A NOVEL HOLD-DOWN AND RELEASE MECHANISM FOR NON-EXPLOSIVE ACTUATORS BASED ON SMA TECHNOLOGY

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ABSTRACT

Non-explosive actuators based on SMA technology have been developed as an alternative to current devices for space applications. One of the most significant advantages of the mechanism, based on SMA technology, is the possibility of being used several times in situ by manually reset. The novel hold-down and release mechanism (HDRM) is triggered by a SMA fibre that can pull with about 70N of force. Since the HDRM handles high external forces (for example preloads of 35KN and pin stroke forces of 500N), the decomposition of these loads is necessary to perform the complete triggering operation.
The proposed mechanism has been used in the development of a Pin Puller and a Hold-Down and Release Actuator (HDRA) called REACT (REsettable non-explosive ACTuator). A comprehensive test campaign has been performed under an ESA GSTP contract showing satisfactory results, which demonstrate the suitability of the actuators for space applications.

INTRODUCTION

SMA technology can be a suitable option for alternative solution in the development of resettable hold-down and release actuators, [1]. Other non-explosive mechanisms, such as the ones based on a burn wire or a thermal knife, require to be refurbished by the manufacturer after every actuation. Similarly, pyrotechnic actuators can be used only once and require special safety measures during the installation and handling. Moreover, the low-shock is another important advantage of the SMA actuators, compared with other technologies (mainly pyrotechnics).
The use of Shape Memory Alloys in the triggering actuators allows the developed devices to have minimum mass, compact and robust designs, [2] to [5]. The proposed mechanism uses a kinematic chain composed of contacting spheres to take advantage of the cone effect. Therefore, the reaction forces among spheres can be reduced depending on the number of spheres in the kinematic chain and the contact angles among them. Finally, the last sphere of the kinematic chain, which is in contact with the trigger (SMA fibre), generates a reaction force that the SMA fibre can overcome with a proper friction coefficient.
The Pin Puller is a linear actuator that contains a pin deployed at the unactuated position and retractable when actuated. The HDRA is a mechanism in charge of holding an element to the spacecraft structure during launch and releasing it at user demand. These devices have to support high preloads during launch and have to be able to release these loads when required. The temperature restriction is one of the most critical limitations of the current devices for their use in space and in other applications. The new deployment mechanisms are able to work in a wider range of temperatures with respect to similar devices available in the market. They are able to operate in a temperature range up to +125ºC under vacuum conditions, [1]. In particular, currently, the ESA Proba 3 and Juice missions are considering using the REACT for the release of the solar array and boom respectively.

OPERATION PRINCIPLE

The proposed mechanism is mainly composed of:

- A trigger part, called Crown, pulled by a SMA wire for operation.
- Spheres that support the mechanical interfaces: pin or rod and nut.
- Sphere that decomposed the external forces down to a force that SMA can handle.

At the initial position, the Crown is blocking the mechanism movement by mechanical interface with the last spheres. When the SMA pulls the Crown, it moves making the last spheres coincide with proper groves in the surface. The reaction forces between the supporting spheres and mechanical interface are transmitted through the chain of spheres to the last spheres generating their displacement.
The force that SMA wire should overcome for the device actuation is the resistant friction between Crown and last spheres. The SMA force depends of the cross-section of the wire, [1], but more energy is necessary to heat up the fibre while bigger the SMA is. Thus, for a device compatible with the current electrical interfaces, SMA wires with about 70N of pull force should be used. Moreover, proper tribology solution should be applied in order to have a low friction coefficient. Anyway, for a real application, the obtained friction coefficient and SMA pull force are not enough to obtain the crown movement under the sphere forces.
In order to obtain a suitable resistant friction on the Crown, the external forces are decomposed through the chain of spheres taking advantage of the cone effect, as shown in Figure 1. In fact, the force transmitted to the

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last spheres can be reduced by tuning the contact angles among spheres. The force is decomposed as much as spheres compose the mechanism. Therefore, lower numbers of spheres are required for Pin Pullers than for Hold-down and Release Actuator. Moreover, the design can be scalable to different sizes of REACT and Pin Puller.

