Deployment of a CubeSat radiative surface through an autonomous torsional SMA actuator

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Abstract. This study aims to provide a proof of concept concerning the integration of an "S" shaped SMA tube into the thermal circuit of a 12U CubeSat. The torsion-based actuator utilizes the heat from the circulating fluid accumulated inside the satellite to enable the deployment of a radiator panel through the manifestation of the shape memory effect in the material, facilitating heat dissipation via radiation.

Introduction

CubeSats have proven over time to be a viable alternative to conventional systems, performing the same scientific operations in a considerably smaller volume. Despite their many innovative aspects, the miniaturization of this class of satellites still presents several challenges to overcome. In particular, integrating hardware components in such limited space restricts design flexibility and poses specific issues in developing adequate thermal control systems due to constrained power supplies.

A commonly adopted strategy for thermal management involves deploying radiator panels to dissipate heat generated by the system's internal components via radiation in the space environment. Among the various deployment mechanism solutions, using shape memory alloy actuators could represent a revolutionary choice.

SMA can lead to very convenient devices with a significant reduction in mechanical complexity and size and better reliability of the actuation system, providing an excellent technological opportunity to replace conventional electric, pneumatic or hydraulic actuators across all sectors, especially in the space segment [1].

The following work aims to develop a torsional SMA tubular actuator to be integrated on a 12U CubeSat's thermal fluid loop circuit in order to deploy a radiator panel, thus maintaining the satellite's internal environment within the appropriate temperature ranges. The torsional behavior of SMA actuators is not widely discussed in the literature and presents critical aspects that still require further investigation, such as cycling stability, a crucial property for optimal integration into a space system.

Concept description

In the proposed solution, the actuator exhibits an S-shaped tubular morphology [2] which enables the integration of the SMA into a closed-loop liquid circuit, allowing for thermal control operations and panel actuation to coexist within the same element, significantly reducing system complexity. In this approach, the mechanism governing the SMA activation is the same fluid flowing inside

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the circuit, which experiences localized heating within the satellite due to heat dissipation from internal components and external thermal loads. Through convective heat exchange, the tube, initially deformed in torsion in the martensitic phase with the panel fully closed, generates adequate torque as the SME unfolds, ensuring a 90-degree opening of the radiator element. As the deformation imposed on the tube's central section recovers, the end embedded within the panel is compelled to rotate rigidly, subsequently facilitating the panel's movement (Figure 1).

After the first recovery of the memorized form, neither the return to the low temperature (even below M_f) nor subsequent heating can induce further variations in the shape, until a deformation provided by an external element is set again. Since the actuator is required to operate cyclically depending on the satellite's thermal demands, a rearming strategy must be implemented (for instance, the rearming element can be represented by a torsional spring).

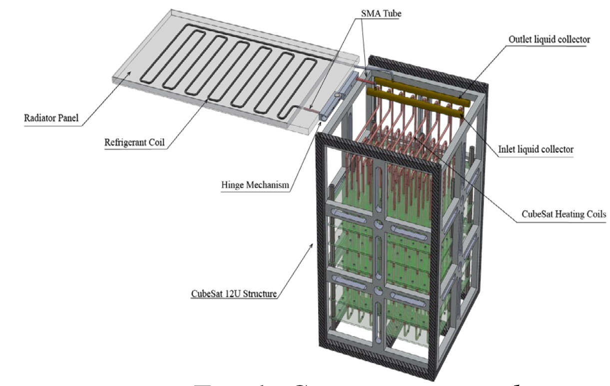

Fig. 1: Concept proposed

Manufacturing and thermomechanical characterization of the SMA actuator

The prototype design process began with the production of various actuator samples using unprocessed tubes made of NiTi alloy. Starting from the unprocessed material purchased, which has an outer diameter of 3 mm, a thickness of 0.24 mm, and pseudoelastic properties, it was necessary to implement heat treatments in order to obtain the desired shape and modify the characteristic temperatures set to achieve shape memory properties. Thermal treatments result in the generation of numerous precipitates inside the material, compromising the maximum performance that the actuator can provide. Therefore, for future developments, it will be necessary to employ tubes that already exhibit characteristic temperatures suitable for the final application.

The tube is firstly inserted into a mold, designed in accordance with the geometry to be imposed on the material, followed by a two-phase furnace heating: a) preheating the tube to a temperature of 565°C and b) maintaining a constant temperature at that level for 45 minutes.

To assess transformation temperatures and behavior, DSC tests have been conducted on a single sample. The results reveal that M_f, M_s, A_s, and A_f are -11.99°C, 20.98°C, 20.43°C, and 43.35°C, respectively.

Rotary recovery tests have also been performed to gain a clear understanding of the actuator's performance, particularly in terms of the material's deformation state recovery capacity. The residual rotation detected at the end of each cycle is related to the vertical distance between the initial and final points of the hysteresis curve, indicating a deformation that the material will not be able to recover. This distance increases as the torsional load applied to the tube increases. For torque values greater than 0.07 Nm, the formation of a non-negligible residual deformation was detected.

Cycling tests have been performed to assess the number of cycles after which a complete recovery of the imposed deformation is no longer guaranteed, due to a permanent modification of the crystalline microstructure of the alloy. The tests were conducted with an applied load of T=0.0655 Nm, as the rotary recovery data indicate that this value represents the minimum load required to impose a 90° rotation on the material in the martensitic phase.

