Design and Development of Miniature Mechanisms for Small Spacecraft

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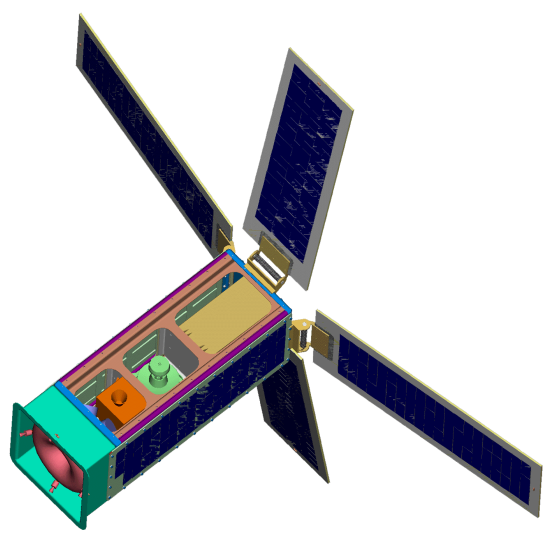
ABSTRACT. With the continued push for smaller, faster, and cheaper spacecraft comes a new era in mechanism design. The desire to develop "Micro Satellites", along with advances in the processing and selection of materials, have created an abundance of opportunities to miniaturize mechanisms. Simple designs with direct applications of developing technologies are ideal for these miniature mechanisms. This paper will focus on the design and development of a miniature satellite "tool kit". Six mechanisms were developed by Starsys Research and the Applied Physics Laboratory (APL) at John Hopkins University (JHU) under a NASA Advanced Technology Development (ATD) Program. The mechanisms developed included a Micro and Mini Separation Nut, a Mini Rotary Actuator, a Micro Burn Wire Release, a SMA Linear Actuator, and a SMA Redundant Release Mechanism. The paper will discuss the concepts evaluated, designs chosen for fabrications, problems encountered during development, achieved performance characteristics, and recommendations for future development.

Introduction

Micro-satellites in the 10-100 kg range are being developed for scientific, commercial and military applications. For their size, these spacecraft will have very sophisticated payloads and missions. This is due to advances in miniaturization of electronics, RF systems, sensors, and instruments. The John Hopkins Applied Physics Laboratory is developing many of these leading edge technologies for a wide variety of micro-sat applications. The JHU/APL micro-spacecraft concept (shown in Figure 1) provides for a modular-customizable bus that is 3-axis stabilized, has redundant IEEE 1394 data bus, on-board instrument processing, and makes use of advances in miniaturized electronics. Other micro-satellite programs in industry, military, and NASA have similar features such as miniaturized payloads and electronics.

One area of miniaturization that has not seen significant increase in development is the mechanisms needed for the deployment of small-scale solar arrays, booms, and instrument devices. Many off-the-shelf mechanisms are reduced in size for small satellites, but are not the order of magnitude reduction in size needed for micro-satellites. The Advanced Technology Development Program at JHU/APL is currently funding research for development of micro mechanisms and is collaborating with Starsys Research to provide an off-the-shelf selection of actuators and trigger devices. This has lead to the creation of the micro-mechanisms tool kit. The tool kit contains 6 new mechanisms for use on instruments, solar arrays, and other deployable or mechanism driven device. All of these mechanisms are further scalable and show promise for additional miniaturization.



30 kg, 0.02 m^3, Composite
3 axis stabilized
Advanced electronics

Figure 1. JPL/APL Concept MicroSat

Table 1. Mechanism Descriptions

Mechanism Type	Actuation Device	Company	Mass (gms)	Size (inches)	Power	Load Capability	Lifetime	Release Time
Micro Sep-Nut	Shaped SMA	Starsys	5	0.280 X 0.180	2-5 watts	3-5 lbf	> 100 Actuations	~30 seconds
Mini Sep-Nut	Shaped SMA	Starsys	10	0.570 X 0.560	2-5 watts	10-25 lbf	> 100 Actuations	~30 seconds
Rotary Latch	SMA Torsion Spring	Starsys	5	0.75X0.50X0.50	10 watts	2-6 inch ozs	> 100 Actuations	< 120 sec
Burn Wire Release	Fuse Wire	JHU/APL	0.07	0.5 X 0.30 X 0.30	< 5 Amps	10 lbf	1 Actuation	< 5 msec
Mini Linear Actuator	SMA Wire	JHU/APL	3.8	1.25 X 0.30 X 0.30	< 5 Amps	10 lbf	> 100 Actuations	< 10 msec
Mini Redundant Release	Shaped SMA	JHU/APL	3.8	0.50 X 0.30 X 0.30	< 5 Amps	5 lbf	> 100 Actuations	< 10 msec