NON-EXPLOSIVE ACTUATORS BASE ON SMA TECHNOLOGY

Two types of Hold-Down and Release Mechanisms have been developed by using the proposed mechanism: Pin Puller (Figure 2) and REACT (Figure 3). Since the design provides scalability for the structure, several devices with different sizes have been developed, such as:

- Pin Pullers of 25N, 50N, 100N, 250N, 500N of minimum pull force.
- REACT of 2.5KN, 5KN, 10KN, 15KN, 25KN and 35KN of maximum preload.

Both hold HDRM have the same material; surface treatment; lubricant and SMA initiator. The mechanical parts under the highest stress are made of a steel alloy with high strength. Examples of these parts under high stress are: REACT rod, Pin Puller pin and the location of the supporting spheres.

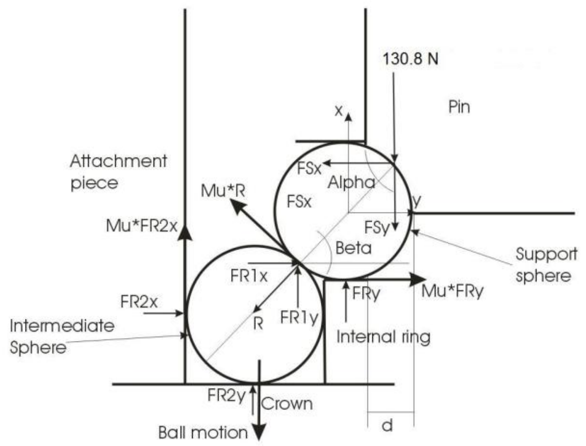

Figure 1. Kinematic scheme of the proposed hold-down and release mechanism.

Figure 2. Pin Pullers

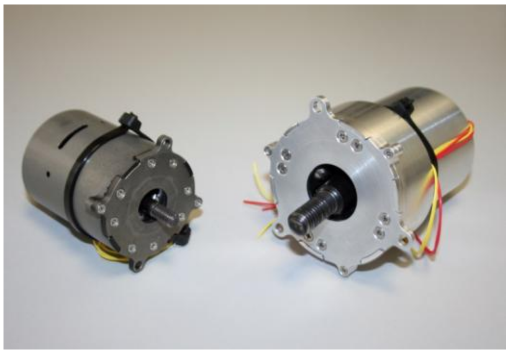

Figure 3. Hold-Down and Release Mechanism (REACT).

The mechanical parts under the lowest stress are made of aluminium alloy with hard anodizing. The hard anodizing increased the hardness of the aluminium surface that improves the tribology characteristics. Examples of these parts under lower stress are: crown and location of the last spheres.

A solid lubricant based of PTFE is used for the lubrication of the mechanical parts of the mechanisms. All parts, both steel and aluminium are coating with the solid lubricant, but the spheres are not coated. This solid lubricant is not sensitive to air, thus non-special measurements are required for handling, storing and shipping.

The SMA works as initiator of the mechanism operation by pulling the crown. The initiator assembly is composed of the SMA wire; mechanical interface; electrical interface; insulation parts; and heater. All sizes of both actuators use the same initiator assembly with the same wire dimension. Therefore, the contact forces between the last spheres and crown are the same in all mechanism but the numbers of the spheres for force decomposition are different. Finally, all devices are composed of redundant and primary initiators.

Figure 4 shows potential applications of the proposed devises, in which a boom and solar array systems can be identified. Since the required force to hold the boom is quite low because the low mass of the structure, Pin Puller can be used, as shown in Figure 4 (lower). Pin Puller can withstand a non-actuation shear force for holding and it can actuate under a shear force for the release.

A specific fixing torque on a nut is necessary to hold the solar arrays because the high mass of the structure. Therefore, REACT can be used for this application, as shown in Figure 4 (middle). Moreover, more than one device can be used depending of the panel weights. A commitment is required between the required fixing torque and the number of HDRA.

The design has been constrained by the FEA results since the high preload requirement during the device operation. Proper features with suitable dimensions and materials have been selected for the mechanical parts in order to obtain a compact and robust solution with lightweight.

Figure 4. Potential applications of the proposed actuators.

