Ultra-low-weight Rotary Actuator for Operation on Mars and Pin Puller Mechanism Based on a Novel Shape Memory Alloy Technology

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Abstract

A novel Shape Memory Alloy (SMA) has been developed as an alternative to currently available alloys. This material, called SMARQ, shows a higher working range of temperatures with respect to the SMA materials used until now. This temperature restriction is one of the most critical limitations of the current SMA devices for their use in space and other applications. A full characterization test campaign has been completed in order to obtain the main material properties and check its suitability for usage as an active material in space actuators. Results of this characterization test campaign have been presented in this work. This new alloy has been proposed for its use as actuators for space mechanisms. One application of SMA technology is an ultra-low-weight rotary actuator that has been developed for operation on Mars. The aim of this actuator is to provide an in-flight calibration system for the Dust Sensor instrument of the MEIGA-MetNet Mission that will perform airborne dust opacity measurements on the Mars surface. The total mass of the actuator is less than 9 grams (without control FPGA). A Qualification Model (QM) and a Flight Model (FM) will be presented in this work. The actuator presented is designed and qualified to withstand an impact inertia up to 2000 g and work at low temperatures (-90ºC) under vacuum conditions. Similarly, two versions of a Pin Puller mechanism working in the temperature range -30ºC to +125ºC have been designed and analyzed. Operative breadboard models of both devices were built and tested. The main characteristics of these devices as well as preliminary operating results will be shown in this work. The use of Shape Memory Alloys on the proposed actuators presents several advantages of lightweight, high force-to-weight ratio, and low volume.

Introduction

Shape Memory Alloys (SMA) can be defined as metals which, after an apparent plastic deformation in the martensitic phase, undergo a thermoelastic change in crystal structure when heated above its transformation temperature range, resulting in a recovery of the deformation that can be used to drive mechanisms [1]. SMA exhibit two properties, different than any other group of materials: the superelastic or pseudo-elastic effect and the shape memory effect [2]. When the material is at its high temperature phase, it can undergo large deformations by the action of an external stress and then instantly revert back to its original shape once the stress is removed. This behavior is known as pseudo-elasticity and it is due to the formation of stress-induced martensite. This martensite can withstand large deformations that can be completely recovered once the stress is removed [2]. When temperature is reduced, the material is transformed into twinned martensite, although if a mechanical stress is applied, the martensite structure is reoriented, producing a macroscopic deformation, apparently plastic. Nevertheless, when the material is heated, it changes to austenite, recovering its initial shape, as shown in Figure 1(a). The strain capabilities of this mechanism are usually limited to 7-8%. The martensitic transformation takes place in a temperature range that is one of the main parameters for the SMA alloys, and is called *transition temperatures*, as shown in Figure 1(b). The transformation occurs in the range defined by Ms (Martensite Start Temperature) and Mf (Martensite Finish Temperature). The reverse transformation (austenitic

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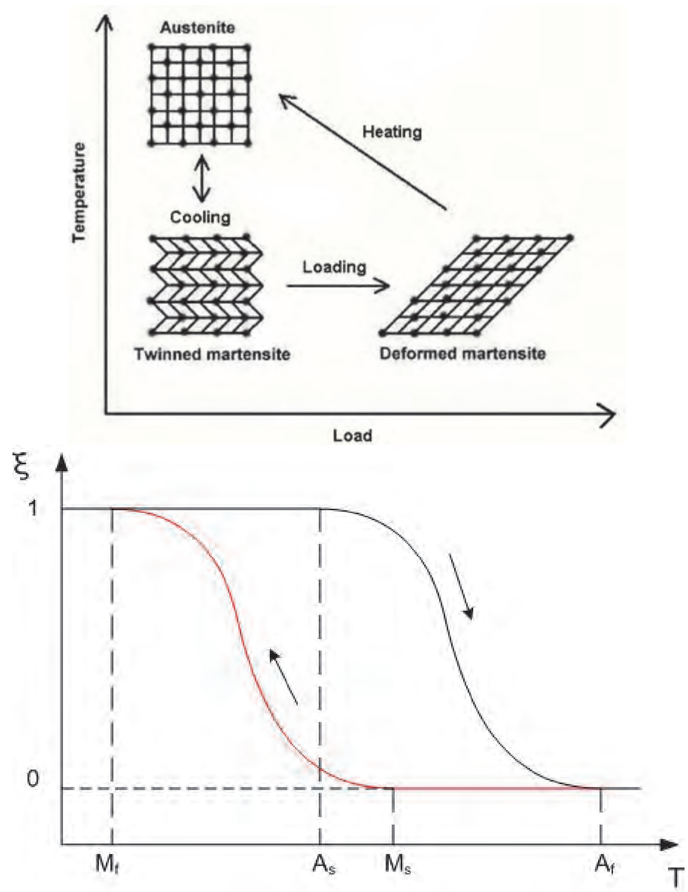
transformation) takes place in the range between As (Austenite Start Temperature) and Af (Austenite Finish Temperature). Both effects are related to the thermoelastic martensitic transformation, which is a diffusionless reversible phase change characterized by a change in the crystal structure [3]. Thus, these characteristics allow SMA to be applicable for force and strain generation, in the case of shape memory, and for mechanical energy storage, in the case of pseudo-elasticity.



(a) (b)

Figure 1. SMA characteristics: (a) microscopic diagram of shape memory effects; (b) martensite variation with temperature.

The main advantage of the SMA technology for its use in actuators is its great strength in relation to its ultra-low weight, optimizing the mechanical work performed by the device with a minimum mass. Furthermore, this technology has the advantage of being immune to electromagnetic interference, its noiseless actuation, and that it does not require lubrication to work.

The alloys currently available in the market, mainly NiTi based alloy, are limited in their operating temperatures. Arquimea suggests using a new SMA with further capabilities to overcome these temperature limitations. SMARQ material, a novel proprietary Shape Memory Alloy, is able to work in an extended temperature range, with transformation temperatures, tuneable during the manufacturing process, up to +180 ºC. We present in this work the results obtained from the SMA characterization. In order to perform the complete characterisation of the SMA material for its use as actuators in space environment, this document explains the way the tests have been carried out by considering the SMA material as the key element of a SMA actuator. This approach requires the space characterization of the complete actuator element in order to identify the performance of the different elements in the space environment. The main objective of these tests is to obtain technical information about the actuator performances. Special attention will be paid to the main advantage of the Arquimea's SMA (SMARQ): its higher working range of temperatures with respect to the SMA materials used until now. This temperature restriction is one of the most critical limitations of the current SMA devices for their application in space missions and other markets. The present project is expected to demonstrate the capabilities of SMARQ to overcome this limitation.

