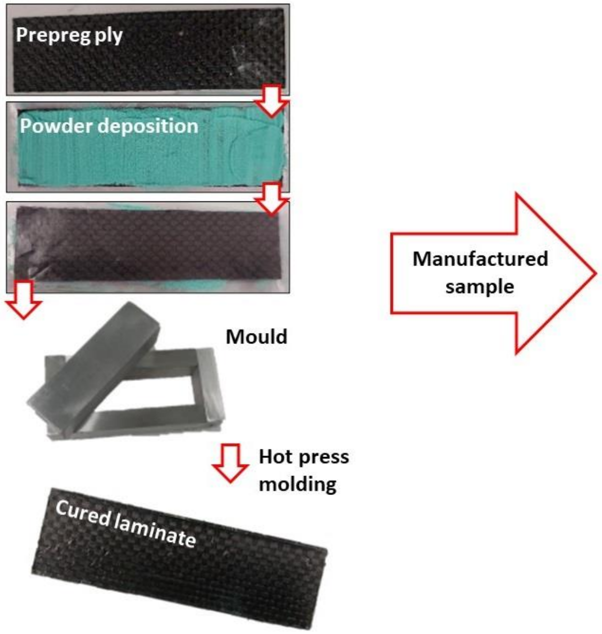
- Finite element modelling
- Batch procedure for parametric design

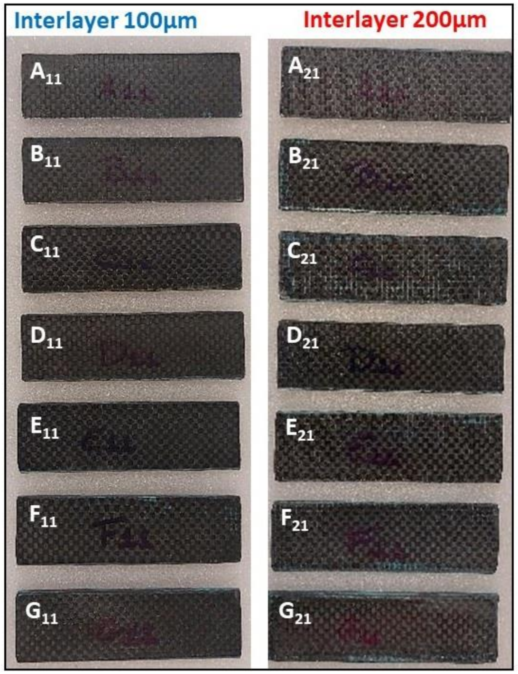


Manufacturing SMPC samples

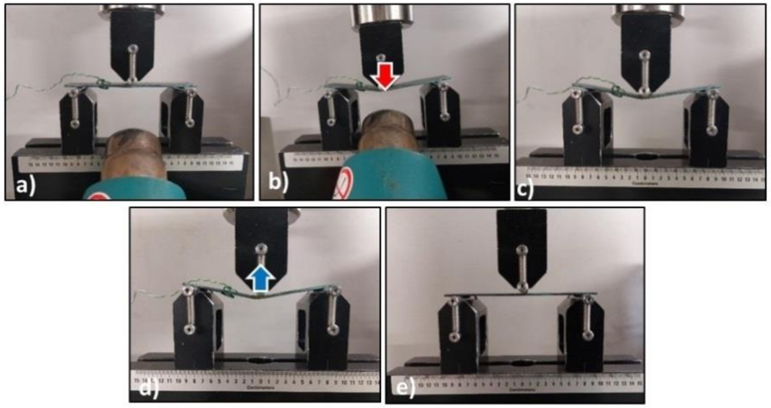
- 2 families of samples have been manufactured: the first for quasi-static bending tests (from 2 to 8 plies, and an SMP interlayer of 100 µm and 300 µm), the second for shape memory tests (from 2 to 8 plies, and an SMP interlayer of 100 µm and 200 µm).