A QUALIFICATION PROCEDURE TO ENSURE RELIABILITY

A procedure has been defined in order to ensure the reliability and repeatability of the qualification results. The procedure is based on using several devices to apply the same test in different units, thus it is possible to have a statistic of the results. Figure 5 shows a flow chart with the test to be performed and the devices used. In case of REACT, five units were used: one REACT of 2.5KN, two REACTs of 15KN and two REACTs of 35KN. Since the REACTs are based on the same technology and the design is scalable, all units can be considered as the same device. Therefore, different sizes of the actuator were used.

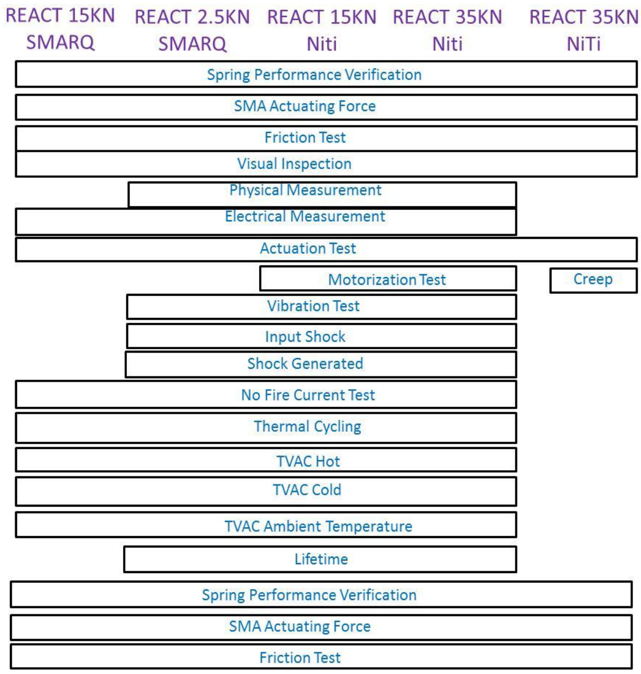

Figure 5. Test sequence of the proposed qualification campaign.

Two types of initiators were used: one with Nitinol alloy and other with SMARQ alloy. The SMARQ provides actuations below +125ºC, [1], and Nitinol provides actuations below +70ºC. Both SMARQ and Nitinol initiators had the same mechanical characteristics (pull force, pull stroke and actuating time) with different electrical characteristics (resistance, voltage and input current). Nitinol initiators were installed in three REACTs and SMARQ initiators were installed in two REACTs, as shown in Figure 5. Moreover, The REACTs with Nitinol initiators had both primary and redundant circuits and REACTs with SMARQ initiators had just primary initiators. The aim of using just primary initiators is to verify the motorization equation of the ECSS used for the design of the initiators.

All test of the qualification campaign were applied to one unit of REACT with SMARQ and one unit of REACT with Nitinol. The creep test was applied to a REACT of 35KN because it is considered the worst condition. The most demanding tests, for example vibration and TVAC, were applied to one unit of REACT of 2.5 KN, one unit of REACT of 15KN and one unit of REACT of 35KN. Finally, TVAC were performed for actuators with both SMARQ and Nitinol initiators.

Similar procedure has been developed by using three Pin Puller units. One Pin Puller with Nitinol initiators and two Pin Pullers with SMARQ initiators were tested. Similar to REACT, the initiators used had the same mechanical characteristics and different electrical characteristics. In case of Pin Pullers, all tests were performed with all devices.

RESULTS OF QUALIFICATION CAMPINGS

The qualification procedure of Figure 5 has been performed with several Pin Puller and REACT units. Now, the most significant results are reported in detail.

SMA Actuating Force

The output force of all SMA fibres used for the actuators has been measured with the characterization test bench of the Arquimea, [1], shown in Figure 6. The measurements were performed before and after the whole campaign in order to verify any degradation of the material. The forces measured have been about 70N and any degradation has been recognized.

Spring Performance Verification

Similar to the SMA initiator, the spring performances has been verified before and after qualification campaign. Both REACT and Pin Puller include a spring to set the Crown at the initial position during the reset operation. Moreover, Pin Puller has a stroke spring that pushes the pin inside the structure during operation.

The reset springs are traction springs and the performance has been verified in the SMA characterization test bench of Figure 6. The stroke springs are compression springs and the performance have been verified in the test bench of Figure 7.