As above-mentioned, in order to perform the complete characterisation of the SMA material for its use in space environment, this document proposes to perform this characterization by considering the SMA material as the key element of a SMA actuator. A block diagram with all the constituent parts of a typical SMA device is shown in Figure 2. It must be taken into account that some of the blocks are basic blocks that must be part of any SMA device and others are optional, being or not a part of the device depending on the application requirements. The tests carried out as part as this work have been focused on the basic configuration of the SMA device, this is, the combination of the SMA Material and the mechanical and electrical interfaces. The characterization of the rest of the elements in space environment can be performed as independent blocks. The performance of the SMA material and the mechanical and electrical interfaces has been tested during the current work, in order to detect possible incompatibilities of the materials involved or mechanical limitations in the SMA actuators in space environment as well as to obtain information about the SMA actuator main parameters and working behavior.

As an application of SMA technology, a Dust Sensor (DS) instrument will be presented in this work. The Dust Sensor instrument of the MEIGA MetNet Mission will perform airborne dust opacity measurements on the Mars surface. The Dust Sensor is designed as a lightweight device (41 g) that performs an active measurement, using back scattering to estimate the concentration of particles in the airborne dust. The unit integrates an infrared (IR) optical active detector (there is an IR emitter and an IR detector) for a spectrographic (discrimination in wavelength) measurement of dust in suspension.

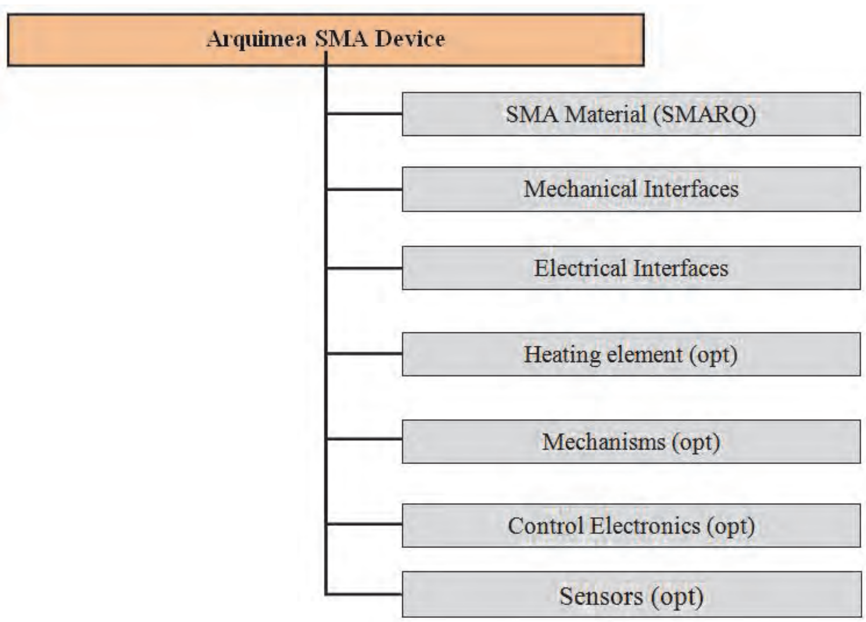


Figure 2. Block diagram of Arquimea SMA Device.

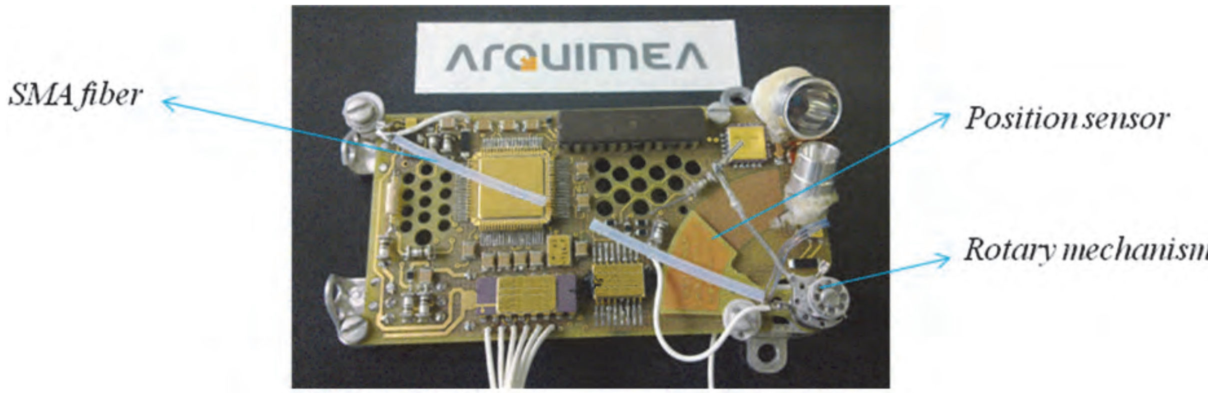


Figure 3. Qualification Model of the Dust Sensor

The emitter points to the airborne dust and the detector collects the scattering signal produced by the emitter light when interacting with particles similar in size to the light wavelength. Figure 3 shows the qualification model of the Dust Sensor device. The DS includes an in-flight calibration system based on a reflector stick that allows directing the emitter optical signal directly to the detector. The reflector stick is inserted in the optical path, when the actuator system is commanded to do so, by means of an actuator based on a Shape Memory Alloy. This in-flight calibration system is used to compensate the error in the entire DS acquisition chain. There is a weight budget of 40 grams for the Dust Sensor instrument, due to the small weight budget of the full MEIGA mission. This has greatly affected design decisions such as the lack of an enclosure, reduced support structures, limitation to the number and size of electronic components, and mainly in the actuator design. The mass budget for the actuator was less than 10 grams, which implied a challenge in design. The Dust Sensor device is controlled by the onboard computer of the MetNet Lander. Periodically, according to a preprogrammed schedule, the Dust Sensor device is powered on and a sequence of instructions is executed. Table 1 summarizes the main characteristics of the Dust Sensor device.

A novel Pin Puller mechanism based on SMA technology will be presented. A Pin Puller is a mechanical device in which a pressure cartridge causes a pin or piston to retract inside the structure frame, usually against a side load. In the extended position, the pin or output shaft can be seen to be loaded by a compression spring.

Table 1. Dust Sensor main characteristics.

