Lock & Release Mechanism for the CHOMIK Penetrating Device and its Tribological Properties

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Abstract

A unique geological low velocity penetrator CHOMIK for the Russian Phobos Sample Return mission has been developed at Space Research Centre PAS (SRC PAS). One of the most important goals of the mission is to collect a soil sample from Phobos and deliver it to the Earth. The sample will be collected from the surface layers of the Mars' satellite by the penetrator and deposited in a container that is going to land in 2014 in Kazakhstan, encased in the Russian re-entry capsule. Apart from sampling, CHOMIK will perform thermal and mechanical measurements of Phobos' regolith. The penetrator itself is an improved version of the MUPUS instrument for the ESA's Rosetta mission. A new lock and release (L&R) mechanism for the instrument has been developed to meet the Phobos lander requirements. The penetrator is held in place by a multi-arms mechanism and released using Dyneema string melting system. This actuation method provides reliable operation with negligible shock and no special handling requirements.

Introduction

The Space Research Centre PAS has been involved in the development of low-speed, hammer-driven penetrators since 1996. It was strictly involved with the MUPUS project for the Rosetta mission to the 67P/Churyumov–Gerasimenko comet. Rosetta spacecraft was launched in March 2004 and will reach the comet in 2014. Recently, in 2010 SRC was invited to take part in the Phobos Sample Return mission and develop a penetration system capable of collecting a sample of the Mars' satellite soil. Such a device has been delivered to Russia in April 2011 and the Phobos-Grunt spacecraft has been launched in November 2011.

One of the most important parts of the hammer-driven penetrator is its insertion device, which constitutes about 90% of the mass allocated for the whole penetrator. The insertion device consists of free suspended elements in one degree of freedom; e.g., hammer or counter-mass that is accelerated in opposite directions during operation in microgravity environment (law of conservation of momentum). The launch of the rocket and landing operations are dangerous for a delicate counter-mass suspension and, therefore, it was locked in the stowed configuration by a specially dedicated L&R mechanism. Such a unit has to hold the device steadily and to move the penetrator head in a predicted direction after release. The operating conditions of the system are about -160°C for MUPUS and about -100°C for CHOMIK in high vacuum environment. For a long time, from launch to landing which might take up to ten years, all components have to keep stable parameters of work. L&R mechanism is an extra element of the penetrator so it needs to minimize its mass and power consumption. Based on the abovementioned requirements, a method of holding and releasing of the penetrators was developed based on the Dyneema string melting system.

The Dyneema fiber (SK65) is a multi-filament fiber produced from UHMW-PE with the following main characteristics: high strength, low density, low elongation at break and negative coefficient of expansion during heating up. Table 1 shows main Dyneema fiber properties compared to steel.

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For long duration exposure, Dyneema fiber can be used from cryogenic conditions up to a temperature of 70°C. A not very high melting temperature (~150°C) of the fiber makes it possible to cut the Dyneema string using a heating element operated by a small amount of electric power. Preliminary investigations have shown that good results can be achieved using a small resistor as a heating element and a 60° string angle of contact. Tests have shown that Dyneema string shrinks during the warming up process providing better contact to the resistor. The actuation time depends mainly on the local temperature. High reliability and repeatability ratio was observed in the presented actuation method.

Table 1. Comparison of the Dyneema fiber and steel selected properties

Material	Density kg/m^3	Tensile strength GPa	Young's modulus GPa	Elongation at break %	Melting temperature °C
DYNEEMA®SK65	970	3	95	3.6	149
Steel 316L	8000	0.6	200	45	1370

The general rule in our designs is using Dyneema string only as an actuator element not as a main holder element. For a string of 0.5-mm diameter, the tensile load capability is about 350 N but we reduce the cord's intensity of stress using leverage to eliminate the necessity of using very tough heating elements. A simple way of putting into use the listed principles is shown on the Figure 1 in MUPUS lock and release mechanism pictorial drawing.