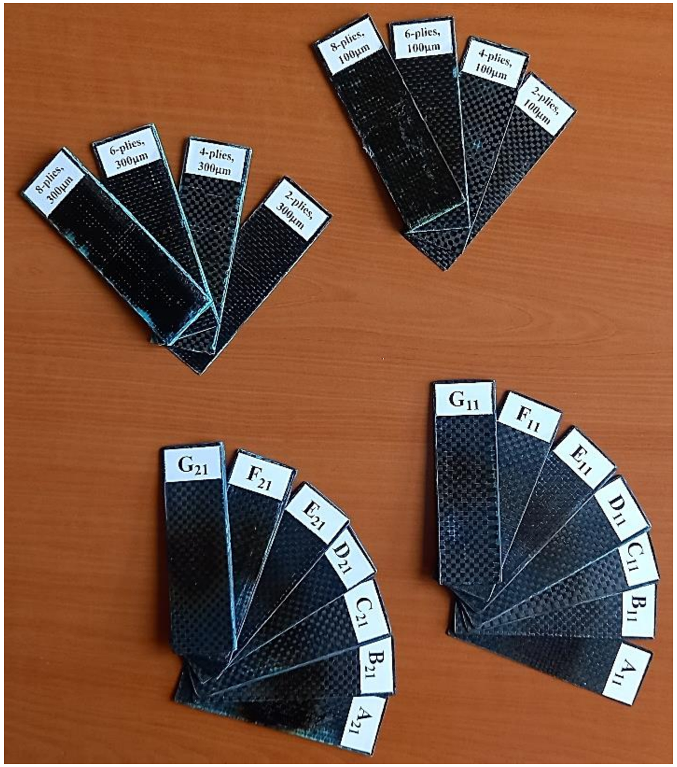






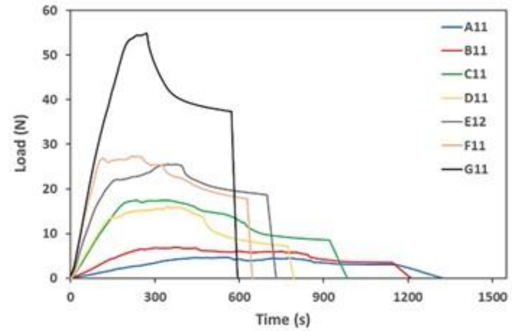
Sample characterization

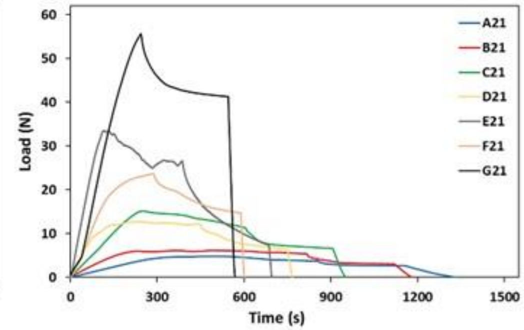


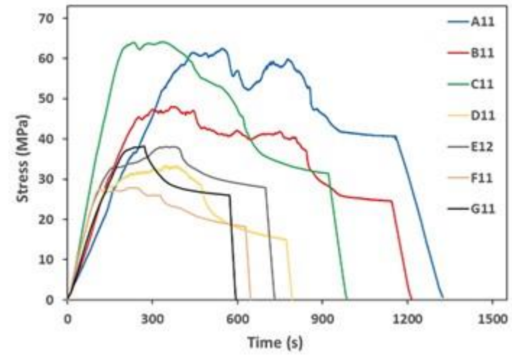


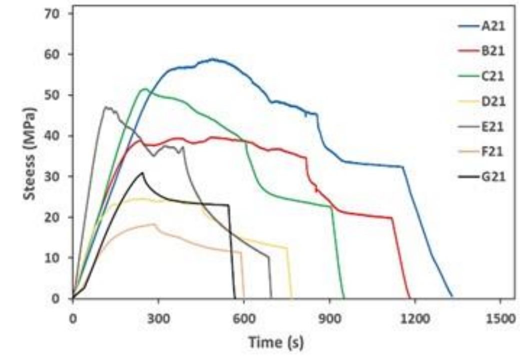
Interlayer 100µm

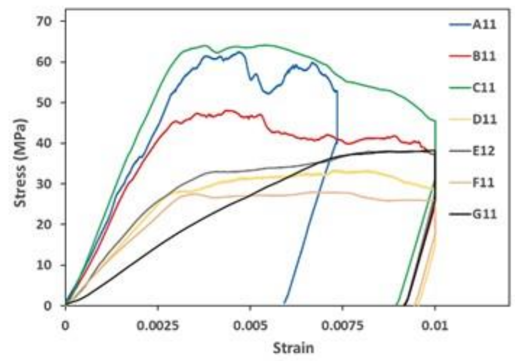
Interlayer 200µm

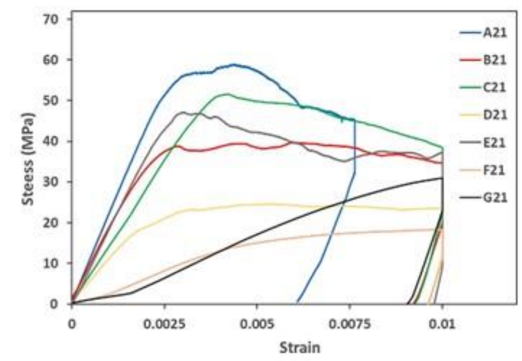










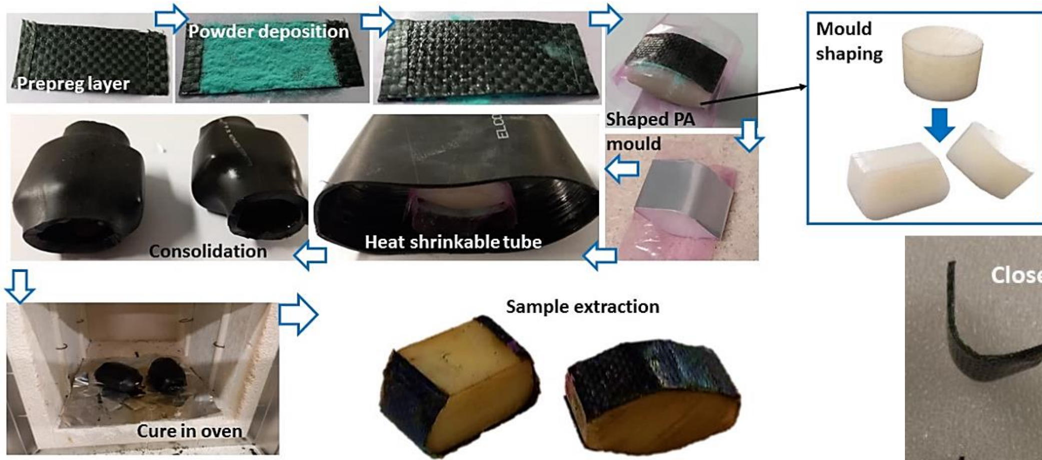


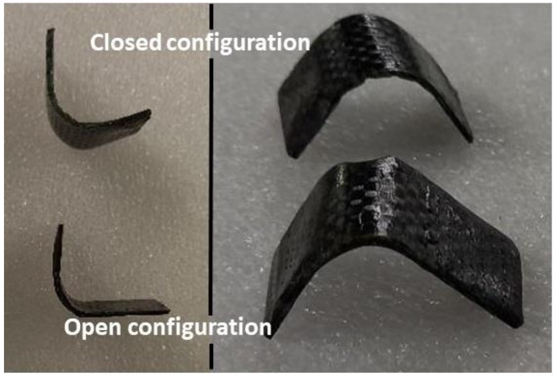
Sample characterization

Sample ID	L_M [N]	L_P [N]	σ_P [MPa]	σ_M [MPa]	R_f [%]	R_r [%]
A_{11}	3.96	3.06	52.69	40.71	80.47	98.89
B_{11}	5.34	3.53	37.14	24.55	91.68	94.80
C_{11}	12.40	8.58	45.48	31.47	89.37	98.68
D_{11}	13.80	7.23	28.71	15.04	95.46	93.56
E_{12}	24.93	18.69	37.22	27.90	91.84	98.24
F_{11}	25.45	17.80	26.01	18.19	94.32	97.64
G_{11}	54.91	37.36	38.24	26.02	91.51	94.78
A_{21}	3.86	2.71	46.65	32.75	86.06	97.59
B_{21}	5.45	3.10	35.02	19.92	95.04	98.04
C_{21}	11.28	6.63	38.36	22.55	92.63	98.23
D_{21}	12.21	6.45	23.58	12.46	96.12	91.86
E_{21}	26.56	7.28	37.28	10.22	97.72	98.99
F_{21}	23.63	14.71	18.29	11.38	95.97	95.60
G_{21}	55.61	41.26	30.95	22.96	90.45	93.09

