Multi-Mission Deployable Boom: Spring Mechanism Design, Failure Investigation, and Resolution

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Abstract

As more ambitious missions are being pursued to better understand Earth and our Solar System, aerospace mechanisms and deployable structures are being approached in new fashions. NASA's Jet Propulsion Laboratory is developing two low Earth orbit satellites that will use radar instruments to better understand temporal changes in the Earth's surface. Both the Surface Water Ocean Topography (SWOT) and the NASA-ISRO Synthetic Aperture Radar (NISAR) spacecraft utilize large carbon fiber deployable antennae to conduct such science. These large antennae have been designed with similar mechanisms. During testing of the spring mechanisms that deploy the antennae, a hardware failure was found. The source of the hardware failure was traced back to the custom torsion springs used within the mechanism. Because of the mechanism volume constraints, the springs were designed with high aspect ratio rectangular cross sections to maximize the spring constant for the mechanism. Ultimately, a failure investigation and testing campaign led to spring mechanisms that have been successfully integrated into both spacecraft.

Introduction

NASA's Jet Propulsion Laboratory (JPL) is currently developing two earth orbiting satellites. The Surface Water Ocean Topography (SWOT) mission will conduct the first global survey of Earth's surface water. The NASA-ISRO Synthetic Aperture Radar (NISAR) mission will study temporal changes to Earth's land and ice-sheets using advanced radar techniques. Both missions serve to better understand how the Earth is changing over time using radar-based instruments. The SWOT mission is a collaboration with the French, Canadian, and UK Government Space Agencies and will launch from Vandenberg Air Force Base on a SpaceX Falcon 9 Rocket in 2021. NISAR is a partnership between NASA and the Indian Space Research Organization (ISRO) and will launch in 2022 from Satish Dhawan Space Center on an Indian Geosynchronous Satellite Launch Vehicle.

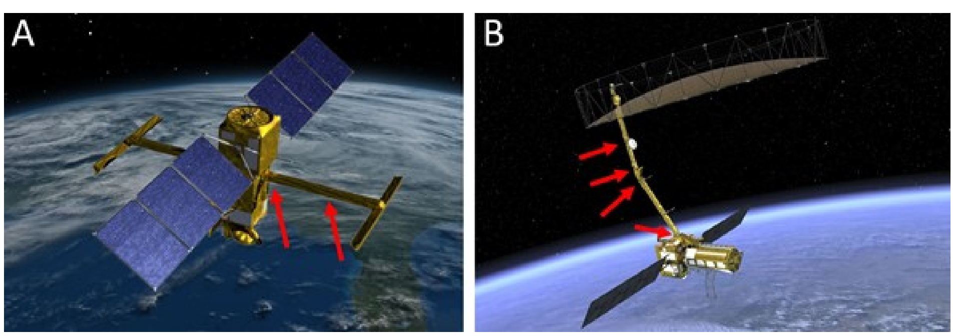

Figure 1. A) SWOT with hinge locations shown on one mast B) NISAR with hinge locations shown.

Both SWOT and NISAR use deployable radar reflector mast designs developed at JPL. These deployable masts, while different in geometry, have similar components and sub-assemblies. Both masts are constructed from bonded Invar and carbon fiber composite structures and employ analogous flight

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deployable hinge mechanisms. The SWOT mission has two identical reflector masts, each with two deployable hinges. NISAR has a single mast with four deployable hinges. These masts can be seen in Figure 1. Operationally, the deployable masts are launched in a stowed state with a launch restraint system composed of separation nut devices. When commanded, the launch restraints release a pre-tensioned spring and damper mechanism which deploys each hinge. Hinge deployment progress is monitored on the ground using a potentiometer as well as a limit switch on each hinge. Upon completion of the deployment, an actuator-driven latching mechanism preloads precision alignment features on either side of the hinge together. Figure 2 displays an overview of the mechanisms.