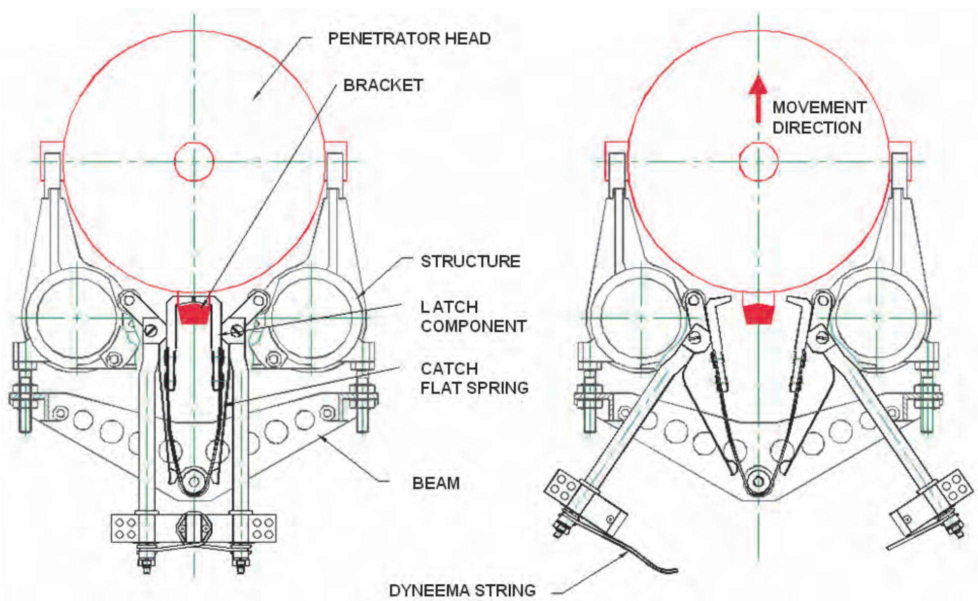


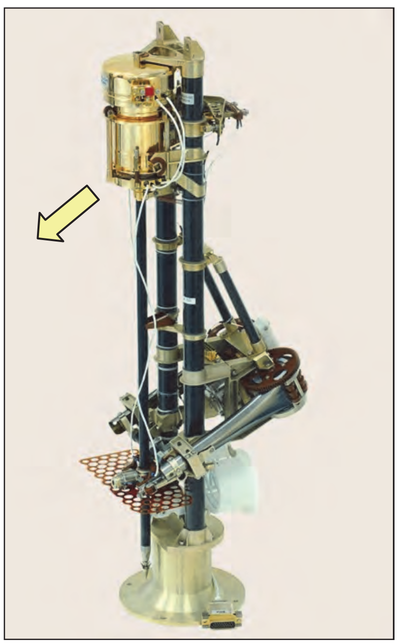
Figure 1. MUPUS penetrator head lock & release mechanism principle of operation

The MUPUS penetrator head, being a part of the counter-mass, has three cylindrical appendages that are placed in three bearings of the structure. The bearings are crossed to provide a zero degrees of freedom grip. When stowed, the penetrator head is held by the clamping of the latch component into its bracket. The proper tension between the cylindrical appendages and bearings is provided by an elastic flat spring and adjusting the gap between beam and structure. Melting of the Dyneema string releases the opening of the latch component and the unlocked bracket allows the motion of the penetrator head in the deployment direction, as it is indicated in Figure 1 by the red arrow.

CHOMIK lock & release mechanism description

CHOMIK L&R mechanism is modified and improved compared to MUPUS'. First of all, it has been designed for different dynamic loads during launch, able to withstand 10g of vibration acceleration and 40g shocks. Such loads result in a relatively high penetrator holding force, which in this case was about 400N. General requirements also influenced the instrument structure that has to contain electronics boards, penetrator guide, and the lock and release unit as a compatible part. The movement direction of the penetrator head after releasing also underwent changes. In MUPUS, the penetrator head has to retreat from the locked elements. In CHOMIK, the penetrator head has to operate inside its holding elements. The instruments with the penetrator head's movement directions pointed out and their lock & release mechanisms are shown in Figure 2 and Figure 3.

The selection of the melting elements determined the parameters of Dyneema string: 0.5-mm diameter with 10-15 N tension force safe loading. Such a system required 1:40 leverage to withstand the penetrator's head holding force. Figure 4 illustrates a kinematic diagram of the developed symmetric multi-arms system. The penetrator holding force is transmitted through the crank arms to a slider by the binary links. An angular shaped slider has a sliding joint with a possible displacement of 18 mm. It is blocked by the holders in the stowed position. During release, initially connected by Dyneema string, holders rotate, setting the slider free. The slider's linear movement cause the crank arms' rotation. Three pairs of adjustable holding pins separate from the penetrator's sockets creating 10-mm gaps between the lock and the penetrator.