This project addressed the design of several types of mechanisms including separation nuts, release devices, linear actuators, and rotary actuators with a range of load capability. Table 1 shows an overview of the mechanisms under development with the current characteristics. Performance requirements for these mechanisms are not well established due to the infancy of the micro-satellite designs. Therefore, assumptions were made to handle loads of 3 – 10 lbf, make the size small as possible, use low power, provide low shock, and make the mechanisms easily resettable. Shape Memory Alloy (SMA) was chosen to drive most of the mechanisms due to its superb capability of providing high forces in a very small package. SMA's are also very quick responding when electrically driven directly through the material. A burn wire mechanism was also developed by JHU/APL due its capability to be highly miniaturized yet provide good strength capability and reliable operation. The following sections will detail the six mechanisms developed.

Mini and Micro Separation Nut

Two mechanisms were designed by Starsys Research that would restrain and release a 0-80 or similar bolt. The separation nut is similar in design to conventional devices in that it is a segmented nut constrained by a collar. With the collar in place, the segmented nut is maintained in the shape of a nut, allowing a mating bolt to be threaded and tightened in place. The collar is maintained in position by a compression spring that prevents the collar from moving due to vibration loads.

The collar is driven in opposition to the spring by a Shape Memory Alloy (SMA) element, which is heated directly or by an attached resistance heater.

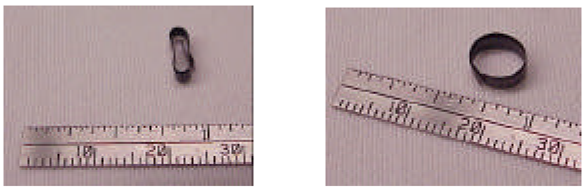
To release the bolt, power is supplied to the heater or SMA element. As it is heated through its transformation temperature, the element recovers previously induced strain, and drives the collar to allow the segmented nut to separate, releasing the bolt. When power is discontinued, the mechanism can be manually reset. The bolt can then be re-inserted into the nut and the sequence repeated.

Design Approaches

In reviewing the options, a number of different approaches were examined and evaluated. Most all of the approaches required that linear motion from a motor be used to generate the required force for release. Four choices were examined for the motor to either trigger the release of the bolt or actually release the bolt; paraffin, Ostalloy, SMA wire, and SMA springs. After some conceptual design work on the motor, the SMA spring was chosen as the most favorable approach. This was due to the high stroke that could be achieved, the fairly quick response time, and the variety of available shapes.

SMA Spring

The SMA spring used is formed from a wire or strip of SMA material. A variety of SMA forms and springs were considered for this application. The shape selected for this application was a round band of SMA strip (see Figure 2). Initially the spring is compressed flat or near flat. As the wire is heated, the spring expands and returns to its round shape. This motion can be used to release a bolt or nut segment. The round shape resulted in a spring with a reasonable amount of stroke and output force in a relatively compact size.



Compressed After Heating

Figure 2. SMA Band Spring

Release Mechanism

With the decision made to pursue a design using a SMA spring, several mechanism designs were developed and evaluated. The two designs that were pursued and fabricated were a segemented nut axial release (Mini Sep-Nut) and a direct SMA release (Micro Sep-Nut)

Segmented Nut – Axial Release (Mini Sep-Nut)

Three SMA springs are used to axially move a collar that is restraining three nut segments (see Figure 3). The mechanism is similar to a number of designs previously developed by Starsys Research and other companies. The three SMA springs (2) are nested in a cylindrical housing (1). On top of these rests the Spring Washer (4) and Retaining Ring (5). In the latched position, a compression spring (7) maintains the Retaining Ring in the proper position to restrain the three Nut Segments (6). The Segment Retainer Screw (3) is further used to constrain the position of the Nut Segments.