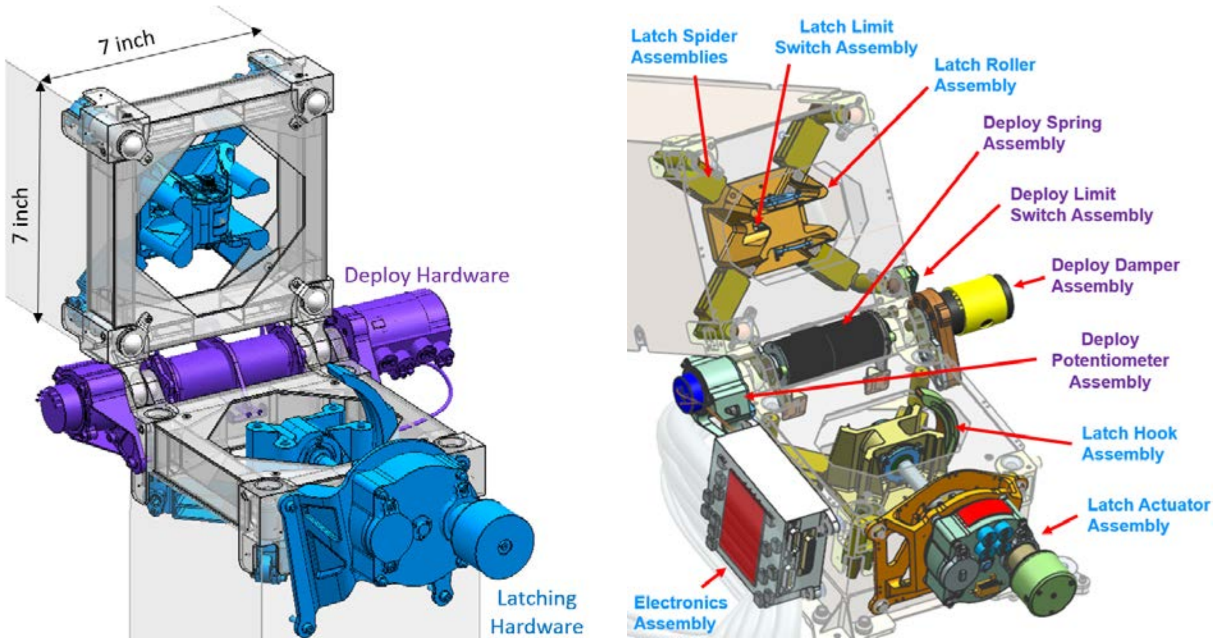

Figure 2. Hinge Deploy & Latching Mechanisms (NISAR configuration shown)

Mechanism Design and Fabrication

Mechanism Design

Each deployable hinge for the SWOT and NISAR masts is outfitted with a spring, damper and potentiometer mounted co-axially with each hinge line. The NISAR mast is composed of 7-inch (18-cm) square composite tubing. The SWOT mast is composed of 10-inch (25-cm) square composite tubing. Figure 3 displays the spring mechanisms for each mission. The smaller, 7-inch (18-cm) mast cross-section of NISAR became the driving factor in the design of the spring mechanism to maximize mechanical commonality between projects. Common mounting interfaces were designed for both projects. Ultimately, this led to a cylindrical volume allowance of 7 inches (18 cm) in length and 1.75 inches (44 mm) in diameter for the NISAR spring mechanism. Because of the differences between the SWOT and NISAR stowed hinge angles, as well as differences in hinge angles at different locations on each mast, four different torsion spring configurations were developed, each with the spring arms located at different angles relative to each other in the relaxed position. This can also be seen in Figure 3 when comparing both images.

A) B)