Characteristic	Value	Notes
Mass	41.2 grams	
Main dimensions	85x65x20 mm	
Power consumption	360 mW nominal	2250 mW peak consumption during 750 ms max.
Voltage operation	5 V	
Communications	422 serial comms	Command oriented instrument.
Temperature accuracy	±1.5°C	
Reflector position accuracy	±7.5°	
Operational temperature range	-90 °C to +25 °C	Also in vacuum

The pin remains firmly locked in this position due to mechanical components that block the stroke. Once actuated, however, the actuator drives specific mechanical components releasing the stroke and allowing the pin to retract under the force of the drive spring. The Pin Puller is reset by manually moving the pin back into the extended position. This is done by either pulling it out from the top or pushing it from the bottom. The Pin Puller acts as a trigger for deployment mechanisms. The inertia force of the Solar Array panels, antennas, booms, aperture door covers, etc. will be reacted through the release mechanism – through the Pin Puller in the shear direction across the pin and the housing to the structure. Pin pullers are normally used in pairs for redundancy. Applications include "Hold Down and Release" of numerous satellite deployable including solar panels, communication antennas, instrument cover doors, radiators, heat shields, tether experiments, and isolation systems. SMA Pin Pullers provide a number of advantages compared to traditional pyro devices:

(1) There is no (or minimum) shock associated with SMA devices (note that there have been reported instances when pyro pullers have tripped relays when fired).

(2) The number of safety personnel providing oversight during the installation of SMA devices would be greatly reduced.

(3) Deployment tests can be performed repeatedly without having to remove/reinstall Pin Pullers.

The product tree for the SMA Pin Puller mechanism, including its classification by trigger mechanism is shown in Figure 4.

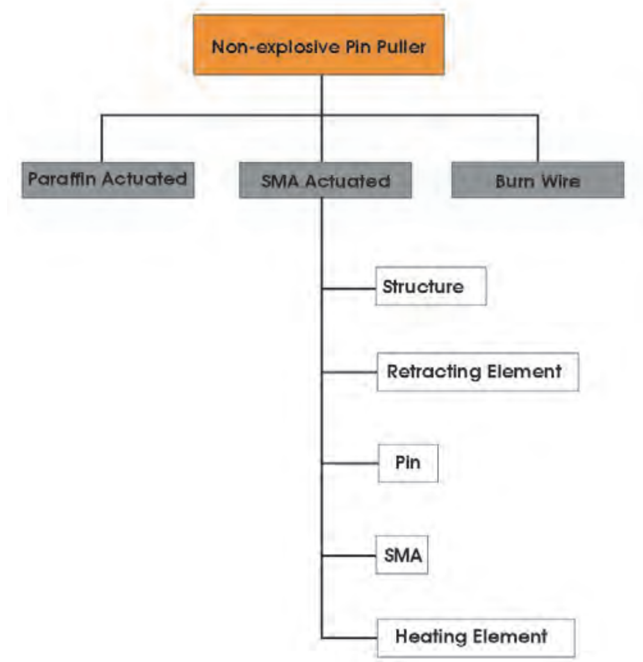


Figure 4. Product tree for the SMA Pin Puller mechanism.

A novel Shape Memory Alloy

SMARQ is a fully European material technology and production processes, based on a low cost production procedure, which allows the manufacture of high quality products. Both material and production processes are currently being evaluated for use in space applications. In order to perform the complete characterization of the SMA material for its use in space environment, the SMA material (SMARQ) has been considered as the key element of a basic SMA actuator, consisting in the SMA material and the mechanical and electrical interfaces (Figure 2). The tests carried out as part as this work have been dedicated to the basic configuration of the SMA device. The tests have been focused on the actuator behavior when heated by means of an electrical current. The characterization of the rest of the elements – such as external heater elements, mechanisms, sensors or control electronics – in a space environment can be performed as independent blocks. A transition temperature (A_s) of +145ºC has been selected for the test samples in order to satisfy the initial environment requirements of operation temperatures between -70ºC and +125ºC.

SMARQ Characterization Test

A complete characterization test campaign for Arquimea's SMA material (SMARQ) was planned and completed. This test campaign included several tests in order to demonstrate the material capabilities to be used as the trigger element in space mechanisms. The following blocks of tests were carried out:

- Strength characterization tests.
  - Maximum Strength Test
  - Reconditioning Force Test
  - Superelastic Test
  - Pull Force Performance Test
- Transition temperatures tests.
- Electrical activation tests.
  - Electrical activation at 22ºC.
  - Electrical activation at +125ºC.
  - Electrical activation at -70ºC.
- Lifetime tests at extreme thermal conditions.
  - Lifetime at +125ºC.
  - Lifetime at -70ºC.
- Material behavior tests in vacuum conditions.
- Assessment of material compatibility in space environment.

Strength characterization tests

The scope of these tests is to obtain information about the force capabilities of the SMA actuator. A maximum strength test was carried out to determine the maximum applied stress the material can withstand without failure. A reconditioning force test has been performed in order to obtain information about the stress necessary to deform the SMA at its martensite phase and its behavior at different temperatures. An additional test, consisting of completing several load/unload cycles at different temperatures over the Austenite Finish Temperature (A_f), in order to obtain the superelastic behavior of the material has been completed. Finally, a test was included to obtain information about the pull force performance (maximum force) of the material, by blocking the actuator movement during the phase transformation and measuring the generated force. A Tensile Test machine with oven has been used for the strength characterization. The equipment is able to perform universal tension tests at a controlled temperature, in the range between ambient and 200ºC.

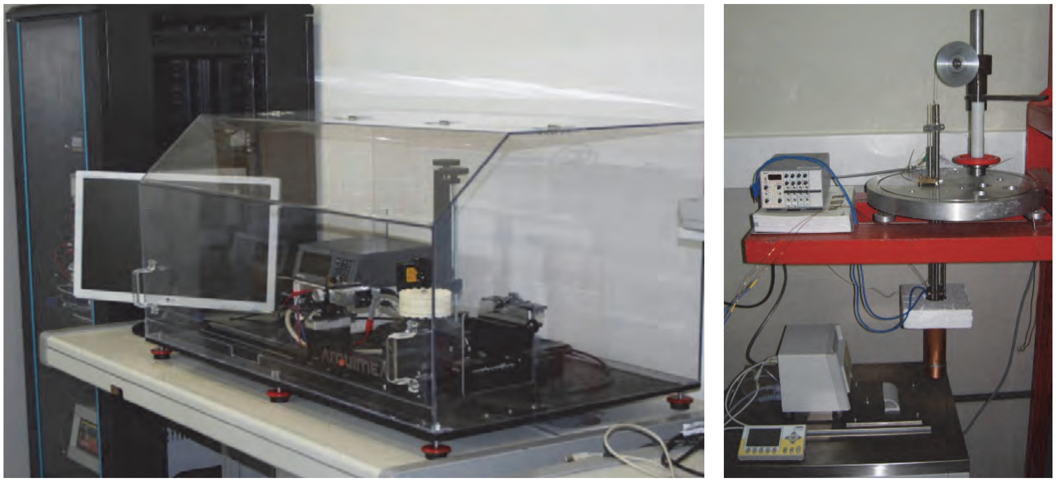
Transition temperatures test

This test has been carried out to obtain data about the material transition temperatures (As, Af, Ms and Mf) for different samples. The non-operation temperature and the relationship between the strain and the temperature during transformation were obtained with this test. Arquimea's Actuators Test Bench was used to complete this test, as shown in Figure 5(a). The equipment is specifically designed to test smart materials and actuators, allowing the execution of complete thermo-electro-mechanical characterization of both, in its actual working configuration. The bench can also control the actuation of the device using an electronic driver and it has an oven that allows heating the sample to a specific temperature.