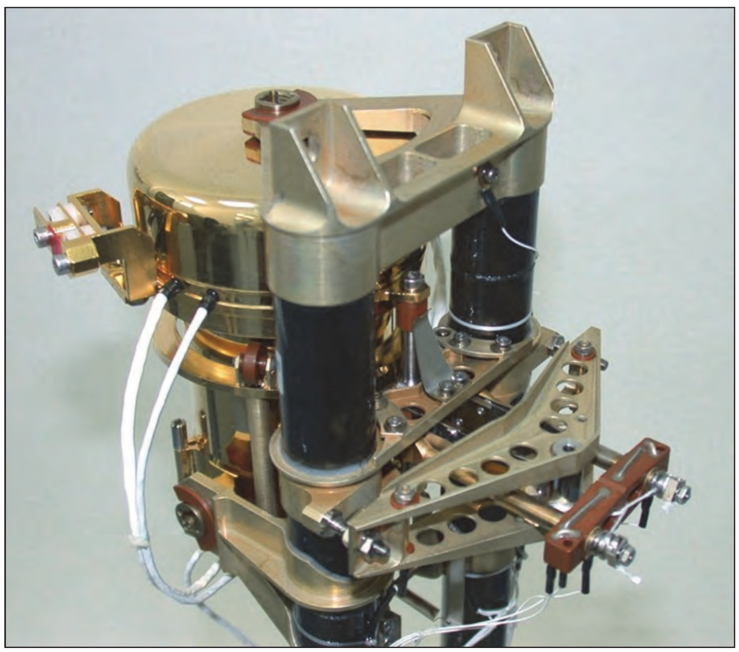


Figure 2. MUPUS penetrator with deployment system (left) and its lock and release mechanism in the stowed position (right)