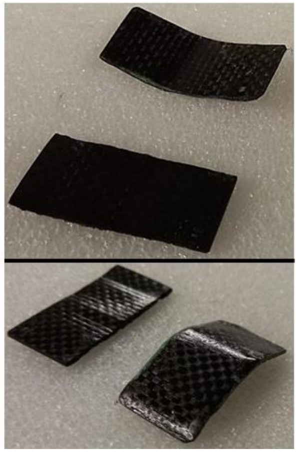
Manufacturing SMPC devices

- Active elements (SMPC hinges, 20 and 40 deg of opening angle)

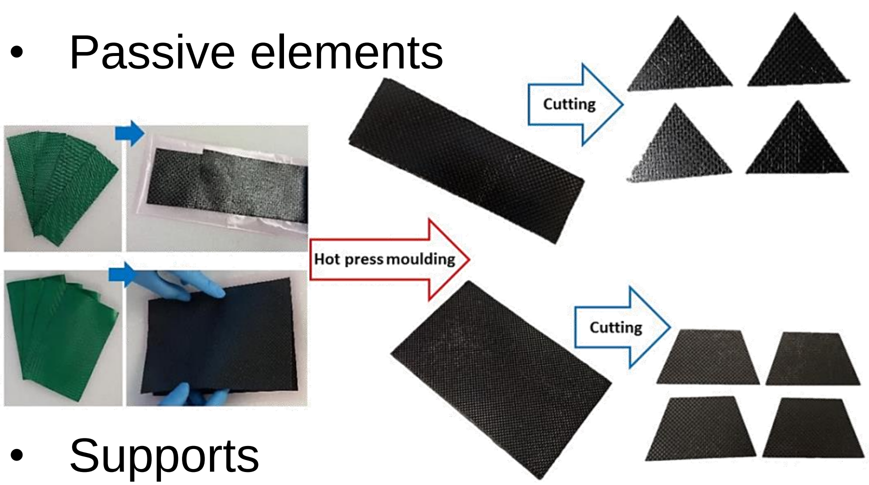




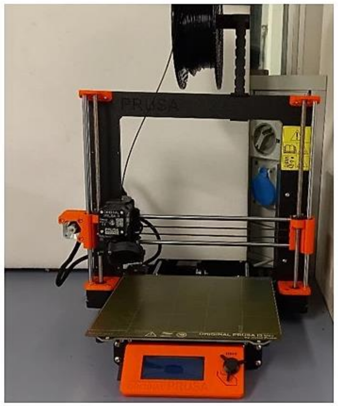
a)


b)

- Passive elements



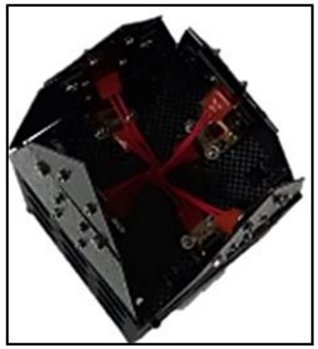
- Supports

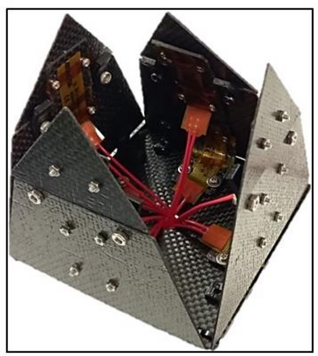

a)

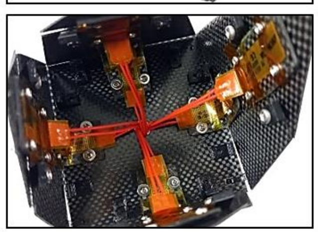
b)