Electrical activation tests

An activation test has been performed at different temperatures in the working range (-70ºC, +125ºC). The material was loaded and externally activated by an electrical current. Measurements on strain, force, power consumption and generated force have been carried out for several samples, providing information to estimate the power consumption and the heating and cooling times. Arquimea Actuators Test Bench of Figure 4(a) was used to complete this test at temperatures between ambient and +125ºC.

For the cryogenic tests (-70ºC), a new test bench has been developed, as shown in Figure 4(b). A thermostatic bath was used to control the environment temperature of the sample at cryogenic temperatures down to -70ºC. The bench used a vertical measurement approach in order to allow the sample immersion in the thermal bath. Special attention was paid to the sample thermal isolation, in order to avoid the direct contact of the SMA with the thermostatic liquid, which would produce an important change in the convection conditions and therefore in the actuator behavior.



(a) (b)

Figure 4. Devices used in the characterization campaign of SMAR: (a) Arquimea Actuators test bench; (b) test bench for cryogenic test.

<u>Lifetime tests</u>

The scope of this test is to obtain an initial approach to the lifetime capabilities of the material. The tests have been limited to probe that the material is able to complete 100 cycles at the worst case temperatures (-70ºC and +125ºC) without degradation of its performance. A lifetime of 100 cycles is a typical requirement for one-use space actuators, such as release and deployment actuators. The test bench of Figure 4(a) was used for the lifetime test at +125ºC, while the test bench of Figure 4(b) was used for -70ºC.

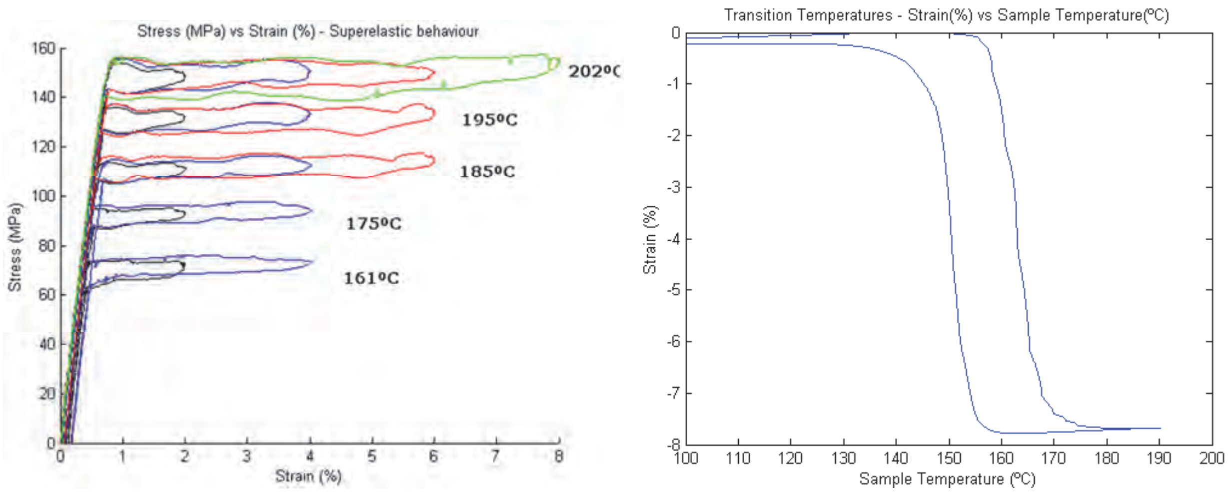
<u>Vacuum tests</u>

Due to the importance of the changes in power consumption and response times under vacuum conditions, a vacuum test was included in the SMA characterization test campaign. The objective of this test is to obtain technical information about the behavior of the SMARQ actuator in vacuum conditions at ambient temperature. A specific test bench has been developed for the vacuum tests. The equipment allows the strain and force measurement as well as the actuator electrical activation in vacuum conditions under constant loads. The test has been done controlling the pressure inside the vacuum chamber (~$5 \cdot 10^{-3}$ mbar) and at ambient temperature (22ºC).

Test Results

<u>Strength characterization tests</u>

The Maximum Strength Test was successfully completed. The material has shown its capabilities to withstand high loads, both in martensite and austenite phases. The material fractures at 500 MPa in its martensite state, showing an elongation over 12%. In the case of the test at higher temperatures, a stress of 400 MPa was applied without fracture of the sample.



(a) **(b)**

Figure 5. Results of strength characterization and transition temperature test: (a) reconditioning force – superelastic behavior; (b) SMARQ Transition Temperatures - Strain vs. Temperature. Actuation above 125ºC is shown.

These stress levels are far beyond the elongation and loads used in the actuators, so the material shows good properties for its application in terms of strength. The results show that a maximum superelastic strain around 10% would be feasible. During the Reconditioning Force Test, important information was collected about the force required to deform the material at different temperatures. The Superelastic Effect test has shown the typical behavior of superelasticity, Figure 5(a), with the existence of upper and lower load plateaus at different temperatures, where the deformation takes place with approximately constant stress. A maximum deformation of at least 8% could be achieved during superelastic cycles. Information about the Clausius-Clayperon curves was also obtained after this test. The Pull Force Performance Test has successfully been completed. The transformation has been observed and the stress levels obtained are high. The material output force capabilities are shown to be over 120MPa.