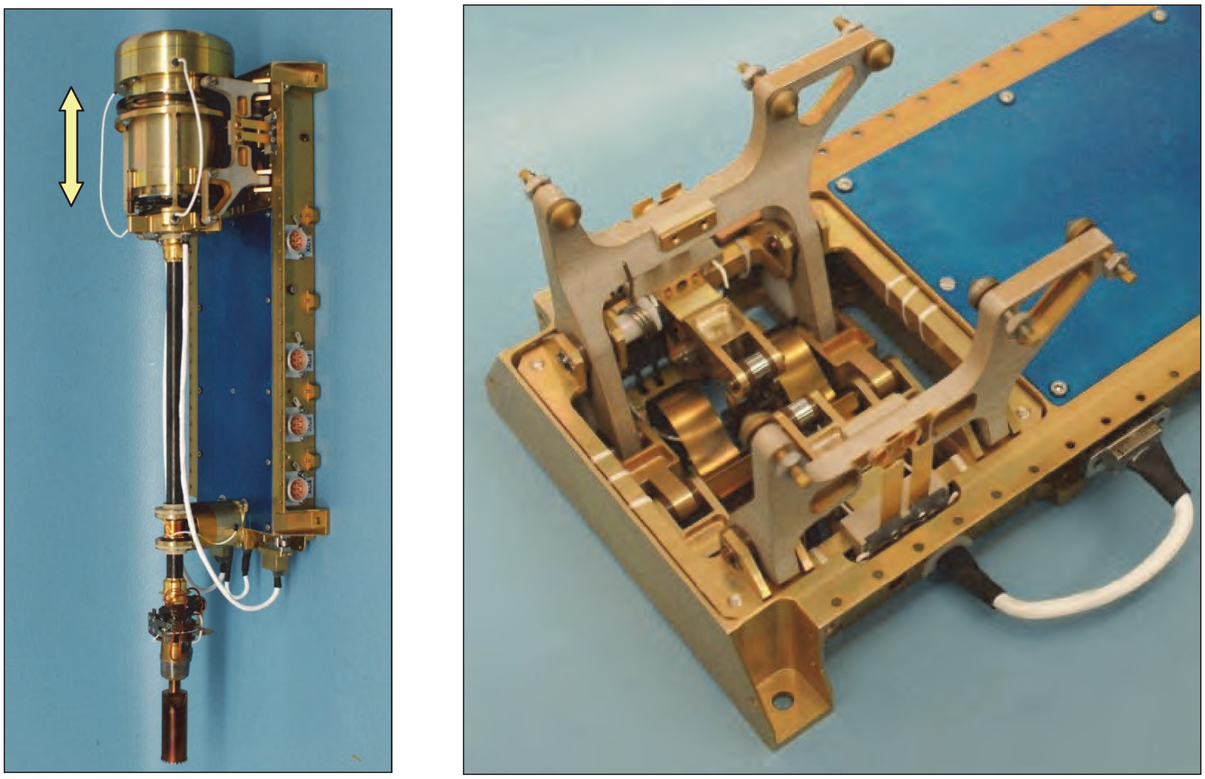


Figure 3. CHOMIK penetrator with electronic box (left) and its lock and release mechanism in the stowed position (right) – penetrator is removed

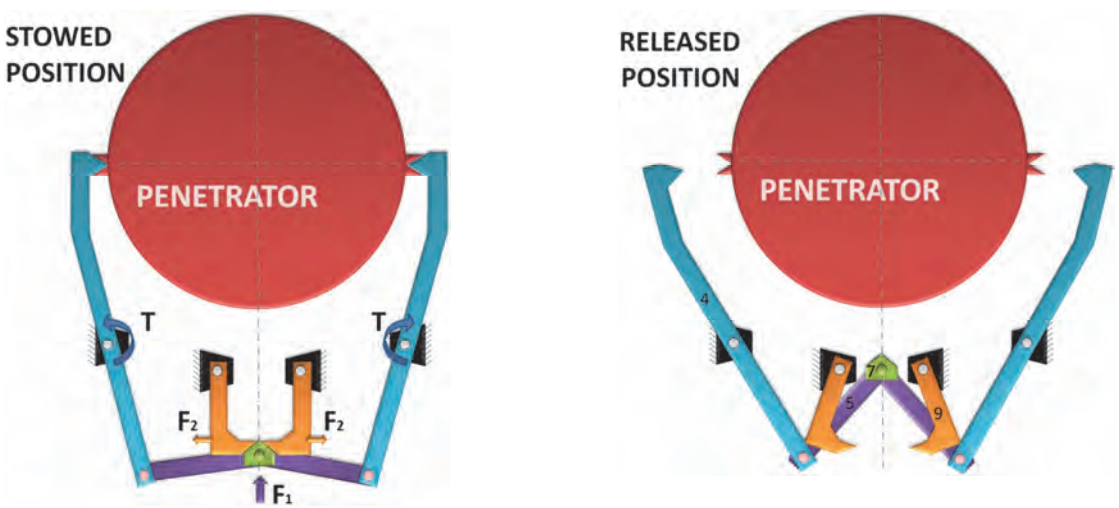
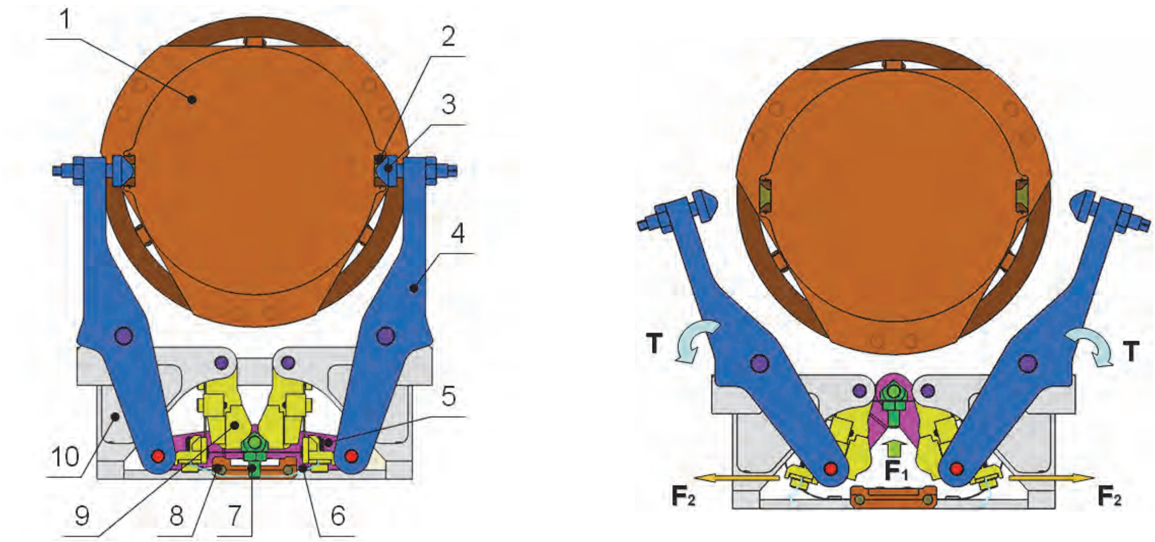