Any degradation has been recognized before and after test campaign. In fact, similar values of spring coefficient have been measured after several actuations of the devices.

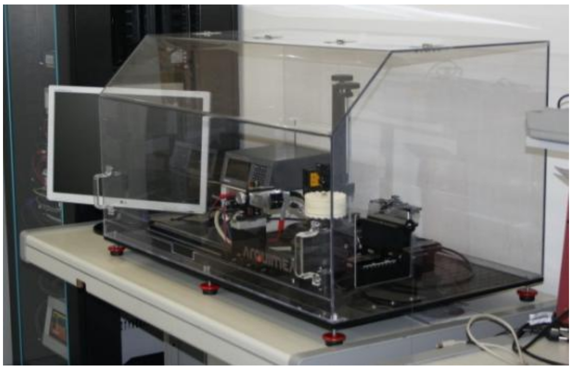

Figure 6. Test bench for SMA characterization.

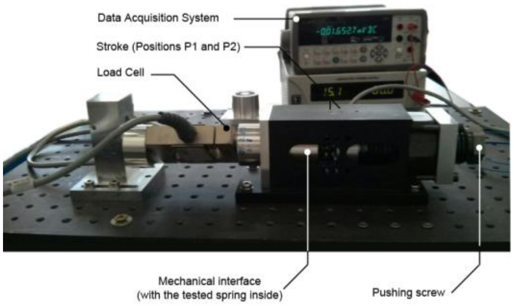

Figure 7. Measurement of spring performance.

Friction Test

The resistant torques on the Crown for the device actuations have been measured by using a pulley system and a force sensor, as shown in figure 8. A proper slot on the Housing provides the access to the Crown from outside of the structure, thus the pulley system can be connected. A stiff cable connects the pulley system to the force sensor, which is installed on a moving track. The track has been moved manually and slowly and the output signal from the force sensor has provided the measured value. With the measured SMA actuating force, spring performance and the resistant torque on the Crown, the fulfilling of the ECSS motorization equation has been verified for the proposed actuators.

Similar, the frictions on the pin of Pin Pullers during the application of the actuating shear forces have been measured with the test bench of Figure 9. In this case, the force sensor was connected directly to the pin by using a stiff cable. The sensor was installed in a track and the force required for moving the pin has been measured by manually moving the sensor. The ECSS motorization equation has been also verified for the stroke springs of Pin Pullers.

Actuation Test

Figure 10 shows the test bench used for the actuation test of REACT. This bench is composed of a hold down stack, hydraulic system and a virtual instrument for motorization of the input signals. The hydraulic system has been used for the application of the required preload with the REACT installed in the hold down stack. The hydraulic system contains a proper manometer that provides the value of the applied force.

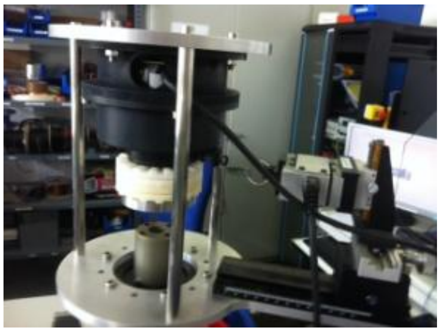

Figure 8. Measurement of resistive torque of REACT.

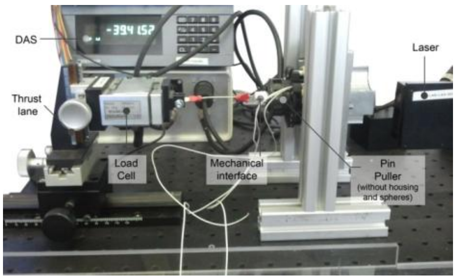

Figure 9. Measurement of pin friction of pin puller.

Figure 10. Hold down stack for REACT actuation.

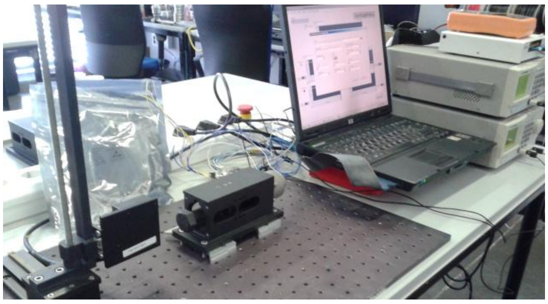

Figure 11. Setup for Pin Puller actuation.