<u>Transition temperatures test</u>

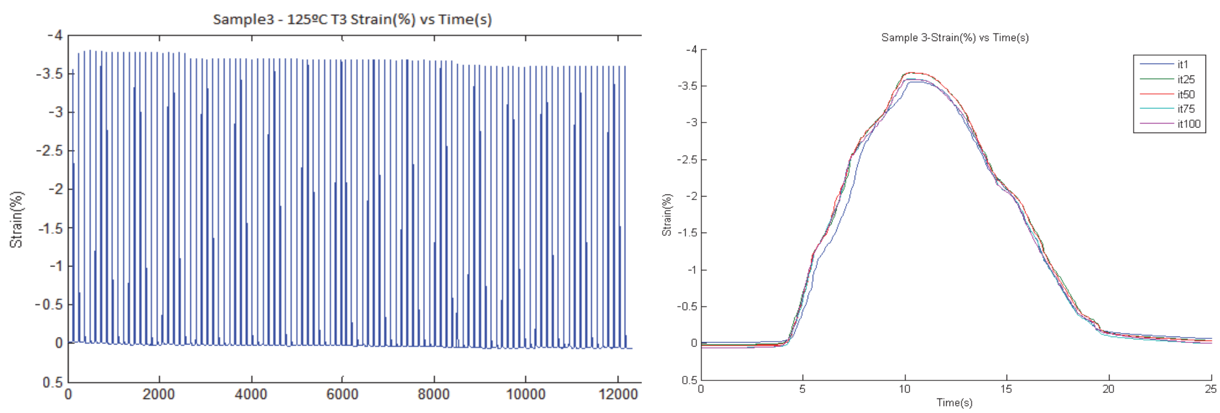
The test results of Figure 5(b) show that the material is able to work at environment temperatures over 125ºC, since the austenitic transformation starts, under the applied load conditions, around 145-155ºC. Besides, the material shows a martensitic transformation which finishes over 135ºC, so the material would be completely in martensite state along the whole environment temperature range (-70ºC, +125ºC). A thermal hysteresis of 15ºC has been obtained during the transformation and an 8% strain has been recovered.

<u>Electrical activation tests</u>

The test has shown the capabilities of the material to be electrically activated in the extreme temperatures in the working range, as well as in ambient temperature. This test shows that the material is able to work perfectly at these temperatures. The main differences between the tested temperatures are the energy necessary to complete the actuation, in terms of power and time, due to the higher difference between environment and transition temperatures. Information about the maximum non-firing current, activation currents, response times, and power consumption at each temperature have been obtained. The behavior of the wire during the electrical actuation was similar to the one produced with the oven in previous tests (transition temperatures test). A good stability and repeatability has been obtained along the cycles. Information about the wire resistance and its relationship with strain has been obtained. Moreover, an estimation of its relationship with the temperature has been carried out.

Lifetime tests
All the samples have successfully completed this test at both extreme temperatures. The values obtained during the 100 actuation cycles at each temperature for strain, stress, resistance and times show a high stability in the actuator behavior along its lifetime at the highest and lowest temperature in the working range.

This shows that the present actuator technology is mature to be used in applications with these environment and lifetime conditions. The test has shown the material capabilities to satisfy the lifetime requirements in the current application. It should be taken into account that the samples have suffered a larger amount of cycles during the whole test campaign, so the actual lifetime obtained is >200 cycles. Figure 6(a) shows the high stability in the strain behavior along the cycles in the lifetime test at +125ºC. A comparative view for some of the cycles is shown in Figure 6(b). Future test will be conducted to verify the full capabilities of the technology in terms of lifetime. Tests will be completed in order to obtain the real lifetime limit for a 3.5% strain. Furthermore, other lifetime tests will be performed with different strain levels.



(a) **(b)**

Figure 6. Results of lifetime tests: (a) Lifetime (+125ºC) – Strain (%) vs. Time (s) (b) Detailed cycles: 1, 25, 50, 75 and 100.

Vacuum test
The cycles were successfully completed during this test. Complete actuations were achieved by using a power less than 1 W. The minimum required power to complete the actuation and the response time, are lower than the obtained in air, as could be expected. Finally, the material has not shown any problem related to the vacuum level during the test. More tests at higher vacuum levels will be done in the future in order to ensure the material works in a space environment. The main results obtained by SMARQ during the characterization test campaign in comparison to NiTi alloys are shown in Table 2.

An excellent behavior in terms of operating temperatures was shown, with capabilities to operate over the limits of current SMA technologies. Good results in terms of reliability and lifetime were also obtained during this work. Successful results were also found during the vacuum tests. Further work is being carried out in order to obtain extra information about the material, especially related to lifetime and vacuum behavior. Research work for the material resistivity optimization are on course and based on the SMARQ heritage, a new generation of mechanisms based on this technology will be developed in the near future.

Table 2. SMARQ Performances.

Property	Units	SMARQ	NiTi
Transformation Temperature (A_f)	°C	> 150 (173°C)	Max. 100
Non-actuating Temperature	°C	> 125 (As=152°C)	Max. 80
Difference (A_s - A_f)	°C	21	20 – 30
Thermal hysteresis	°C	15	30
Max. Strain recovery (One way memory)	%	~ 8	6 – 8
Maximum Strain (Superelasticity)	%	> 8	8
Recovery Stress (Martensite to Austenite)	MPa	~120	300 – 600 (Max)
Maximum Strength (Martensite)	MPa	~500	800 – 1000
Elongation at Failure	%	12	10 – 15
Stress Rate	MPa/°C	2	4 – 20
Electrical Resistivity (Martensite)	10^{-6} Ω ·m	0.1	0.5 – 1
Power Consumption	10^{-6} W·m^2/m	24.2 (min @ -70ºC, air convection)	< 60
Response time	s	4.5 s (Tested geom. @-70ºC, 4.5W, A_f=173ºC) (*)	4.3 s (Test geom. @-70ºC, 4.5W, A_f=90ºC)
Lifetime	Cycles	Tested > 100 (3.5%) (*)	100 (6%) 10^5 (2%) 10^7 (0.5%)

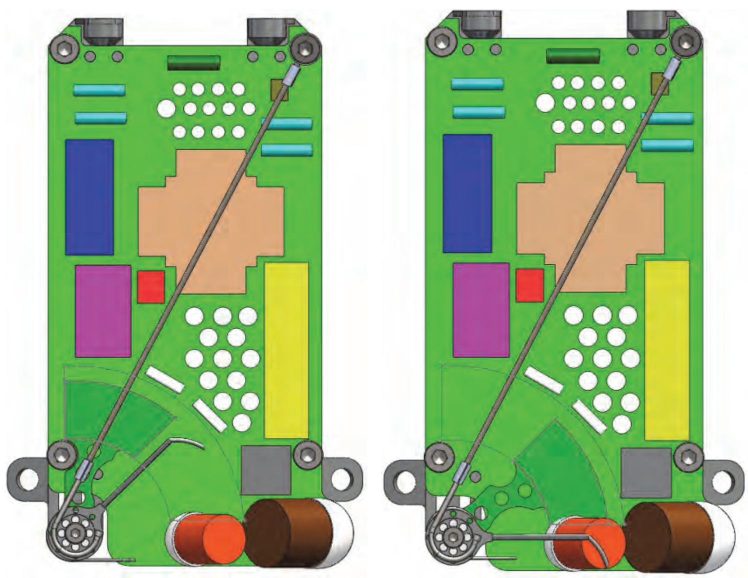
(*) No complete tests were performed to establish these parameters. Partial tests were carried out as a first approach. Nevertheless, the values are expected to be competitive with respect to NiTi.