Manufacturing SMPC devices

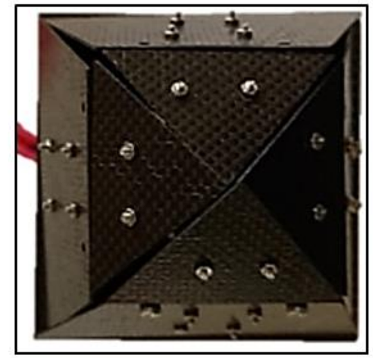
β-DREAM in open configuration





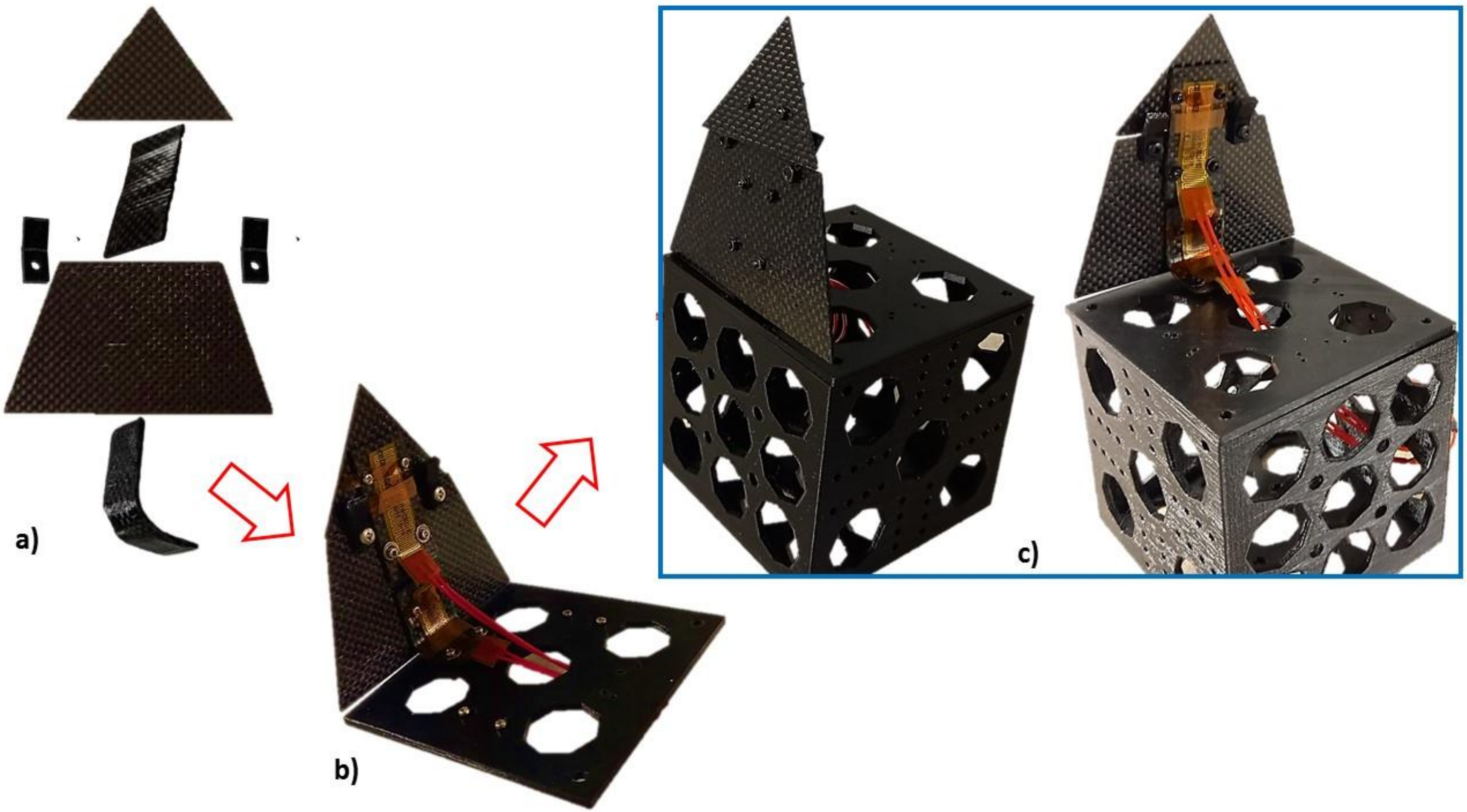


β-DREAM in closed configuration



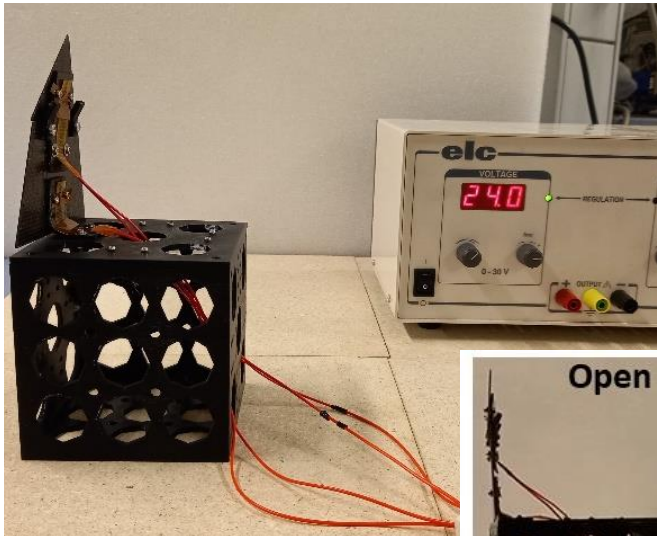
The β-DREAM prototype is about 130 g in weight, and is operated at 26 V, by a current of 2.45A, for a maximum power of 60 W.