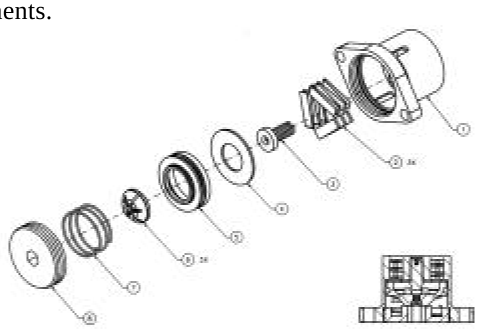


Figure 3. Mini Sep-Nut Assembly

When power is applied to heat the mechanism, the SMA springs are warmed and extend. This extension pushes the Spring Washer and Retaining Ring forward, which allows the Nut Segments to separate, releasing the bolt (not shown). After power is discontinued and the SMA springs have been allowed to cool, the Retaining Ring must be manually reset before the bolt is installed. The actual mechanism fabricated is shown in Figure 4.

Figure 4. Mini Sep-Nut Mechanism

The SMA springs were fabricated by Shape Memory Application on a best effort basis. The spring for the Mini Sep-Nut used .0058" thick by .088” wide ribbon formed in an oval shape (shown in Figure 2). The springs were capable of approximately 1/8" of travel with a minimum output of 0.5 lbf.

Retractor side

A retractor was also developed for the Mini Sep-Nut. The retractor assembly (shown in Figure 5) acts to pull the bolt away from the release side of the mechanism after operation. This is done using a standard compression spring. Depending on the application, a retractor unit may or may not be required.

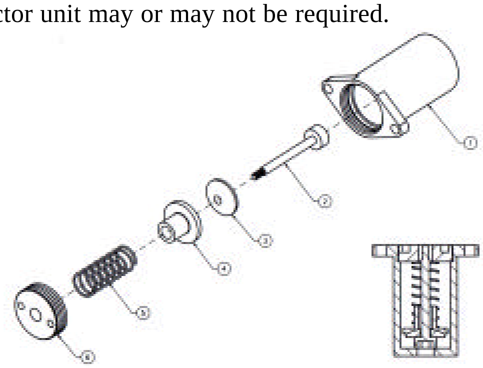


Figure 5. Mini Sep-Nut Retractor Assembly

Direct SMA Release (Micro Sep-Nut)

This mechanism uses a single SMA ribbon that has been formed into a circular shape (as shown in Figure 2). The mechanism (shown in Figure 6) is reset by inserting the Bolt (4) through the Housing (1) and past the inner diameter of the SMA spring (3). The Cap (2) holds the SMA spring properly in the Housing. The SMA spring is then manually compressed from two sides until it is secure around the bolt. The mechanism may now be preloaded and is ready to be released.

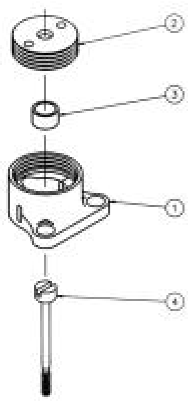


Figure 6. Micro Sep-Nut Assembly

The Micro Sep-Nut is released simply by applying heat to the housing. As the SMA spring is heated, it returns to its circular shape, releasing the bolt. The actual mechanism fabricated is shown in Figure 7.

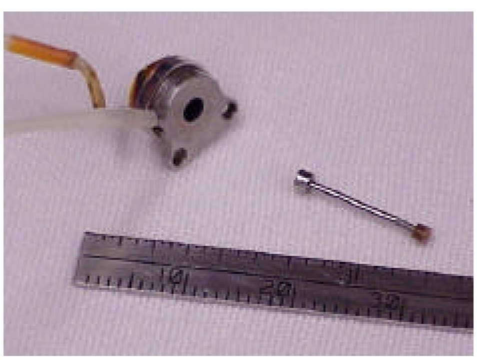


Figure 7. Micro Sep Nut Mechanism

The SMA springs were fabricated by Shape Memory Application on a best effort basis. The spring for the Micro Sep-Nut used .0058" thick by .088" wide ribbon formed into a circular shape (with two complete turns).

Materials

Since the SMA springs are not powered directly, all the materials in the mechanism are metallic, primarily stainless steels, to better conduct the heat to the springs. Most of the components have been heat treated to increase the hardness, due to the small size.

Problems Encountered

During the development, both mechanisms encountered a number of problems that will be reviewed.