The manometer was calibrated by using a proper force sensor during a commissioning test. A virtual instrument of National Instrument was used to plot the curve of voltage and input current.

Similar, Figure 11 shows the setup used for the actuation of Pin Puller. This setup is composed of a base, a laser sensor, a calibrated spring and a virtual instrument. The calibrated spring was used to verify the pull force and it has been calibrated during a commissioning test. The laser sensor was used to verify the pin stroke when the calibrated spring is totally compressed. A virtual instrument was used to plot the signal for the laser sensor, the voltage and the input current. The different between the beginning of signal of the input current and the end of the signal from the laser sensor is the actuating time.

The GSE has been used for the lifetime test of the devices that has consisted in the actuation test repeatedly. Successful actuations of the devices have been performed during all the actuation tests.

Vibration Test

Sine and random vibrations have been applied to the devices along both axial and radial axes. Figure 12 shows vibration along the axial axis of Pin Pullers and Figure 13 shows the vibration along a radial axis of REACT. The same vibration levels of 31 gRMS have been applied to all devices along all axes during 2.5 minutes. No-damage to the structure and/or self-actuation have been recognized during the vibrations tests.

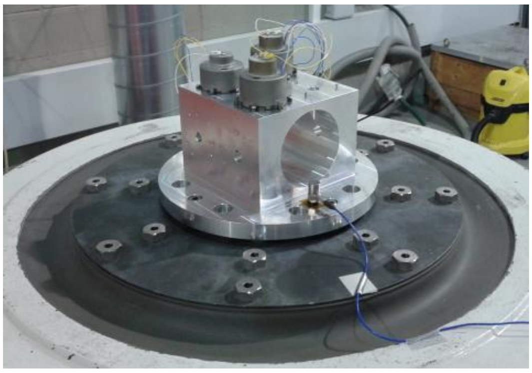

Figure 12. Axial vibration of Pin Puller.

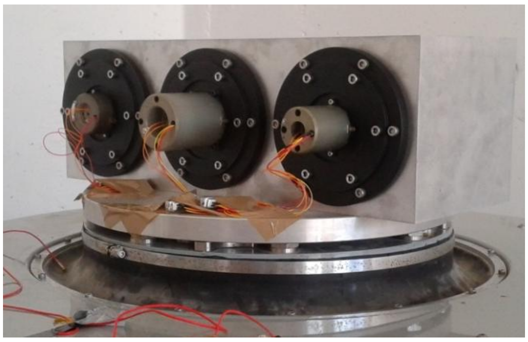

Figure 13. Radial vibration of REACTs .

In the case of REACTs, the vibration tests were performed with the device preloaded. The hold down stack of Figure 10 presents a modular structure that provides the separation of the REACT from the hydraulic system after the preload application. Therefore, the upper part of the hold down stack with the REACT can be fitted into the vibration cube, as shown in Figure 13.

Shock Test

Figures 14 and 15 show the inputted shock test for REACT and Pin Puller. In particular, Figure 14 shows the inputted shock of REACT along a radial axis and Figure 15 shows the inputted shock of Pin Puller along the axial axis. The accelerator was located as close as possible to the device, as recognized in Figure 15. The shock levels applied to REACT have been 1300g @ 2000 Hz and the levels applied to Pin Puller have been 2000g @ 2000 Hz. Each test has been performed nine times: three times along the three Cartesian axes. No damage to the structure and/or self-actuation have been recognized during the inputted shock tests.

The shocks generated by the devices during the actuation have been measured in the test bench of Figures 14 and 15 just after the inputted shocks. In fact, the accelerometer kept recording and actuation was performed measuring the shock. The maximum output shock has been 700g obtained with both REACT of 35KN and Pin Puller of 500N.