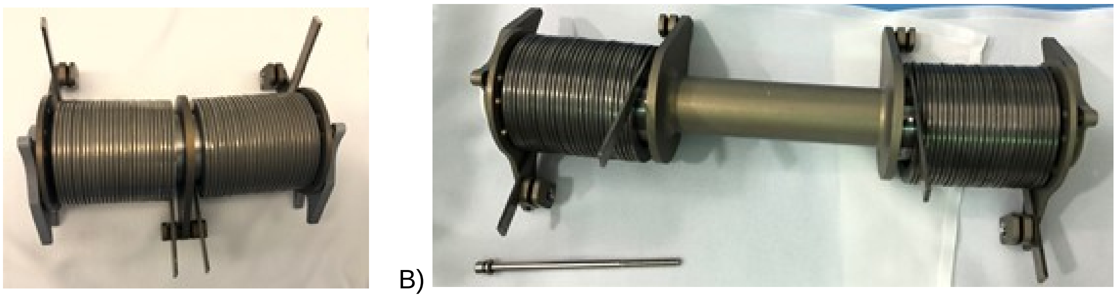

Figure 3. View of A) NISAR and B) SWOT spring mechanisms

The spring mechanism is required to meet JPL design requirements for mission critical spring design. As such, springs are required to have a minimum no test yield factor of safety (FS) of 1.50 and an ultimate FS of 1.65. Furthermore, JPL design principles impose a minimum mechanism torque margin of 100% in worst case environments at end of life. These driving requirements meant the torsion springs needed to produce a minimum deployment-direction torque of 28 inch-pounds (3.2 N-m) at hinge closure. A standard round wire 17-7 precipitation-hardened stainless-steel torsion spring would not produce adequate torque in the volume available without violating mission critical factors of safety. Alternative materials such as Elgiloy and MP35N were considered, but all of the vendors considered for fabrication of these springs had a significantly higher volume of experience working with 17-7 stainless steel and developmental risk was deemed higher with these alternative materials. Therefore, a geometric solution was developed: a rectangular cross section spring to maximize the moment of inertia within the available volume.

After developmental fabrication test runs, the spring wire height-to-width ratio selected for the spring cross section was 3.88:1. This value was determined to be the highest ratio achievable with available CNC spring winding manufacturing capabilities. Spring manufacturing still included many challenges given the propensity of the spring wire to rotate about the axis of the wire during winding and inconsistencies in spring back resulting in non-uniform torsion spring inner and outer diameters. The CNC spring winding configuration is shown in Figure 4. Guide support features were added to the flight spring mandrel design to prevent twist about the axis of the spring wire at either end of each spring.

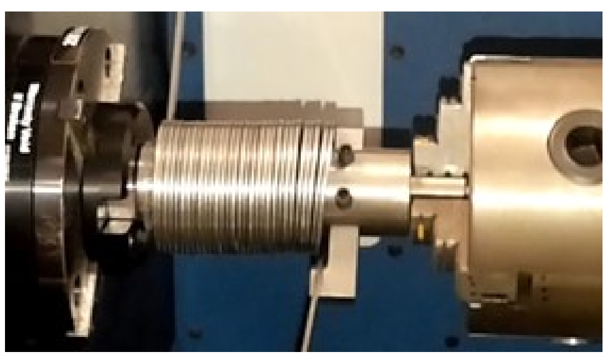

Figure 4. Torsion Spring on CNC Coiling Machine

The rectangular cross section caused early manufacturing issues for the flight units. The springs did not initially meet axial length requirements. Further the wire was prone to unexpected twisting during winding. The initial inclination of the team was to attempt to relax the overall spring length requirement, but that would have had significant ripple impacts into the mature design of the hinge and mast structures. To address length requirement non-compliance, the initially baselined spring with 29 coils was modified to a baseline design of 27 coils. With this change, the spring design violated JPL design requirements minimum factor of safety requirements. Reducing the number of windings increased the stress in the spring. In consultation with JPL materials experts, material coupon testing for the flight lot of material was conducted to establish higher strength allowables for the flight lot of material to address the slight negative strength margins. Ultimately, the final flight springs were successfully manufactured with a variation of less than 0.007 inch (178 µm) in diameter and 0.012 inch (305 µm) in length across twenty-eight units. The torsion spring design that was developed met all requirements, as verified via tensile test witness coupons of the material, destructive winding testing, dye penetrant inspection, and other verification techniques.