Figure 4. A planar kinematic diagram of the lock and release mechanism

There are three types of springs responsible for the mechanism release: (I) torsion springs generate torque *T* to the crank arms rotating them by 18°, (II) flat C-shaped springs guide and produce a pushing force F_1 to a slider, (III) flat springs, which are integrated with holders and execute two functions: kick-off and Dyneema string tensioning with F_2 force.



1 - PENETRATOR 2 – SOCKETS 3 - HOLDING PINS 4 - CRANK ARMS 5 - BINARY LINKS
6 - DYNEEMA STRING 7 - SLIDER 8 - HEATERS (RESISTORS) 9 - HOLDERS 10 - STRUCTURE

Figure 5. Practical realization of the mechanism

The tight string protects the holders after their displacement caused by the Dyneema cord elongation of about 3.5%. The design of the mechanism is shown in Figure 5. The complete lock and release mechanism weighs 150 grams and occupies a volume of 81x82x36 mm. Two redundant melting elements have 110 Ω of resistance and the actuation power voltage is 28V. Two connectors provide confirmation of the holding arms release.

The main challenge during the mechanism development was the elimination of the self-locking effect. To avoid such a situation, the design process was preceded by detailed kinematic studies, and then a structural-thermal model was assembled and tested. The investigation showed some problems with slider elements that potentially could produce a non-symmetric release. This issue has been solved by blocking one of the kick-off spring's motions and implemented in the qualification model.

Tests also showed that it is very important to place all moving arms in their suitable positions during the arming process. Figure 6 presents the mechanism's arming equipment which is helpful to provide symmetric arms' settings and to generate the preliminary tension making it possible to install the Dyneema string.

The mechanism successfully passed the vibration resistance test, shock test and linear overload test. A functional test has been carried out in the vacuum-thermal chamber. The temperature on the instrument structure was about -150°C and vacuum of about 10^{-6} Pa. The Dyneema string application needs 6 seconds for release in those simulating Phobos environmental conditions, compared to less than 1 second at room temperature (laboratory air). Shock generated during release is very low compared to those created by a pyrotechnic actuator.