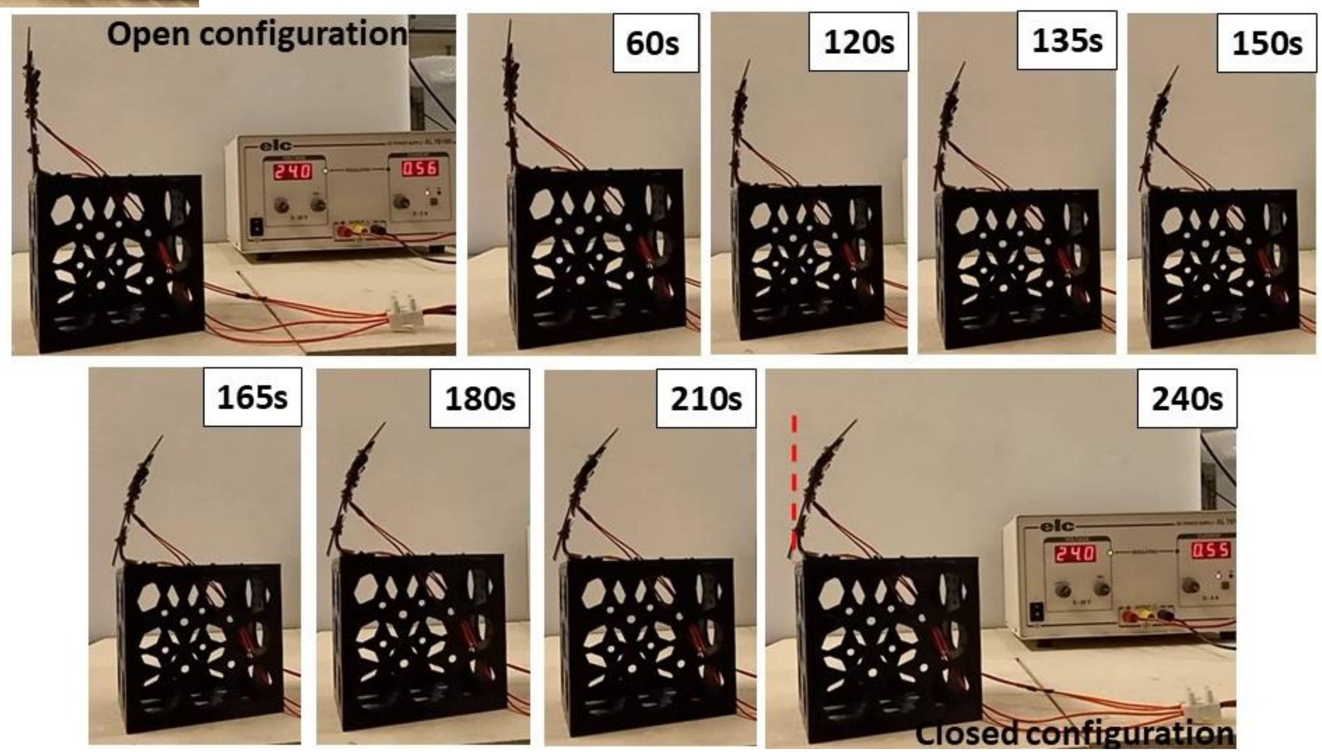
Manufacturing SMPC devices



Testing SMPC device functionalities

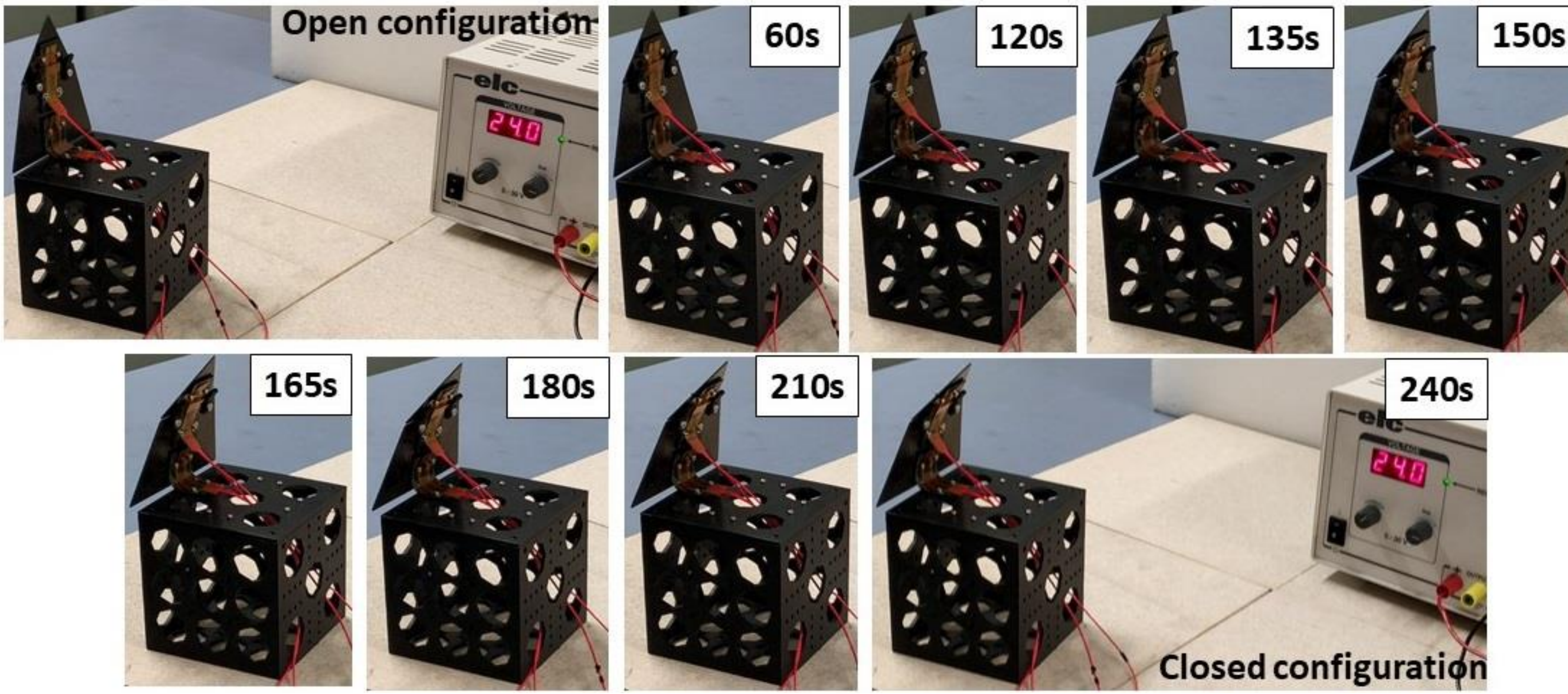
- Single arm closing (24 V, 0.55 A, 13.2 W per heater)





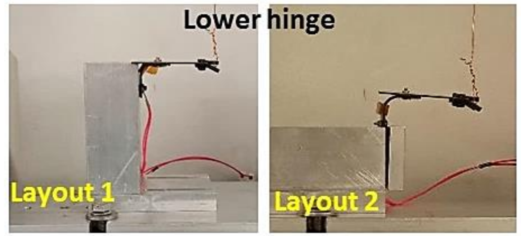
Testing SMPC device functionalities

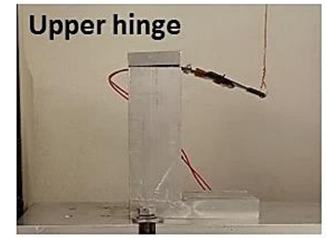
- Single arm closing (24 V, 0.55 A, 13.2 W per heater)

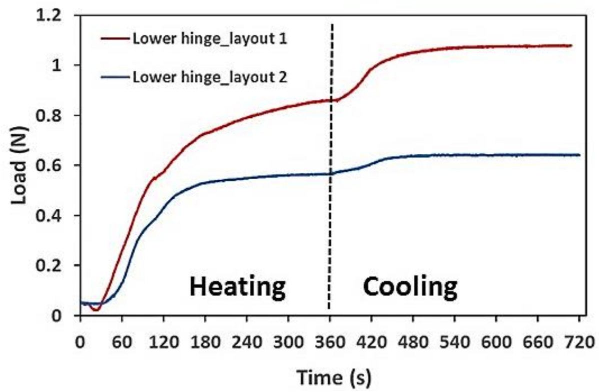


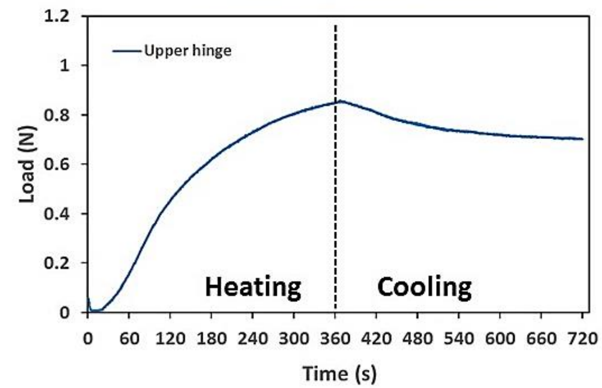
Testing SMPC device functionalities

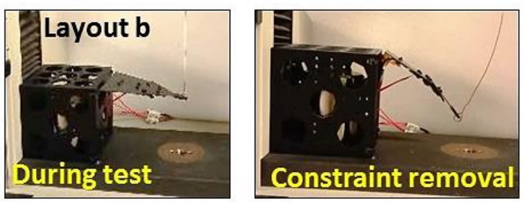
- Load measurement (1 N)