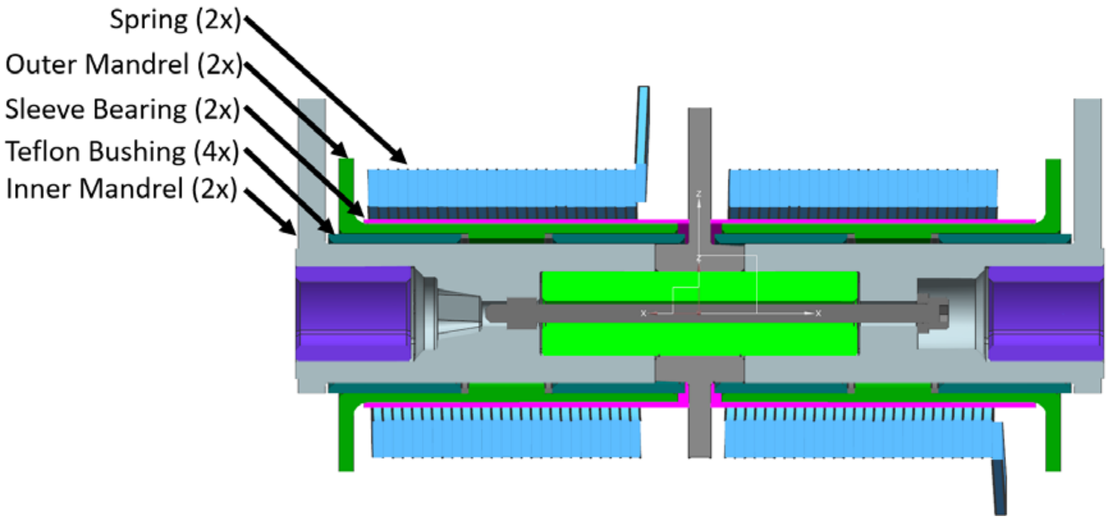

Figure 5. Cross section of NISAR Spring Mechanism

Once the spring mechanism design solution was reached, prototype units were built. A prototype test program was successfully completed prior to flight hardware fabrication to reduce risk of issues in the flight hinge and latching mechanism development. The prototype test program included both ambient and thermal functional testing and thermal characterization testing on a flight-like hinge fixture. The prototype program did not include vibrational testing or life testing due to programmatic constraints. The lack of these prototype tests prevented design issues described in the next section from being uncovered prior to the qualification test program.

Mechanism Integration and Hardware Failure

<u>Hardware Failure</u>

Upon successful completion of the prototype test program, fabrication of qualification, flight spare, and flight piece parts ensued. Seven SWOT spring mechanisms were assembled with a qualification unit slated for thermal testing to characterize torque output at the worst case cold, ambient, and hot qualification temperatures. The qualification unit was of a SWOT design but was deemed similar to the NISAR design. Therefore, a single qualification unit was used for both missions. Thermal life testing was conducted after the qualification unit had undergone vibrational testing. Thermal test temperatures and vibrational test levels were set to encompass the environments for both missions.

During thermal testing, the spring was wound and unwound manually through its operational range of motion using a rotary turn table. Torque output and rotary angle were tracked with a transducer and encoder, respectively. At the qualification hot temperature, hardware failure was observed. From repeated torsion springs cycling (winding and unwinding), fragmented Teflon Foreign Object Debris (FOD) was generated. This can be seen in Figure 6. The source of the FOD was determined to be from two glass-filled Teflon sleeve bearings in contact with the inner diameter of each spring inside the mechanism. The spring mechanism continued to function and torque performance was not measurably altered by the fragmentation. Upon further investigation it was determined that the sleeve bearing had begun to fail prior to hot thermal testing.

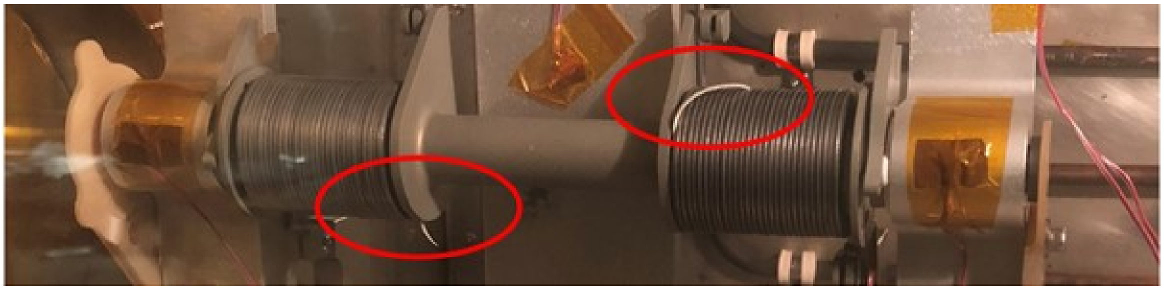

Figure 6. Image of spring mechanism during thermal testing with evidence of hardware failure circled

After the failure, the qualification spring mechanism was disassembled. The root cause was identified to be invalid analytical model simplification. The analytical model simplified the torsion spring geometry as a cylinder with uniform inner diameter. The real rectangular cross section torsion springs had slight variations in the inner diameter between coils, with sharp cutting edges presented to the Teflon bushings during cycling. Therefore, the contact stress in the real hardware at the cutting edge was substantially higher than in the idealized analytical model. In addition, the sleeve bearing had been designed with a helical cut along the axis of the bearing, designed to allow radial compliance as the torsion spring inner diameter changes during winding/unwinding operations. However, the helical cut also drastically reduced axial stiffness of the part. As such, when the spring coils moved axially during winding, the edges of the bushing began to contact each other and plastically deform. These failures can be seen in Figure 7.