Heater Size

Finding a heater for both mechanisms was difficult, especially for the Micro Sep-Nut. The small area available on the Micro Sep-Nut makes it hard to attach a standard foil trace heating element. For heating the prototype Mini Sep-Nut, a resistance wire was simply wound around the outside of the body and attached with shrink tube. This approach worked for the Mini Sep-Nut but the mounting features and reset access prohibited this method from being used on the Micro Sep-Nut. The Micro Sep-Nut prototype used traces from a larger foil trace heater that were soldered together and attached to the body with a small band of shrink tube. Another heating approach tried on the Micro Sep-Nut was to use a diode. As power was applied to diode, it heated, eventually providing enough heat to operate the SMA band and release the bolt. Although it provided adequate heat to operate the SMA spring, the diode size nearly doubled the height of the Micro Sep-Nut. Toward the end of the program, two sample custom heaters were delivered for the Micro Sep-Nut. The heaters were Kapton laminate with foil traces connected to lead wires. Unfortunately they were made with a fairly large lead wire (26 AWG). The lead wire size made the heater stiff and difficult to bend around the diameter of the housing. Both sample heaters ended up being damage during to installation.

Tolerances on Parts

Working with such small parts inherently means tight tolerances. This leads to difficulties in machining and assembly. On the Mini Sep-Nut, the initial parts were machined with too great of tolerance, preventing the nut segments from forming a tight nut to thread the bolt into. In a second iteration, the Retaining Ring was machined-to-fit to achieve a close fit with the housing and nut segments, providing a tight interface for the bolt threads. It is important to remember when designing small components that some of the parts may need secondary machining to achieve the desired assembled fit.

Machining

The size of the components created some difficulties in fabrication. As discussed, tight tolerances required on small dimensions made the parts more expensive. The most difficult parts to machine were the bolt and nut for the Micro Sep-Nut. The bolt was a 0.8-127 thread with a .030" shaft. The bolt size and thread made the component very fragile. During the cutting of the threads, the shaft would deform. It would have been beneficial to locate a specialized vendor with experience in fabricating miniature components or find an off-the-shelf component.

Assembly

As expected, the size of the components also created difficulties in assembly. Parts were difficult to handle and properly install. It is valuable to have custom assembly tools to handle and manipulate the parts.

Testing Performed

Testing on the Mini Sep-Nut was limited to releasing various loads and verifying proper operation. The majority of the testing was focused on the Micro Sep-Nut. The testing summarized below applies to the Micro Sep-Nut. Testing was initially performed to determine the voltage required to heat the SMA to its transition temperature. Table 2 shows the maximum temperature reached with a range of given input voltages.

Table 2. Micro Sep-Nut Max Temperature

Input Voltage (VDC)	Current (amps)	Power (Watts)	Maximum Temp (C)
0.5	0.06	0.03	29.1
1	0.11	0.11	34.7
1.5	0.16	0.24	52.7
2	0.22	0.44	68.2
2.5	0.26	0.65	88.0

After the prototype unit was fabricated load tests were performed to determine the affect of load on the release time and temperature. The main goal was to determine the maximum load that could be restrained and released consistently. Testing on the Micro Sep-Nut showed the mechanism repeatedly released in less than 30 seconds and between 60°C and 80°C at loads up to 7 lbf.

Thermal testing was also performed on the Micro Sep-Nut. The Micro Sep-Nut was taken to –30°C and up to +40°C and released with a nominal load of 5 lbf. There were some inconsistencies in the load at low temperature. It is not clear the cause of these variations. Table 3 summarizes the results of the thermal testing.

Table 3. Thermal Testing, Micro Sep-Nut

Test Temp (C)	Amb. Load (lbf)	Release Load (lbf)	Release Time (sec)	Release Temp (C)
-30	5	4	65	64.4
41	5	6	16.8	72.6
39	5	7	16.1	62.8

Recommendations for Future Development

The ultimate success of these mechanisms will rely on further refinements of both designs. The mechanisms generally operated as expected and performance was close to the required characteristics. The following changes will be implemented in future design iterations.

New Heaters

As discussed, the methods used for heating the mechanisms to operate the SMA and release the bolt were fairly crude for these units. A vendor has been found to make a heater that would fit onto the Micro Sep-Nut and should easily be able to develop a heater for the Mini Sep-Nut. For future heaters, the smallest possible gauge lead wire (30 or 32 AWG) should be used for both mechanisms. Also, the manufacturer should preset the bend size to match the body diameter, by hot forming the heater around a mandrel.

Better Methods to Characterize the SMA Springs

Over the course of the program, much effort (both time and budget) was spent on developing various approaches. Less focus was spent to characterizing the SMA springs. We relied mainly on the vendor being able to meet the design criteria specified. Since the SMA springs were made on a best effort basis, the vendor performed no verification. Additionally, there was limited testing performed by Starsys on the springs themselves. Much of the effort was focused on trying to assemble and characterize the mechanisms.