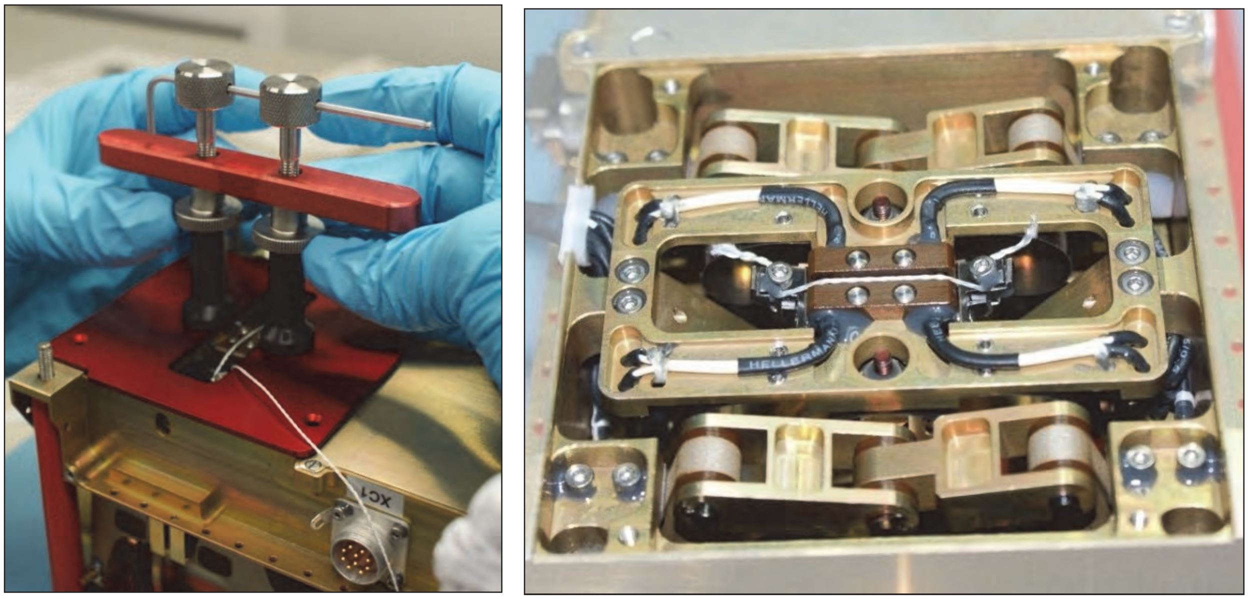


Figure 6. Mechanism arming equipment (left) and L&R mechanism with Dyneema string installed (right)

High-speed camera record has shown that the maximum speed of the holding pins is about 4 $^{m}/_{s}$ during releasing (at room temperature). The time period, from Dyneema string melt to the crank arm full rotation, is about 5 milliseconds; then the crank arms rebound several times dissipating energy, and stop after about 52 milliseconds. As it is shown in Figure 7, the first crank arms movement is very equal, which is the result of accurate positioning of the mechanism element during Dyneema string installation using the arming equipment. Figure 8 shows selected moments of the mechanism action. Frame A shows the locked mechanism. In Frame B, the Dyneema string is melted but holders still occupy the slider lateral surface. In Frame C, the slider is shifting resulting in the binary links pull and that makes the crank arms rotation possible. Frame D shows a mechanism in the fully released position. The moments captured on the presented frames has been marked in Figure 7.