Table 3. Rotary actuator main characteristics.

Characteristic	Value	Notes
Mass	< 9 grams	without control FPGA
Power consumption	2250 mW during 0.75 ms	
Voltage operation	5 V	
Torque	15.75 N/mm	
Rotary movement	40º	
Life	>700 cycles	
Operational temperature range	-90 °C to +25 °C	
Survival temperature range	-90ºC to +70ºC	
Operation time in vacuum	<750 ms	750 ms correspond to the worst case. This value depends on the initial temperature of the actuator.

A Rotary Actuator for Dust Sensor

One application of SMA based actuators is the presented, which comprises a rotary mechanism actuated by a SMA Fiber, a position sensor, an electronic driver and a control algorithm. Table 3 presents main technical details of the rotary actuator integrated in the Dust Sensor device. The actuator integrated in the Dust Sensor is an ultra-light weight rotary actuator based on a Shape Memory Alloy (SMA) fiber. The SMA fiber contracts when heated beyond the characteristic transition temperature of the material. This contraction is used for generating a rotary movement of a stick reflector. The stand-by or relaxed position is reached thanks to a return spring. The actuator has an integrated rotary position sensor for control and characterization of the actuator movement. This rotary sensor is a double capacitance detector which gives a rough position value of the reflector. The consumption of this sensor is negligible and its weight is very low since part of the sensor is integrated in the PCB of the Dust Sensor. A limit switch (end of stroke) is included as a redundant element to switch off the activation of the DS. This switch will detect that the reflector stick has reached its final position, the signal will be interpreted by the FPGA and immediately the actuator will be powered off. The actuator hardware includes an electronic driver that provides the SMA fiber a power line of +5V, ~500 mA. For reliability reasons, the driver is commanded using a signal above 1 KHz from the control FPGA, neither a 5 V DC nor 0 V DC signal will activate the SMA. A control algorithm completes the actuator system.



(a) (b)

Figure 7. Initial (a) and further (b) position of the reflector stick.

The algorithm running on the Dust Sensor FPGA commands the actuation receives information of temperature, rotary position and limits switch sensors and sends a feedback to the electronic driver. Figure 7 shows the initial and further position of the stick reflector during an actuation

<u>Qualification Campaign of Dust Sensor</u>

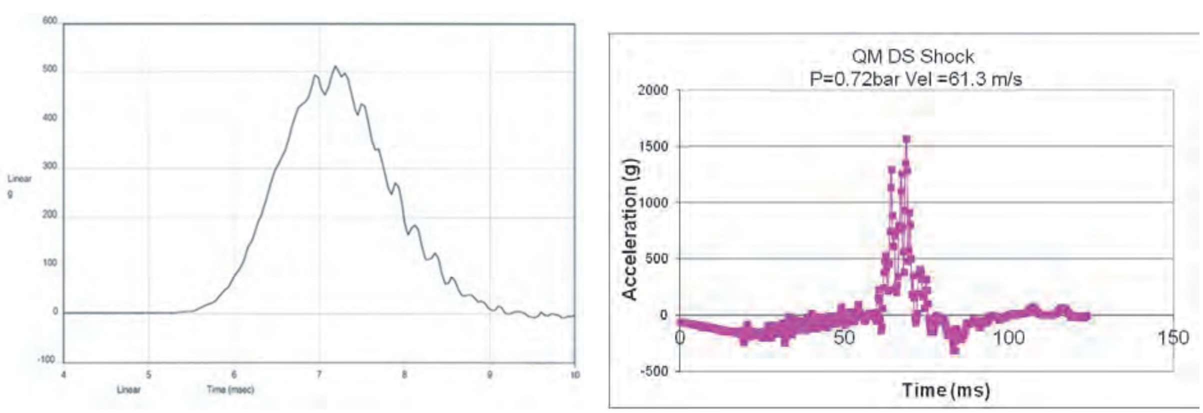
Qualification objective is to demonstrate that the Dust Sensor conforms to the requirements of the mission including margins. The following tests have been applied to the Qualification Model of the Dust Sensor:

- Thermal cycling and vacuum test from -90ºC to 70 ºC, 6 cycles.
- Vibration. QM DS was subjected to qualification levels of sinusoidal and random vibration.
- Bioburden reduction. Due to planetary protection requirements, a bioburden reduction process shall be applied to the DS unit.
- Humidity low-temperature verification test. A low-temperature verification test in a humidity atmosphere was carried out.

- Shock. QM of the DS was subjected to three different shock tests in each of the three axes. Qualification levels of the test are as following:
  - o Axis X and Z: 500g in the form of sinusoidal half-wave with a duration of 2 ms.
  - o Axis Y: 2000g in the form of sinusoidal half-wave with a duration of 15-20 ms.

<u>Test results</u>
The following qualification tests results are presented:

- Vibration. After vibration tests, a visual inspection, physic properties verification and several functional tests were carried out with the result of no anomalies or deviations detected. Consequently, the rotary actuator can survive the vibrations expected from travel, landing and take-off without any expected problem.
- Shock. Figure 8(a) shows the accelerations obtained during the shock test in X axis using the free fall machine. Similar results were obtained in Z axis. Figure 8(b) shows the accelerations obtained during the shock test in the Y axis using the pneumatic cannon. After the shock test, no anomalies were detected in the Dust Sensor, nor in the actuator subsystem. The levels in the Y axis during the shock test are slightly below 2000g. In the initial calibration tests using a mechanical dummy model, the values obtained arrived at 2000g. Unfortunately in the QM test this value was not reached due to the variability of the method applied. As seen in Figure 8(b), the levels reached have several peaks during approximately 17 ms of duration, which is more restrictive than the single sinusoidal half-wave requested. Even though the values obtained demonstrate that the DS can support shock values near 2000g: no damage or defects were observed in the mechanical dummy model (that reached 2000g), neither in the QM of the DS.
- Thermal cycling and vacuum test. Thermal vacuum cycling is a critical test for the rotary actuator subsystem due to the complex thermal processes that take place during the huge thermal variation in vacuum (from -90ºC to +70ºC). During the test, several data from the sensors of the DS were logged. Also, more than 100 actuations over all the temperature range were logged. Figure 9 presents an actuation capture during the TVAC test at -90ºC. As it can be seen, due to the absence of thermal convection losses, the SMA fiber heats very fast (less than 300 ms) and takes more time during the cold down (~1.25 s).