Mini Rotary Actuator

A rotary actuator was designed and developed by Starsys Research that would provide 2 to 6 inch-ozs of torque in two directions over a 120 degree rotational range. The rotary actuator could be used to open and close an instrument cover approximately 1 to 2 inches in diameter.

The rotary actuator was to incorporate a detent latch that would be capable of maintaining the cover in either the open or cover closed position without the use of power. The holding torque for either of the two positions was to be equal to or slightly greater than the output torque of the rotary actuator (2 to 8 inch-ozs).

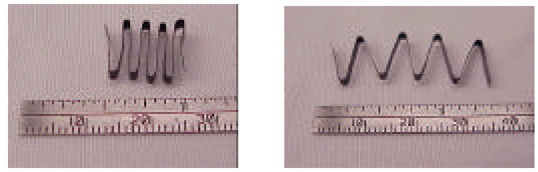
The design used a Shape Memory Alloy (SMA) element to rotate the output shaft. The motion will drive the output shaft the mechanism through 120 degrees at which point the detent will engage. Power will then be discontinued and the rotary actuator will remain in the open position until the opposite side is operated.

Design Approaches

In reviewing the options, many different approaches were examined and evaluated. Most all of the approaches required linear motion (from a motor) be changed to rotary motion to obtain the required output. Three choices were examined for the motor to operate the mechanism; a small paraffin actuator, SMA wire, and SMA springs. After some conceptual design work on the motor, the SMA spring was chosen as the most favorable approach. This was due to the high stroke that could be achieved, the fairly quick response time, and the variety of available shapes.

SMA Spring

SMA materials are able to return to a preformed shape when heated. The simplest and most readily spring available is a compression spring that is fabricated from SMA wire. As the wire is heated, the spring expands linearly. This motion can then be converted to rotary motion through a variety of mechanical devices. When cool, the spring can easily be compressed to its initial position. A second form considered was flat strip of SMA material that can be annealed in a number of different shapes. The shape selected was a wave shape spring (see Figure 8). This shape resulted in a spring with a reasonable amount of stroke and output force in a relatively compact size.



Compressed After Heating

Figure 8. SMA Wave Spring

The final spring evaluated was a torsion spring formed from SMA wire (see Figure 9). When installed, the torsion spring is wound past its nominal position. As heat is applied, the spring returns to its nominal position, providing the output torque.

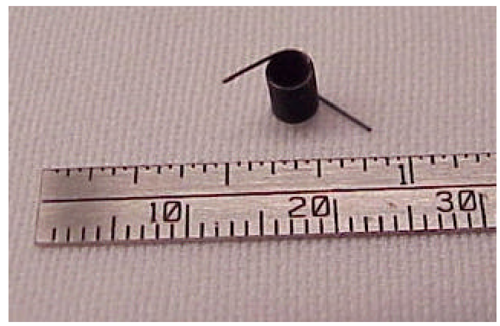


Figure 9. SMA Torsion Spring

Rotary Mechanism

With the decision made to pursue a design using a SMA spring, several mechanism designs were developed and evaluated. The final design selected to be fabricated used a SMA torsion spring to directly generate the output torque (see Figure 9). Early on in the development process, an attempt was made to simply wrap a length of wire around a round dowel. As the SMA was heated, it was thought that the contracting wire would rotate the dowel. The results were inconsistent and wire difficult to accurately control. Eventually, a vendor was found to fabricate the SMA torsion springs. We worked with the vendor to determine the basic dimensions of the torsion spring for the desired output and designed the mechanism around the resulting size of the torsion spring.

The mechanism design evolved into a size that was more desirable than other approaches considered. The mechanism assembly is shown in Figure 10. It contains the output shaft, the housing, two covers, two opposing SMA torsion springs, and a drive disk. For each torsion spring, one end is routed through a notch in the body and held in place by the covers. The other end contacts a pin on the drive disk. The drive disk is metallic and provides a common contact for the torsion springs.