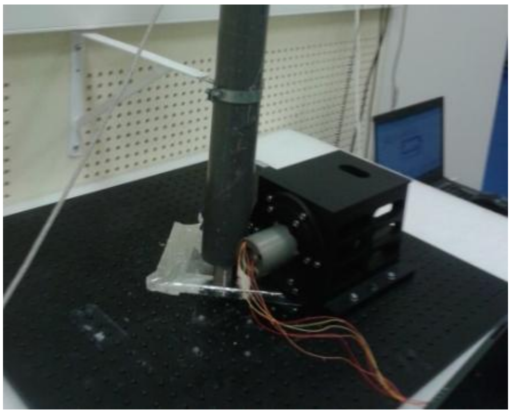

Figure 14. Radial shock of REACT.

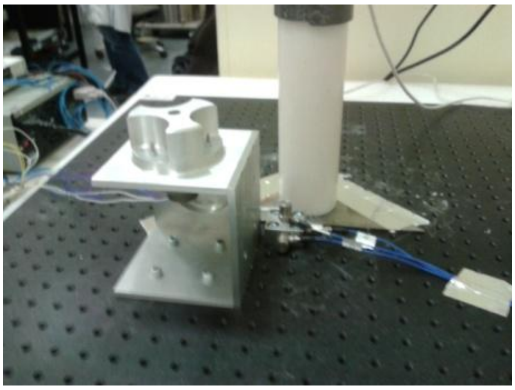

Figure 15. Axial shock of Pin Puller.

Similar to the vibration test, REACT has been tested preloaded. A proper base is recognized in Figure 14, in which the upper part of the hold down stack was fitted with the REACT under preload.

Thermal Vacuum Test

Actuations at maximum, ambient and minimum temperatures have been performed by the actuators under vacuum conditions. Moreover, thermal cycling of 8 cycles between maximum and minimum temperatures in vacuum condition has been applied. Figure 16 shows the REACT in the thermal chamber and Figure 17 shows the Pin Puller. Note in Figure 16, the base used for the shock tests inside the vacuum chamber with the REACT preloaded. Similar, the bases of Figure 11 for the Pin Puller actuation were used for the thermal vacuum test.
The thermal cycling has been performed between -120ºC to +70ºC for the actuators with Nitinol initiators and to +120ºC for the actuators with SMARQ initiators. Degradations to the structures were not recognized and self-actuations have not been performed. Similar, successful actuations have been obtained at +22ºC and at +70ºC for the actuators with Nitinol initiators and to +120ºC for the actuators with SMARQ initiators.

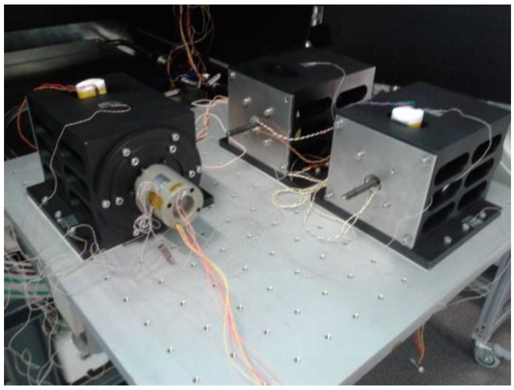

Figure 16. Setup for thermal vacuum test of REACT.

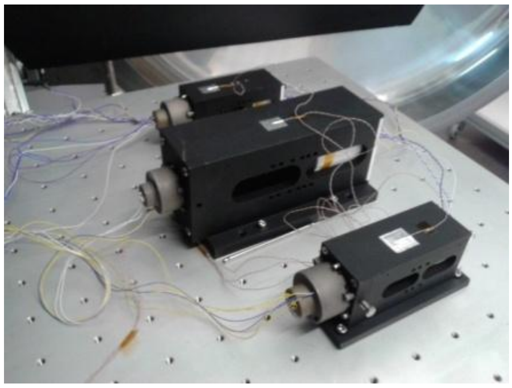

Figure 17. Setup for thermal vacuum tests of Pin Puller.

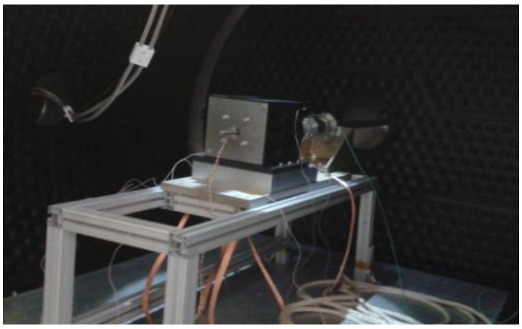

Figure 18. Measurement of resistance torque of REACT Crown in thermal vacuum.