(a) (b)

Figure 8. Results of shock test: (a) acceleration Vs Time obtained during the 500g shock test of the DS; (b) acceleration Vs Time obtained during the 2000g shock test of the DS.

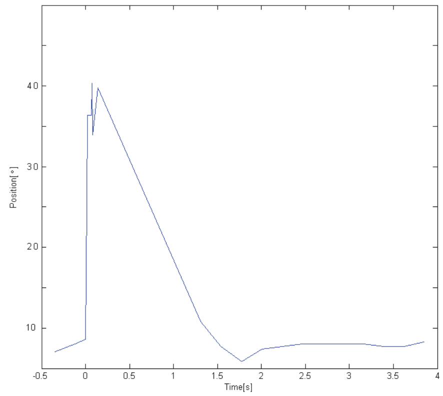


Figure 9. Position sensor output Vs time during an actuation at -90ºC.

- Bioburden reduction. Bioburden reduction test verified that the actuator was not damaged after 50 hours at 111ºC. No anomalies or deviations were detected. The SMA fiber was not damaged and the rotary actuator worked perfectly.
- Humidity low-temperature verification test. During the verification test, inside the thermal chamber, the rotary actuator was completely operational. At low temperatures, convection losses were high enough to increase the actuation time to values as high as 3 seconds. Convection losses made the fiber not to contract completely and, as a consequence, perform a partial actuation (limited angle movement) at temperatures below -30 ºC. It must be noted that the rotary actuator is intended to be used in nearly vacuum atmosphere, with negligible thermal convection losses. As an additional test, in open atmosphere (49% of relative humidity) the critical parts of the rotary actuator were superficially completely frozen at -50ºC. Ice appeared all over the mechanism. Several actuations were performed in these conditions. The Dust Sensor rotary actuator was able to actuate in an atmosphere with vapor water within the temperature range without being blocked.

The main lesson learned is that the complex thermal processes that take place along the whole temperature range of the mission are critical for a reliable and proper performance of this type of actuator. Here, the position sensor and end of stroke sensor included in the design play an important role for proper performance, and have allowed the completion of more than 700 cycles without failure during the qualification process. Future work includes the FM development and implementation in the MetNet platform.

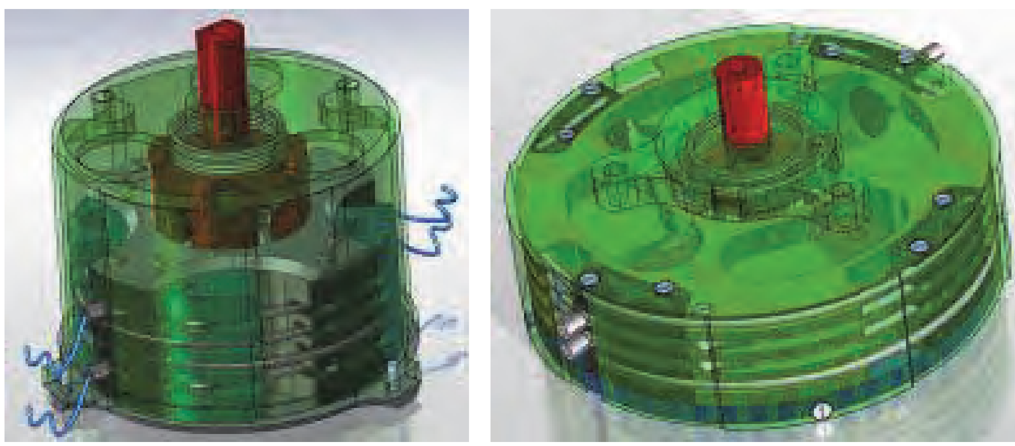
A Pin Puller Mechanism

A Pin Puller is another application for SMA-based actuators. Two different versions of the pin puller were designed during this activity. Figure 10(a) shows a CAD model of the first design of the *Pin Puller V.1*. This design has been conceived to have a cylindrical shape in which length and diameter present similar dimensions, such as 80.0 mm of external diameter and 71.5 mm of length in un-actuated position (pin deployed). The mechanical parts have been designed to be made of an aluminum alloy. The commercial components have been modelled assuming their mechanical characteristics from the data sheets. The estimated weight of the whole structure, including commercial components and mechanical parts is 248.0 g. The Pin Puller mechanism is activated by a SMA actuator. Spheres support the pin at the initial position and a compression spring is loaded to perform the driving force once the release takes place. When the SMA actuates, a crown rotates allowing the spheres displacement, and thus the pin release and its movement to the actuated position (pin retracted). The mechanical design has been conceived in order to optimize the device’s weight, reduce the parts complexity, and achieve a suitable stiffness. The assembly ensures the alignment of components and compactness of the design. Note a M4 drill on the pin tip that allows installing a threaded tool that can be used to pull for the device reset. Flat surfaces both in the pin shaft and in the frame do not allow the undesired rotation of pin, preventing the mechanism to be released by an external force.

Figure 10(b) shows an overview of the second design of Arquimea Pin Puller, named *Pin Puller V.2*. This design has been conceived in order to obtain a flat model structure. The device external diameter is 100.0 mm, the length is 50.9 mm with the pin retracted, and its estimated weight is 250 g. The *Pin Puller V.2* presents a mechanism similar to the *Pin Puller V.1*. Nevertheless, the V.2 pin is supported by rigid bars that keep it deployed during the un-actuated position. When a crown rotates by a SMA operation, the bars move, allowing the pin stroke by means of a compression spring. *Pin Puller V.2* has also been conceived in order to have a low weight structure, no complex features, and a suitable stiffness. The reset is also planned to be done by pulling a M4 threaded tool located in the pin tip. The components alignment is also ensured in this Pin Puller, as result of the accurate design process, by using an internal ring that also ensures the design compactness, locating the supporting spheres. Note that *Pin Puller V.2* has been designed to avoid any rotation of the pin.