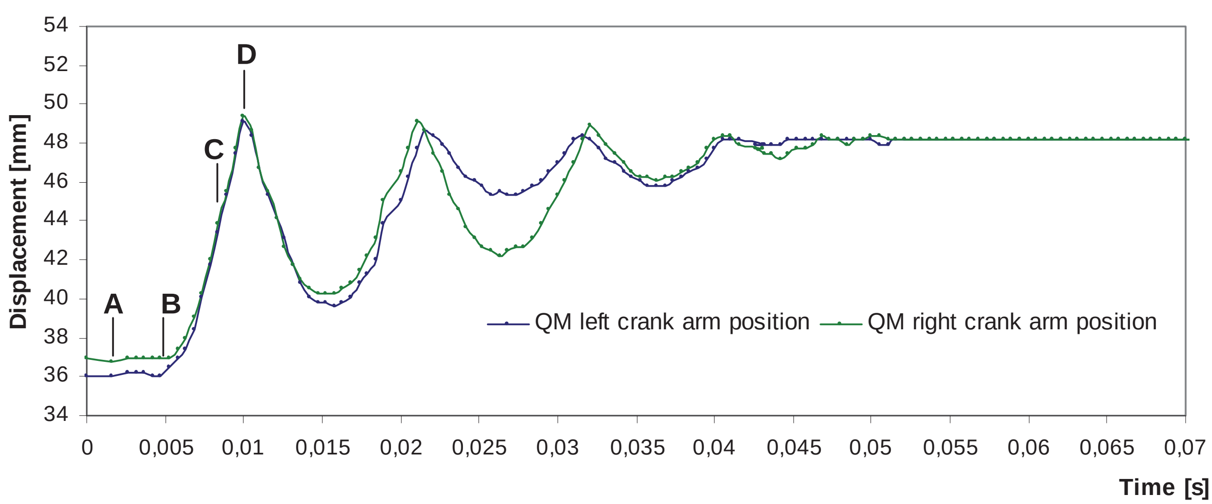


Figure 7. Holding pins displacement during mechanism release

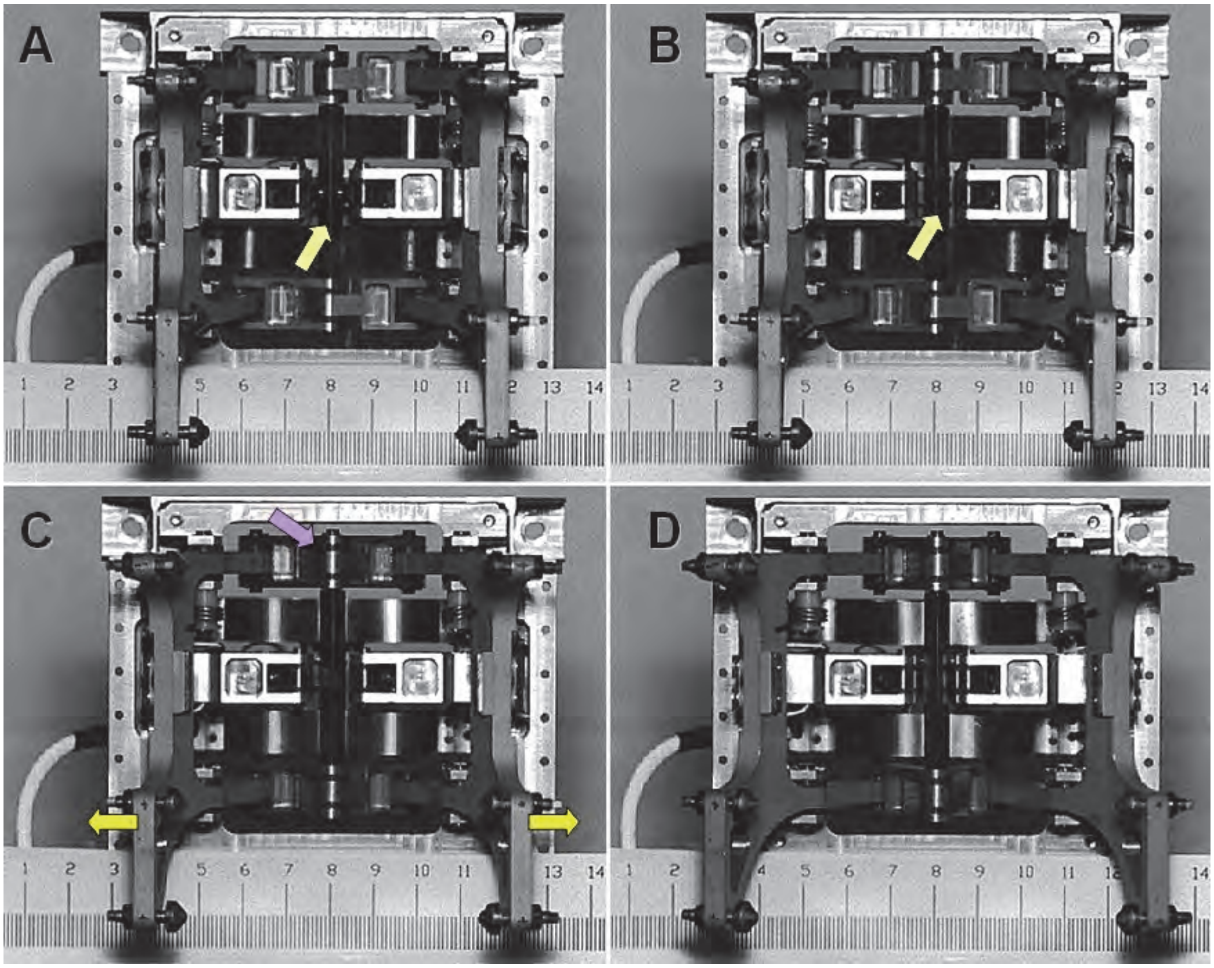


Figure 8. Lock & release mechanism action - penetrator is removed

Tribological tests

All rotating and sliding joints in the mechanism (Figure 9) have to work in very low temperatures and vacuum, with a small movement range and with only one, short time actuation. This influenced the slide bearings selection. Titanium alloy with titanium nitride layer and polyimide-based plastic Vespel SP1 were chosen as mating parts materials. Tribo-components made of Ti6Al4V alloy (shafts, pins, latches) with Vespel SP1 (bushings, sliders, guides) have been used in many SRC PAS mechanisms, including the CHOMIK device. This selection was based on our experience, previous material properties tests, and the ability to manufacture good quality layers on parts with a complicated shape by our partners.