The friction of the mechanism at lower temperatures is rapidly increased as low as the temperature is. The solid lubricant based on a polymer and the high contact stresses among spheres yield this characteristic. Thus, TVAC at lower temperatures (-120ºC) were not possible with the proposed actuator. Anyway, the resistant torque of the Crown for actuation has been measured at cold temperatures in vacuum conditions, as shown in Figure 18, in order to identify the temperature in which the motorization equation is fulfilled. The results report that at -50ºC the Pin Puller actuates compliant with the ECSS and at -40ºC the REACT actuates compliant with the ECSS.

Table 1. Summary of qualification status.

Test	PP 50N	PP 100N	PP 500N	REACT 2.5KN	REACT 15KN	REACT 35KN
Physical measurement (gr)	75	96.5	312	93.5	200	412
Electrical measurement (Ω)	1.8	22	1.8	12	10/1.8	1.8
Actuation test	OK	OK	OK	OK	OK	OK
Non actuating share force (N)	450	1800	2500	N/A	N/A	N/A
Motorization Test	OK	OK	OK	OK	OK	OK
Vibration Test (GRMS)	31	31	23	31	31	31
Inputted Shock (g)	2000	2000	1300	1300	1300	1300
Shock generated (g)	200	300	700	< 100	100	700
No-Fire Current (1A and 5 min @ 40 ºC in air)	OK	OK	OK	OK	OK	OK
Thermal Cycling (ºC)	-120 to 70	-120 to 120	-90 to 70	-120 to 120	-120 to 70/120	-120 to 70
TVAC Hot (ºC)	70	125	70	120	70/120	70
TVAC Cold (ºC)	-50	-50	-50	-40	-40	-40
TVAC Ambient (ºC)	23	23	23	23	23	23
Lifetime (cycles)	> 110	> 110	> 110	> 50	> 50	> 50

Table 1 lists the qualification status for the REACTs and Pin Puller. Note that Pin Puller of 500N is included in Table 1 because it has also been qualified by following the procedure of Figure 5. In this case, all tests have been performed with two units with successful results.

The Pin Puller and REACTs not listed in Table 1 are in TRL-3 and 4. Qualification of REACTs of 10KN and 25KN are expected for 2017 in the frame of H2020 program.

CONCLUSIONS AND LESION LEARNED

- The proposed mechanism is a suitable solution for actuators based on SMA technology. These actuators are resettable and low-shock, which are significant advantage to pyro and refurbishable actuators.
- Reduction of SMA output force has been measured with the fibres installed in the Crown (curved) respect to the fibres in straight operation. The effective force of SMA is decomposed when it is rolled around the crown. Therefore, efficiency about 70% should be considered in the actuator design.
- The mechanical parts were mechanized and good external appearances were presented. The assembly of the whole mechanical structure, parts and commercial components, showed good robustness and compactness.
- No self-actuations and degradation have been found after the environmental test and thermal vacuum cycling. Successful operations have been obtained before and after these tests, which validate the mechanism resistance to the applied thermal and mechanical loads.
- Thermal vacuum actuations have been obtained at 125 and 22ºC. Nevertheless, the actuations have not been performed below -50ºC in vacuum. The influence of just cold temperature has been checked by testing the devices in inert atmosphere. Successful actuations have been obtained under these conditions, but the combination of cold and vacuum is a worst condition that has not been overcame below -50ºC.
- Lifetime has been validated since the actuators have actuated for several cycles without degradation. Therefore, the successful operation of the device is ensured under the worst operating conditions in air environment.
- Finally, future works will need to be carried out in order to improve the actuator performances in cold TVAC.

ACKNOWLEDGEMENT

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ABBREVIATIONS AND ACRONYMS

ECSS European Cooperation for Space

	Standardization
ESA	European Space Agency
GSE	Ground Support Equipment
GSTP	General Support Technology Program
HDRM	Hold-Down and Release Mechanism
HDRA	Hold-Down and Release Actuator
REACT	REsettable non-explosive ACTuator
SMA	Shape Memory Alloy
SMARQ	SMa of ARQuimea
TVAC	Themal Vacuum ACtuation

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