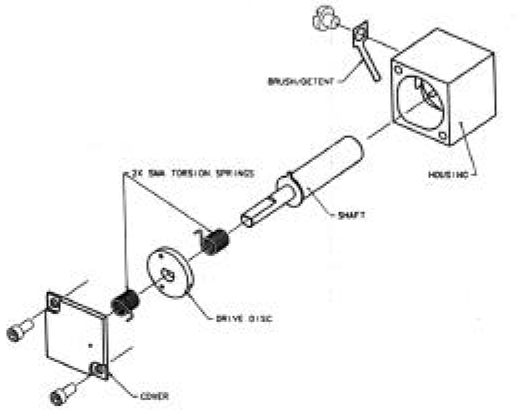


Figure 10. Torsion Spring Mechanism

For operation, one power lead is applied to the drive disk (providing a single common for either torsion spring). The other lead is attached to one of the exposed ends of the torsion springs (depending on the direction of desired output). The drive disk is keyed to the output shaft to transfer the rotation from the torsion springs. The output shaft also contains a stop that interfaces with one of the covers. This stop limits the rotation of the output shaft in either direction. Figure 11 shows a picture of the fabricated mechanism.

Figure 11. Torsion Spring Mechanism

The SMA torsion springs were fabricated by Shape Memory Application on a best effort basis. Two iterations of the spring were made. The first used .012" diameter wire with approximately 120 degrees of required motion. The second iteration used .014" diameter wire with approximately 180 degrees of rotation. It was assumed the larger diameter wire would increase the output torque of the spring. Although this was true to some extent, it was not nearly enough to provide the desired output torque for the mechanism. With both iterations, we were able to achieve the desired rotation angle. However, the output torque for each was considerably less than the design goal.

Materials

Since the SMA torsion springs are powered directly, all the materials in the mechanism are non-metallic with the exception of the drive disk. The Housing and Covers are made from Utlem, which is a high strength polyimide. The mechanism is not designed to carry structural loads, so the Ultem provides adequate strength with a lower mass. The Drive Disk was fabricated from stainless steel to provide a conductive path for the power to operate the torsion springs. The Output Shaft was made from Vespel SP-3. Vespel is also a high strength polyimide and the SP-3 type provides some lubrication since it is impregnated with Molybdenum Sulfide. The self-lubricating material was beneficial since the output shaft is rotating on both covers during operation.

Problems Encountered

Of all the design options considered, the most favorable was the direct SMA torsion spring approach. It was a much smaller size and weight and the most direct application of the SMA technology. A number of problems were encountered during the development of this mechanism.

Dual Motion Required

The most difficult requirement of the design was that it was necessary for the mechanism to operate in both directions. This meant the mechanism had to be capable of opening and closing the cover. A simple unidirectional drive mechanism would have been much simpler, yet not nearly as useful. The main problem that the dual motion presented is that the output spring is always working to reset the opposite direction spring. This greatly reduces the available output torque, since approximately half the output torque is required to reset the other spring.

Power-On Time

Testing showed the mechanism to be sensitive to power-on time. If a constant current was applied to the SMA spring, there was a risk of damaging the SMA spring by heating it to a temperature where the spring material is re-annealed. The best firing sequence for this mechanism would be several short (1-second maximum) pulses until telemetry signals the cover is to the open or closed position.

Detents

Another problem encountered during the design was how to incorporate a detent (required to maintain the rotary latch in either of the end positions). The initial approach used with the torsion spring design was a leaf spring of metal that contacted a flat on the drive disk in either the open or closed position. The leaf spring also provided the common contact point for the electrical circuit, since one end of both torsion springs was in contact with the drive disk at all times. This approach resulted in too much drag on the drive disk, decreasing the amount of output torque available. The leaf spring also provided little actual holding torque for the mechanism in either of the end positions.

Machining

The size of the components created some difficulties in fabrication. Tight tolerances required on small dimensions made the parts more expensive. The wall thickness and material choices also made the components very fragile. It would have been beneficial to locate a specialized vendor with experience in fabricating miniature components. Some of the components may also be good candidates for molding or stamping, although with the quantities required, this may not be practical or cost effective.

Assembly

As expected, the size of the components also created difficulties in assembly. Parts were difficult to handle and properly install. It is valuable to have custom assembly tools to handle and manipulate the parts.

Performance Characteristics

Because of the small size of the mechanism, it was difficult to measure some of the performance characteristics. We were unable to obtain an accurate measurement of the internal friction.

Testing Performed

Testing of the mechanism was limited since most of the effort was focused on developing the various designs and developing the torsion spring design into a functional prototype. No thermal testing or life cycling was performed on the mechanism.