This failure resulted in the opening of a JPL Problem Failure Report. As such, a technical team was assembled to oversee the investigation and resolution of the failure. Because of the multi-mission applicability of the hardware design, the team was composed of representatives from both the SWOT and NISAR projects. Any resulting actions needed to be approved by both missions. There was programmatic motivation to utilize as much of the existing hardware as possible.

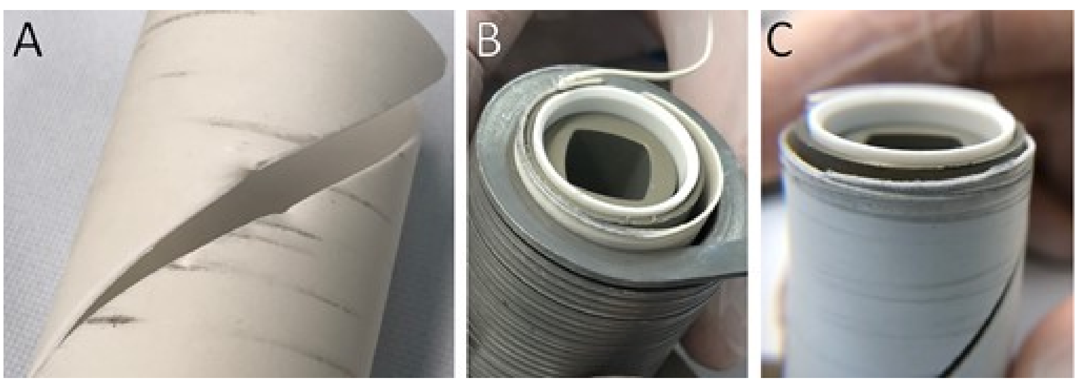

Figure 7. Images of Teflon sleeve bearings after thermal testing

<u>Mechanisms Modification</u>

Ultimately, a solution was developed that replaced the Teflon sleeve bearing with a grease-plated 440C stainless steel sleeve bearing with modified geometry. Over 400 functional cycles and 20 disassembly procedures of the qualification mechanisms were carried out during the hardware failure. Table 1 summarizes the test campaign that was conducted to find a new sleeve bearing design. The fundamental approach was to change one parameter at a time from the original bushing design and evaluate its effect on the health of the component and test performance until an acceptable solution was found. An acceptable solution had to simultaneously meet mechanism torque performance needs as well as avoid significant FOD generation or damage to the bushing through three times the planned number of flight unit life cycles.

Table 1: Summary of hardware failure investigation testing

Index	Material	Bearing Design	Test Type	Test Result	Notes
1	Teflon	Helical Cut	Vibrational, Thermal, Cycle Life	Fail	-Initial Failure
2	6061		Torque Characterization	Fail	-Torque requirement failure
3	304C		Torque Characterization	Fail	- Noise from mechanism -Torque requirement failure - Helical cut deemed unacceptable
4	Bronze	Solid Sleeve Bearing	Torque Characterization	Fail	- FOD found
5	440C		Torque Characterization	Fail	- FOD Found
6	Copper	Extended, solid sleeve bearing	Torque Characterization	Fail	- FOD found - Torque requirement failure
7	440C		Torque Characterization, Cold	Pass	- Noise witnessed - Good Torque
8	Bronze		Torque Characterization	Fail	- FOD found - Good torque
9	440C		Vibe, Cold, Hot, Cycle Life	Pass	- Full Life Test - Good Torque - Noise witnessed
10	440C		Torque Characterization	Pass	- Confirm lubricant alleviates noise