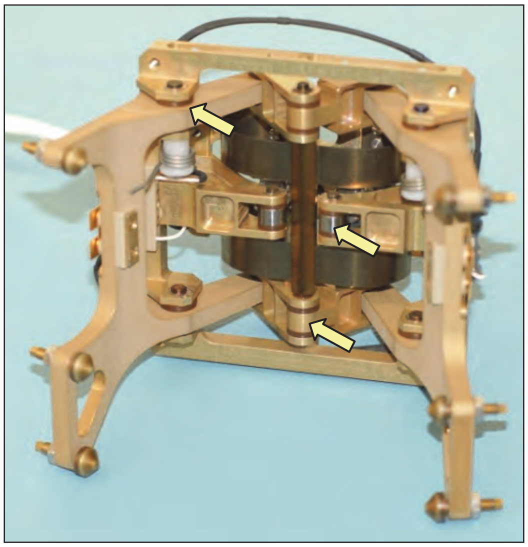
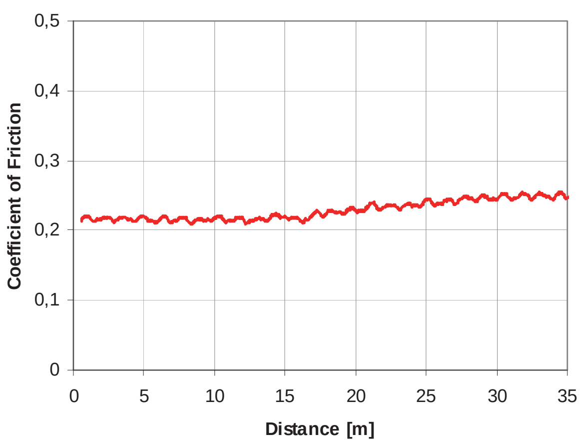


Figure 9. L&R mechanism with its exemplary plastic-metal slide components

Figure 10. Pin-on-Disk tribometer mounted in the SRC thermal-vacuum chamber

To develop a unit without a self-locking effect, a coefficient of friction for selected mating plastic-metal parts had to be known. Another unknown was a repeatability of the mechanism behavior during room and low temperature operation. Adequate tests were conducted in a newly built vacuum pin-on-disc tribometer (Figure 10). Ti6Al4V alloy with titanium nitride layer as a pin while Vespel SP1 as a disk were used.



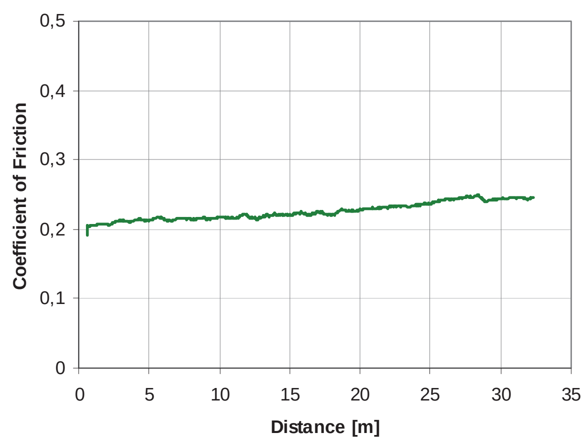


Figure 11. Coefficient of friction versus sliding distance for Ti6Al4V pin with TiN layer and Vespel SP1 disk for vacuum environment: room temperature (left), very low temperature (right)

The tests were conducted in the following conditions: (1) pressure: 0.01-0.04 Pa, (2) load: 50N, (3) sliding speed: 0.1 $^{m}/_{s}$, (4) contact area: 10 mm^2. Figure 11 (left) shows coefficient of friction versus sliding distance at room temperature, whereas Figure 11 (right) is a diagram of coefficient of friction for -80°C. Tribological tests in the Phobos-simulated environment showed that the coefficient of friction for Vespel SP1 and Titanium alloy with titanium nitride layer is low, about 0.22. Moreover, friction properties are stable and on the same level, both at room or low temperature.

Conclusions

Development of the CHOMIK L&R mechanism provided successive arguments that thin Dyneema string melting method can be applied for releasing medium-high loaded space devices. The alike systems are developed at SRC PAS taking into account the superior reliability of the melting process. Medium-higher loads need a high leverage mechanism, which is the main subject of the presented paper. The conducted tests proved it. One of the lessons learned is that in case of the high leverage mechanism, additional springs counteracting the self-locking of the mechanism must be applied. Usage of a system that counteracts the cord elongation is also recommended. The investigations that have been made confirm that the Dyneema string melting actuation method is very reliable and Vespel SP1 and titanium alloy with titanium nitride layer are suitable mating materials for low temperature applications.

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