Recommendations for Future Development

The ultimate success of this design will rely on further refinement of the SMA torsion spring. The torque of the spring is considerably less than needed for the desired output torque of the mechanism. Increasing the wire diameter will eventually result in an increased output torque, but it will at some point lead to a larger overall mechanism.

New SMA Torsions Springs

As discussed, the torsion springs used did not provide adequate output torque to fully rotate the simulated cover open. Additional effort could be undertaken to work closer with the SMA vendor to develop a higher torque torsion spring.

Develop Better Fixturing

The methods used measure the output torque of the mechanism was relatively crude. A calibrated torque gauge with a range from 0 to 18 in-ozf was attached to the output shaft of the mechanism. As the mechanism was powered, the output torque was measured. A method to measure the actual output torque of the torsion springs would have provided useful data on the characteristics of the springs themselves. However, no fixturing was developed by Starsys or Shape Memory Applications to test the springs themselves.

Better Methods to Characterize the SMA Torsion Springs

Over the course of the program, much effort (both time and budget) was spent on developing various approaches (some of them probably further than required). This left inadequate resources to develop methods for characterizing the torsion springs. We relied mainly on the vendor being able to meet the design criteria specified on the drawing. Since the SMA torsion springs were made on a best effort basis, the vendor performed no verification. Additionally, there was limited testing performed by Starsys on the springs themselves. Much of the effort was focused on trying to assemble and operate the mechanism.

Develop Detent

The detent approach initially used in the design did not provide adequate holding torque and added friction that reduced the output torque of the mechanism. With this method, no power was required to operate the detent. Another approach considered but not incorporated was to use another SMA device to latch and unlatch the mechanism in either end position. Ideally this would be connected in series with the torsion spring so that when power is applied, it both releases the latching device and operates the torsion spring. However, the practical implementation of this could be difficult. It may be necessary to add a second circuit to operate the latching component if a SMA device is used. This too could add complexity in being able to properly time the events. The latching SMA device would first need to release, then the torsion spring operated to rotate the output shaft.

Electrical Connections

The mechanism is currently operated by connecting one power lead to the exposed end of the SMA torsion spring and touching the other end to the drive disk for short periods of time. Although this approach operates the prototype mechanism, it is not practical for actual flight use. The SMA wire does not easily accept standard solder. Therefore, crimp contacts on the exposed ends of the torsion springs that could be mated with a matching contact would be a more favorable approach. For the common contact, the drag generated by the wire on the drive disk increased the friction and therefore reduced the available output torque. One solution may be to add a metal shaft through the output shaft to contact the drive disk and then crimp or solder a contact onto the end of this. The end would then be allowed to rotate freely as the mechanism rotates.

Miniature Burn Wire Release

This tiny release mechanism was developed at APL for a miniature instrument cover or similar device needing an extremely compact, low mass, and low power actuation device. It uses a burn wire to directly carry the tensile load of a cover or screw that is attached to its retainer. Current applied to the wire will break or fuse the wire at the location of the retainer to cause release of the hardware attached to it. This is unique from other types of satellite burn wire releases. This mechanism uses the wire to directly carry the tensile load, therefore it is a highly simplified design that can be greatly miniaturized. It is also an easy design to scale up or down according to the requirements of the device it is attached to.

Design Approach

It was determined early in the design process that to highly miniaturize this mechanism, it had to contain the fewest parts possible. The burn wire release mechanism (shown in Figure 12) has only 5 components with only one of those that are released with the cover. These components are also multifunctional. The burn wire is used to hold the mechanism together, carry the restraint load, make electrical connection, and initiate the release action. Wire size was based on restraining a 100-gram cover. The rest of the mechanism was designed to package as compactly as possible and provide thread for a 0.060-80 screw. A kick-off compression spring was incorporated to overcome friction or other small forces that might hang-up the mechanism. It was assumed the cover would not have much release torque due its small size.