From the cycling tests, it was concluded that after 70 cycles, the material starts to exhibit a destabilization of performance. These results are extremely promising when compared to those of linear actuators with a high degree of precipitates within the matrix, in which the destabilization of shape memory properties emerges after a few cycles.

Prototype design and fabrication

A conceptual mockup has been designed (Figure 2) and constructed to evaluate the feasibility of the proposed solution through experimental tests conducted in a terrestrial environment, simulating only the internal heating within the CubeSat. Consequently, no rearming mechanism has been implemented. As a result, after each opening process, the system must be cooled inside refrigerators and manually rearmed.

The prototype features a liquid fluid loop integrated into a fixed frame, with dimensions identical to those of a 12U CubeSat structure, and a 3D printed frame free to rotate, representing the radiator panel. The actuator is housed inside a hinge mechanism necessary to ensure the alignment of the tube to the desired axis of rotation for the panel deployment and its connection to the fixed frame.

Fig. 2: Experimental mockup

The hinge mechanism is composed of two elements, one intended to be attached to the fixed frame and the other to the mobile frame, both capable of rotating with respect to each other.

The two components are then forced to rotate relative to each other by 90° thereby generating a torsional stress state in the central section of the tube and thus preloading it in order to mount the panel in a closed configuration. Subsequently, each element is connected to the corresponding frame, and finally, the support element for the panel is inserted and mounted onto the panel itself. The liquid fluid loop consists of two copper serpentines, each one connected to an end of the actuator, positioned respectively inside the CubeSat structure and the panel. The circulation of the liquid is mediated by a micropump, in turn, connected to the serpentines via PTFE flexible hoses that close the loop.

Test results

A test of the prototype was conducted to demonstrate the functionality of the design. The test started with the prototype at room temperature with the SMA tube already in the armed configuration (i.e., panel closed). The circulating liquid was heated at the internal coil within the fixed frame using an electric resistance wire, wrapped upstream of the actuator's inlet section, powered to dissipate 400W due to the Joule effect.

The entire process was monitored by a FLIR infrared thermal camera and two thermocouples, positioned at the inlet and outlet sections of the tube. The angles reached were measured using a graduated scale located beneath the panel.

The heating proved to be adequate, allowing the tube to reach temperatures suitable for complete austenitization of the alloy. As a result, the panel achieved a rotation of 85° in 155 seconds from the time the current supply was turned on, as shown in figure 4. The inability to reach a fully open position (i.e, 90° of rotation) is related to the thermal treatments the material underwent. These treatments lead to the formation of precipitates, which compromise the macroscopic recovery of the imposed deformation state

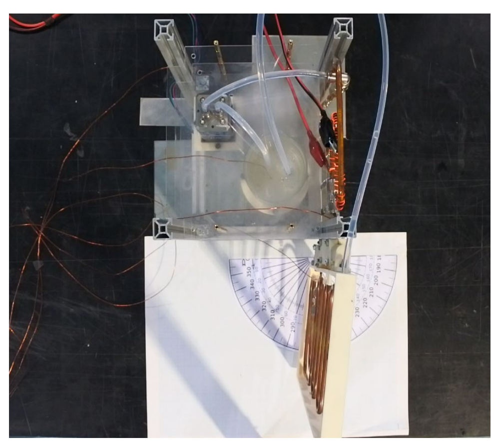

Fig. 3: Final angle reached

during the development of the shape memory effect at the material level.

Conclusions

The presented work aims to provide a proof of concept on the feasibility of developing a torsional tubular SMA actuator, which is activated by the internal circulation of a fluid heated to an appropriate temperature. The goal is to integrate this actuator into a 12U CubeSat's thermal fluid loop circuit for the purpose of deploying a radiator panel to 90° angle of rotation.

The fabrication process started with the production of various actuator samples using precursor tubes for stents, made of NiTi alloy, due to the purchasing easiness. The outer diameter of these tubes is 3 mm and the wall thickness is 0.24 mm. Since these precursor tubes exhibited pseudoelastic behavior, it was deemed necessary to implement thermal treatments in order to obtain the desired morphology and shape memory features. Torsion tests demonstrated that significant rotations could be achieved at low strain/stress levels, highlighting the suitability of this approach for the 90-degree deployment of a radiating panel on a small satellite. Moreover, cycling tests revealed that, despite the high degree of precipitates within the matrix, the material's stability is ensured for approximately 70 cycles. This result is particularly noteworthy, as it is well known that linear SMA actuators with high precipitate content tend to become unstable much earlier. Consequently, it has been shown that the choice to implement a torsion-based actuation system can be considered highly valid. Subsequently, a prototype was designed and developed to assess the feasibility of employing the actuator in a real satellite operational context. The system was then tested in a terrestrial environment, yielding highly interesting results, as the panel reached an angle of 85° within a relatively short time. The incomplete achievement of the desired rotation can be attributed to the high concentration of precipitates in the actuator, which compromises its maximum attainable performance. Nevertheless, these results are extremely promising, as, even with this non-optimal material, a comprehensive feasibility study of the system to be developed was provided, demonstrating a solid foundation for reliability.

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