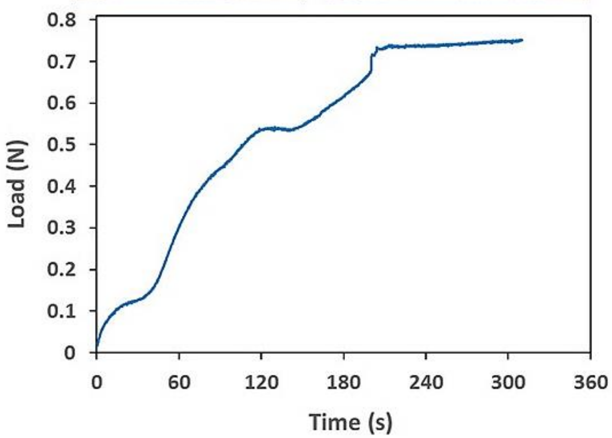


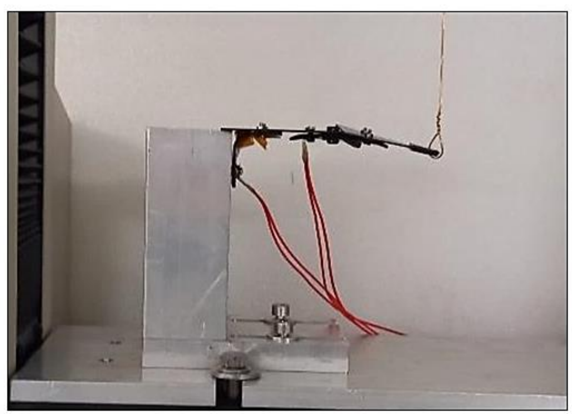


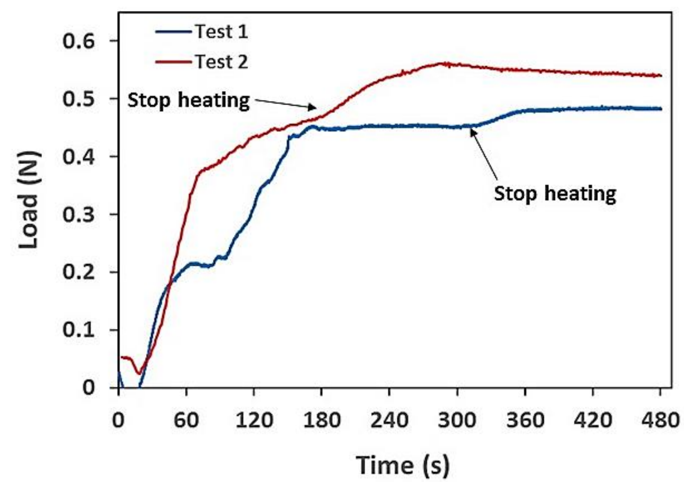






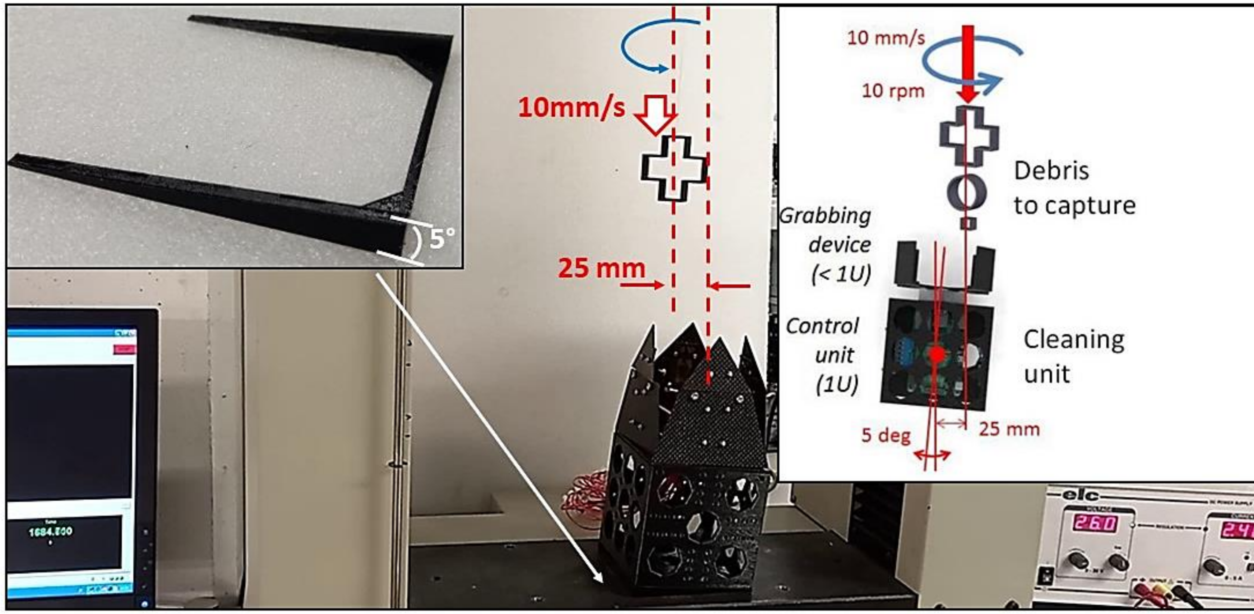


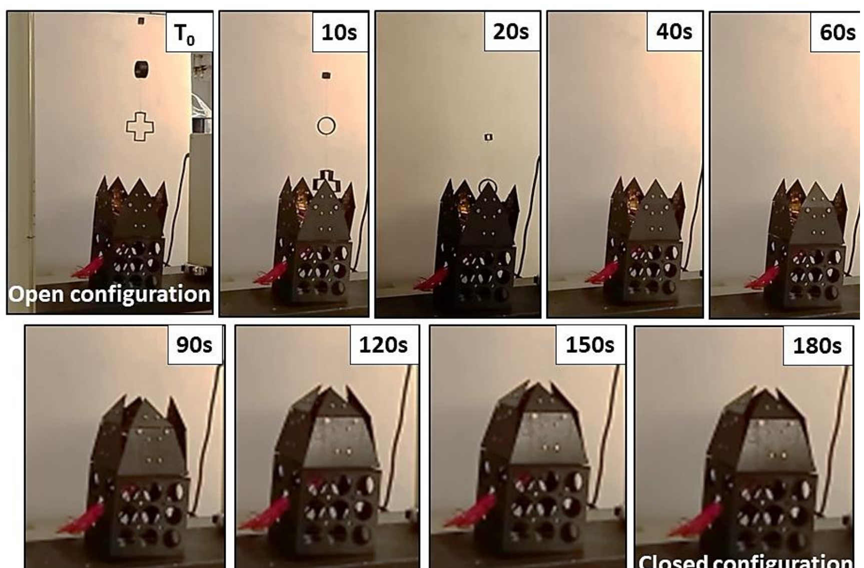




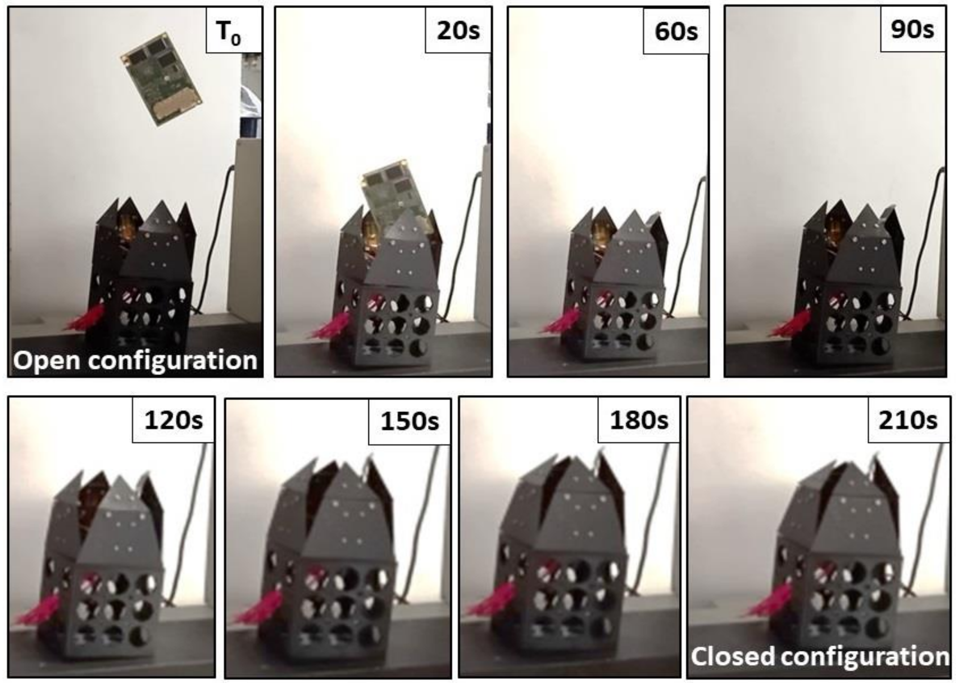
Testing SMPC device functionalities

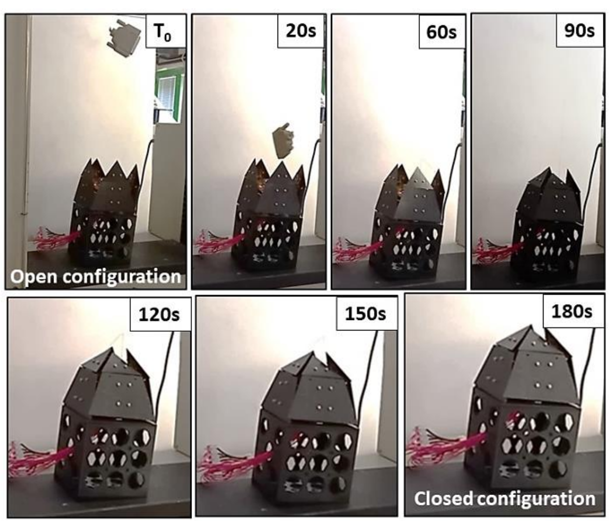
- Full prototype
- Supply 26 V

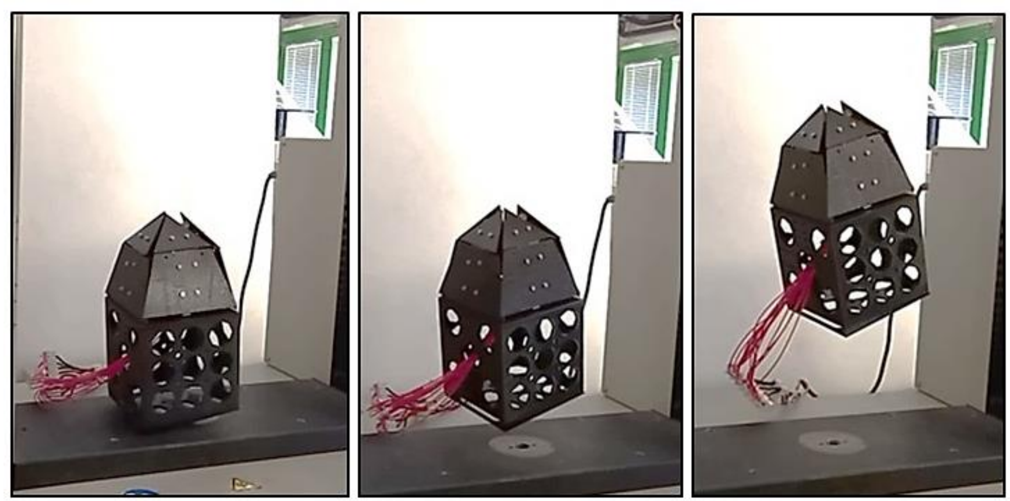




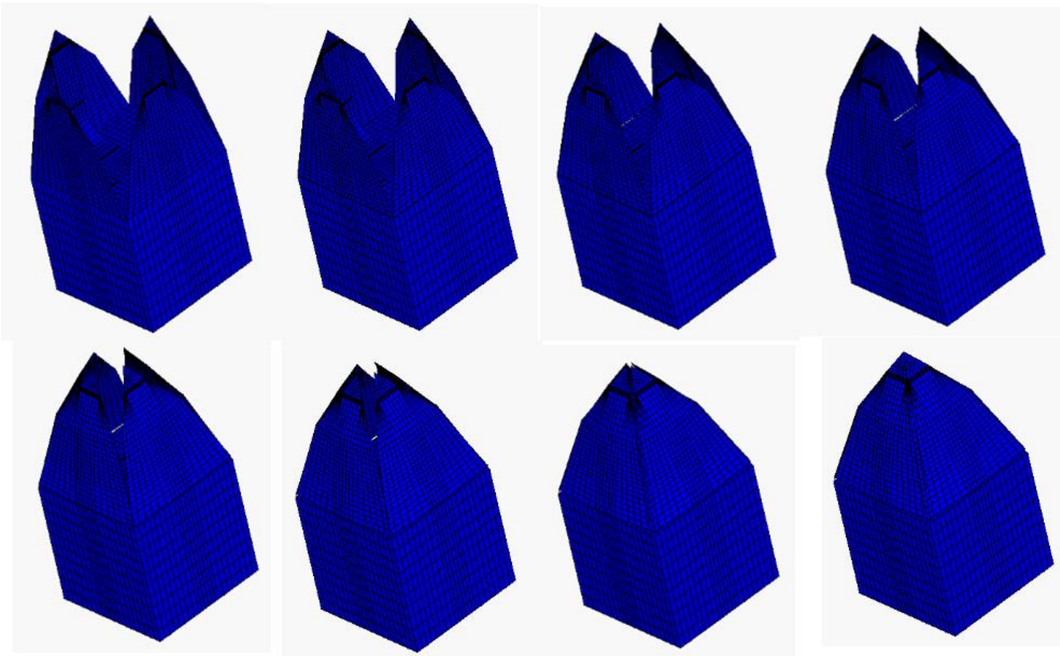
Testing SMPC device functionalities

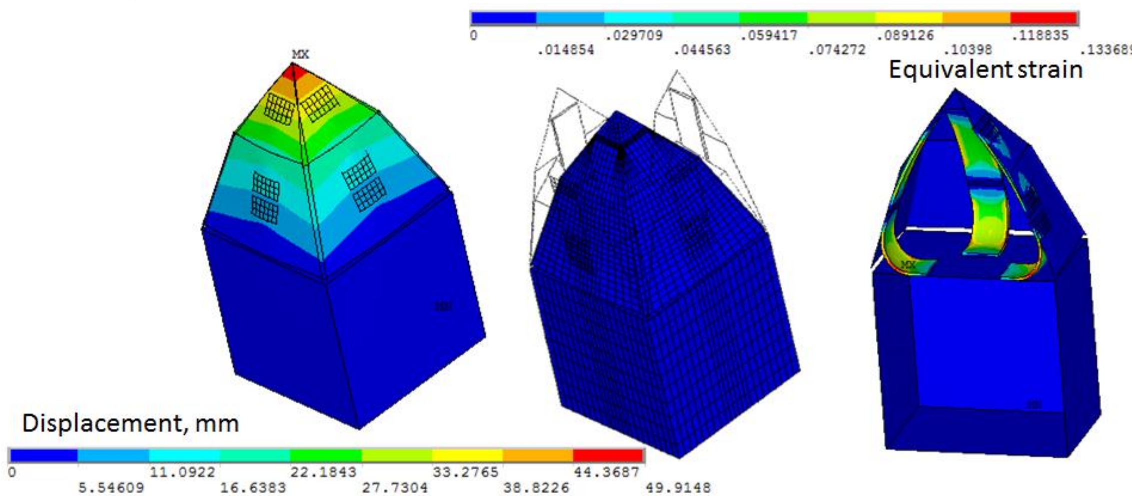






Validating numerical models





Conclusion

All the expected goals of the e-Spades project have been reached with good results and very high potential. A first prototype of a SMPC grabbing device (called β-DREAM, Debris Removal by the European Autonomous Module) has been manufactured and tested under several