Mechanical and Thermal Analyses

The 3D-CAD models of both versions of the Arquimea Pin Puller have been used to develop finite element analyses (FEA) of the structures. The goal of this analysis was to check the feasibility of the design as well as the components and assembly resistance. Two cases have been studied during the FEA, axial load condition and shear load condition. In particular, the axial load condition has been assumed as 180 N applied on the pin tip plus 1264 N applied by the stroke spring. The shear load condition has been assumed as 1000 N applied along a transversal axis of the pin. A factor of safety (FOS) of 1.25 has been suitably assumed both for incrementing the applied forces and for the numerical results in order to obtain a conservative design.

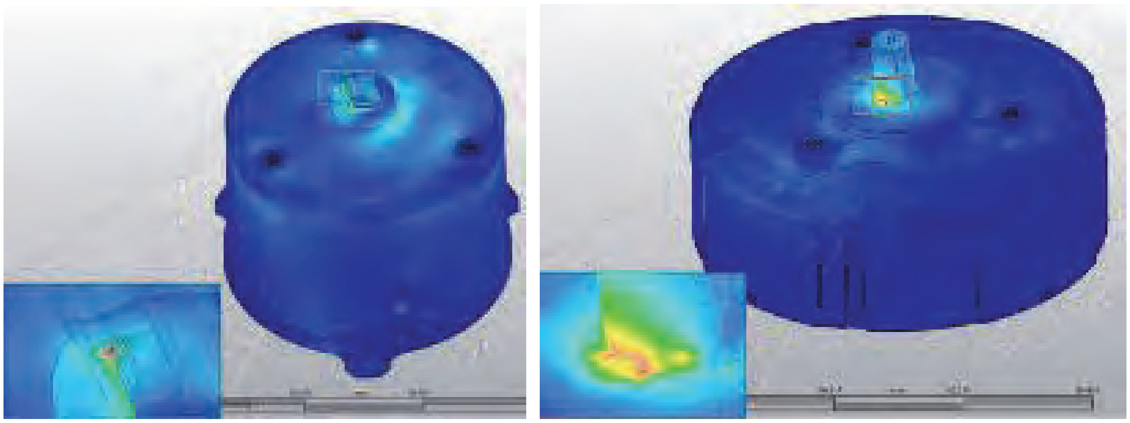


(a) (b)

Figure 10. CAD models of Arquimea Pin Pullers: (a) V.1; (b) V.2.

Figure 11(a) shows the results of the Von Misses stress from the FEA of *Pin Puller V.1* structure for the second case of study (shear load). 450 $^{N}/_{mm}{}^{2}$ has been computed as the maximum value (lower than the yield limit of the selected aluminum alloy). Figure 11(b) shows the stress results of the *Pin Puller V.2* FEA. The maximum stress result has been computed as 290 $^{N}/_{mm}{}^{2}$ (lower than the yield limit of the selected aluminum alloy too) during the second case of study (shear load). Successful results have also been obtained during the vibration analysis of both Pin Puller structures. The same set-ups used for the above-mentioned FEAs have been used for computing the limits of resonance, obtaining 2128.6 Hz for version 1 and 2350.4 Hz for version 2. These limits are above the expected operating frequency for both devices.

Since mechanisms present difficulties during vacuum and extreme temperature conditions, tribology and thermal assessments have been done for both Pin Puller operations. Critical contact zones have been recognized in order to avoid high friction and adhesion. Certain solutions are proposed to resolve the problems, such as application of solid lubricant coating (MoS_2) on moving parts and designing the mechanical parts assuming specific features that reduce contact among components up to contact lines even contact points. Similarly, suitable tolerances have been assigned to moving part features in order to avoid any jamming produced by the material expansion or contraction at extreme temperatures.



(a) (b)

Figure 11. FEA results: (a) Pin Puller V.1 - shear load; (b) Pin Puller V.2 - shear load (right).

Finally, the response time has been computed, as part of the actuator analysis, for both Pin Puller versions. In order to fulfil the environment requirements (working temperature between -30ºC and 125ºC), wires with Austenite Start Temperature (A_s) of 150ºC have been considered. Therefore, FEA have been developed in order to obtain the temperature profile along the wire axis during operation and the actuator response time. The actuator maximum response time at worst case environment (-30ºC) has been estimated to be 4.3 s for version 1 and 2.8 s for version 2.

(a) (b)

Figure 12. Built demonstrator of the both Arquimea Pin Puller versions: (a) devices of 500 N of stroke force; (b) devices of 100 N of stroke force.

<u>Pin Puller as built Configuration</u>

Demonstration models (DM) of both versions, Figure 12, were constructed in order to test the mechanical device concepts and to debug the design. The DMs have been constructed in Alumide material by rapid manufacturing process. Alumide is a composite of plastic and aluminum that provides a suitable resistance to prototypes for preliminary operation test. Moreover, this material does not conduct electricity that ensures the electrical insulation of the structure. Since the device reset is planned to be made manually by pulling the pin, a reset tool has been designed and built too. The reset tool can be recognized in Figure 12 next to the Pin Puller DM. Finally, the DMs contain commercial components, such as screws, cables, crimps and SMA actuators, for completing a successful demonstrator device of a Hold-Down and Release Mechanism. Figure 12(a) shows the demonstrator models of a Pin Puller with a stroke force of 500N. Good functional performances were obtained from both models. Promising performances and some design concept improvements have been obtained for both versions of the device in this phase of the development. The designs presented in this work can be easily scalable to different sizes and requirements. Figure 12(b) shows the demonstrator model of a Pin Puller with 100 N of stroke force, in which an engineering model (EM) is currently under development.

Conclusions and Future Work

Arquimea has characterized the proposed SMA material (SMARQ), demonstrating the material capabilities to be used as a triggering actuator for space mechanisms. The material has shown a good behavior as Shape Memory Alloy. The project requirements in terms of operating temperatures, strain and force capabilities and lifetime have been satisfied.

A rotary actuator included in the QM of the DS for environmental conditions requirements of the MEIGA-MetNet Mission has been presented. DS will perform airborne dust opacity measurements on the Mars surface, as can be confirmed from the qualification campaign results obtained. The rotary actuator operational temperature range from -90ºC to +25ºC was an initial challenge that has been completely reached thanks to a correct thermal design and a proper control algorithm. The temperature range obtained exceeds the operational range presented for other SMA-based actuator for a Mars surface application as stated in [4].

Two complete Pin Puller mechanisms were conceptually designed and analyzed, with promising results. Demonstration models for both devices were constructed and tested, obtaining a successful proof of concept of the mechanisms. The results of the work presented show that SMARQ technology is ready to be used in the development of EM, QM and FM actuators for future space missions. Other potential applications are the design of actuators for multi-cycle operation, for working in hard environments, such as cryogenic applications, or for applications where an ultra-light weight is required. Finally, the technology developed during this project can be applied to other industrial applications outside the space market.

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