As described previously, torque testing of the mechanism included using a transducer and encoder to measure torque and rotational position, respectively. This torque testing was carried out for each potential bushing design. If the torque was deemed acceptable, the unit was then disassembled and inspected for any FOD or other potential failures. Figure 8 displays the torque performance of the spring mechanism for the final bushing design in ambient and cold conditions during cycle life testing (defined as at least three times the expected number of mechanism cycles). Torque performance is seen to degrade up to 1.1 N-m (10 in-lb) over the course of 30 cycles at ambient. Further, torque performance degrades at cold temperature about 1.1 N-m (10 in-lb). Despite performance degradation, torque never violated the 3.2 N-m (28 in-lb) torque requirement. Also notable, the unwinding torque at cold temperature is seen to be nearly constant. This differs from the analytical model of linearly decreasing torque. The cause for near-constant torque is suspected to be internal mechanism friction caused by migration and degradation of lubricant on the bushing as it is cycled.

Toward the end of the Problem Failure Report investigation, during final life cycle testing of the hardware, audible sound was observed from the hardware. This sound triggered further investigation and resulted in the development of an assembly-level relubrication process for the mechanisms. This procedure eliminated the source of the concerning noise. The relubrication process seeks to augment lubrication in areas on the sleeve bearing where lubricant may have worn away during mechanical cycling.

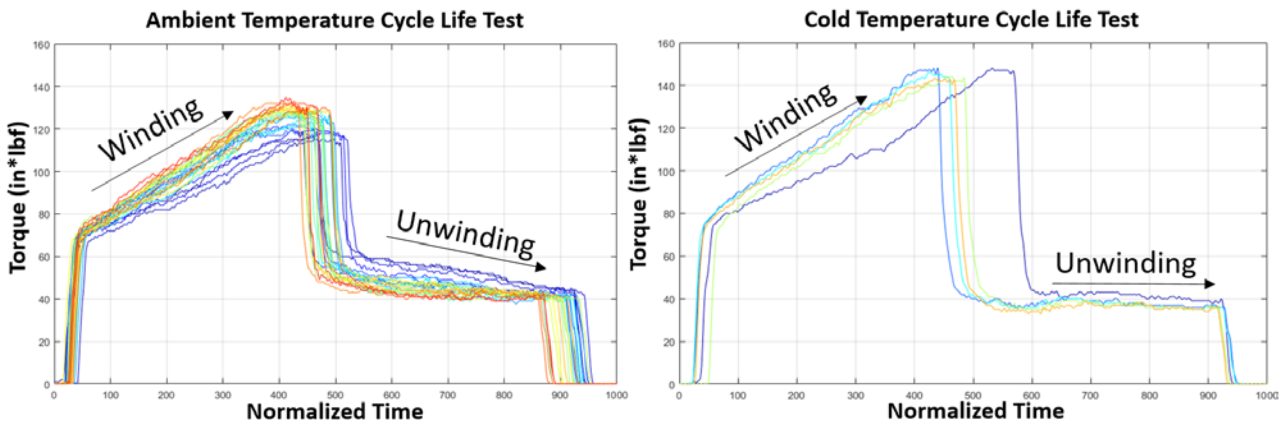

Figure 8. Torque profile of mechanism as it is wound and unwound at ambient and cold temperature. Blue indicates initial cycles, yellow intermediate cycles, and red represents later cycles.

Conclusion

Following resolution of the hardware failure, all flight spring assemblies have been updated, passed flight acceptance environmental testing, and have been integrated into both SWOT and NISAR flight masts. The mechanisms have successfully been tested at higher levels of assembly and performance is consistent. The spring mechanisms require relubrication every 8 cycles of ground testing based on the process developed in the hardware failure investigation, which is achievable at the integrated level of assembly.

Key lessons learned from the development of these torsion springs:

- Avoid rectangular cross section springs unless volume limitations necessitate their use. Round wire springs have greater geometric and performance consistency and are simpler to analytically model.
- Beware of analytical model simplifications that may oversimplify and invalidate the results.
- Rectangular cross section springs will twist about the axis of the wire when wound. This twisting needs to be considered when designing any hardware coming in contact with the spring.
- Consider both the wound and unwound geometry of the spring during design of the mechanism.
- There is high value in a complete mechanical cycle life test at the prototype stage of development.

References

1. Paul Lytal and Marcel Renson. “Spacecraft Common Deployable Boom Hinge Deploy and Latching Mechanisms.” Proceedings of the 44th Aerospace Mechanism Symposium, (May 2017), 403-416.

Acknowledgement

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