memory-recovery cycles without evident damages. A limit for the maximum number of cycles has not been found yet, but previous studies allowed testing SMPC samples under 10 consecutive memory-recovery cycles without failures. The prototype of the grabbing device is fully in composite, without mechanical parts apart from screws and bolts. The β-DREAM prototype is about 130 g in weight, and is operated at 26 V, by a current of 2.45A, for a maximum power of 60 W. The recovery time is 3 min. The current report summarizes the state-of-the-art of this new technology with all the manufacturing procedures of passive and active elements, the design strategy of the SMPC hinges, and the modelling of the unit shape evolution. A large experimental campaign on SMPC laminates is also reported for future implementation of this technology in different shapes or configurations. Next step would be improving the manufacturing procedure, reducing the hand operations by inserting automatic procedures for composite molding and assembly. In fact, the limit of the laboratory procedure on this aspect has been reached. In this further step, involving the collaboration of external entities, mainly industrial manufacturers and space related enterprises, would be beneficial for the quality of the SMPC device and its mission-oriented design. Moreover, in this project follow-up, system level assessment could be performed effectively, and a valid economic assessment could support future technology exploitations.

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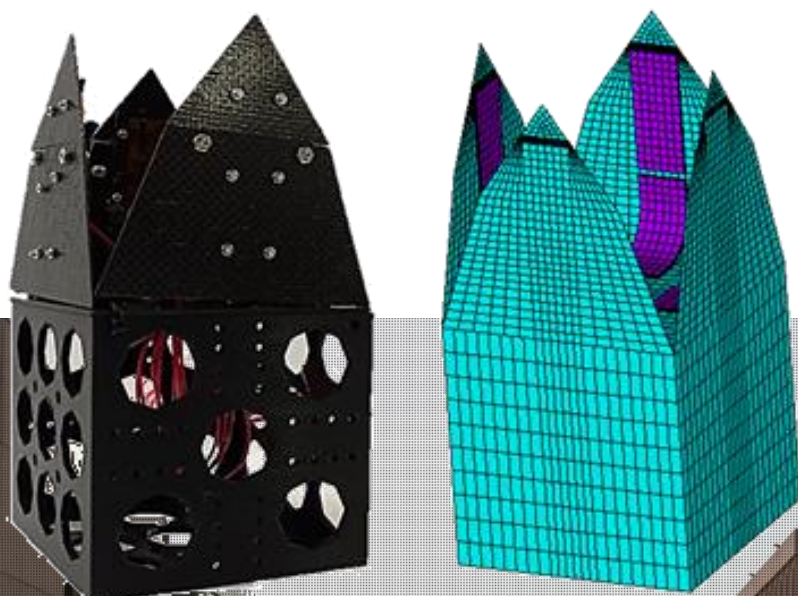
European SPace DEbris Suppression



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Final Presentation Slides