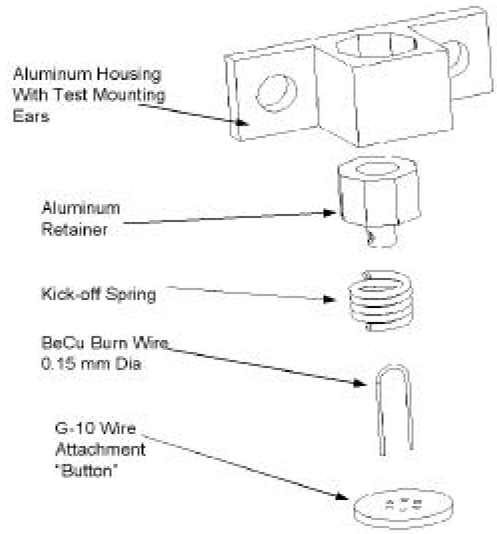


Figure 12. Mini Burn Wire Release Assembly

Beryllium copper was chosen for the wire material based on its excellent mechanical properties as well as its high resistivity. Its resistance is 20 times that of pure copper, therefore less current is required to heat the wire to a breaking point. Initial tests have shown 1-2 amps @ 28 VDC is required to burn a 0.008" diameter BeCu wire. Pure copper wire of the same diameter will take a much greater current to burn. Stainless steel wire has similar properties as the BeCu and would work well in this mechanism. The fabricated mechanism is shown in Figure 13.

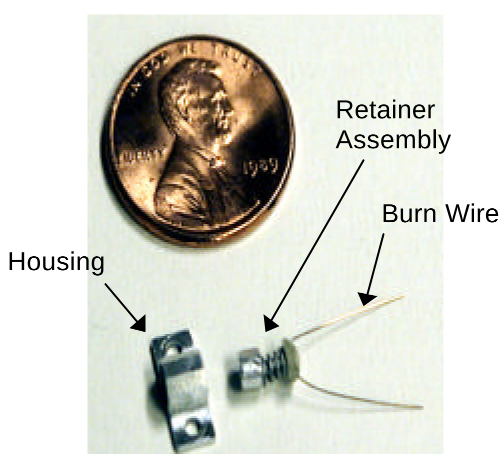


Figure 13. Mini Burn Wire Release Mechanism

Mechanism Operation

The beryllium copper burn wire loops through a retainer and is bonded to an isolating "button". Between the button and the retainer is a kickoff spring, which pre-loads the burn wire and maintains the position of the retainer within the housing. When current is applied to the wire, resistance heating burns the wire in a predictable manner like a circuit fuse. A short section of the wire is etched to a slightly smaller diameter to ensure the break occurs in the correct location. Additionally, the kick-off spring creates a stress concentration in the area of the etching, which causes a higher resistance and greater control of the wire breakage. Reaction time of the mechanism is very quick and it produces no shock. The kickoff compression spring assists deployment by quickly separating the two halves of the mechanisms. It is a single cycle mechanism and needs replacement after usage. The housing can be made to plug-and-play, similar to a fuse, and allow quick changes between uses.

Fabrication and Assembly

The housing and retainer for this prototype were machined from aluminum alloy on conventional machining equipment with high-speed spindle rates. The high speed is necessary when use extremely small tool diameters and achieve proper cutting. An Electrostatic Discharge Machine (EDM) burned the center bore from the housing and worked very well for handling the thin walls and precise tolerances required.

Assembly of the components required custom assembly jigs in order to hold components with precision while an adhesive cured. The jig was also designed to pre-load the burn wire, button, retainer, and compression spring assembly. The pre-load was not held very accurately even though the assembly was held at a measured compression distance. The assembly relaxed when released from the tooling and some of the pre-load was lost. The mechanism was still operational, but the kick-off effect of the compression spring was not as effective.

Testing Performed

Tests were conducted on the wire to determine an optimum etching process and to verify the process produced consistent wire mechanical properties. Problems were encountered in the initial etchings. First, an etching solution of ENDPLATE AD-485 was used which is commonly used in circuit board manufacturing. All of the wires came out of this process very brittle and snapped easily when lightly handled. This solution may have been too aggressive causing hydrogen embrittlement or other material property change. Nitric acid solutions were tried next at various strengths and found to take extreme amounts of time to achieve the desired corrosion of the wire. Etching was successfully completed with a mixture of AD485 and sulfuric acid in water (this solution is commonly used in circuit board manufacturing). The AD485 solution provided good corrosion rates without affecting the mechanical properties of the wire. A fixture was designed to suspend multiple wire samples for batch processing and to contain the etching to a precise section of wire. A sample etched wire is shown in Figure 14.

Figure 14. Etched BeCu Wire

Strength tests were conducted on over 50 BeCu wire samples of varying etched diameters to determine mechanical properties and process consistency. Figure 15 shows the ultimate strength values for 0.008" diameter wire etched up to 63% of its original size. Electrical tests were also consistent. Breakage occurred at the etched portion with consistent power usage.

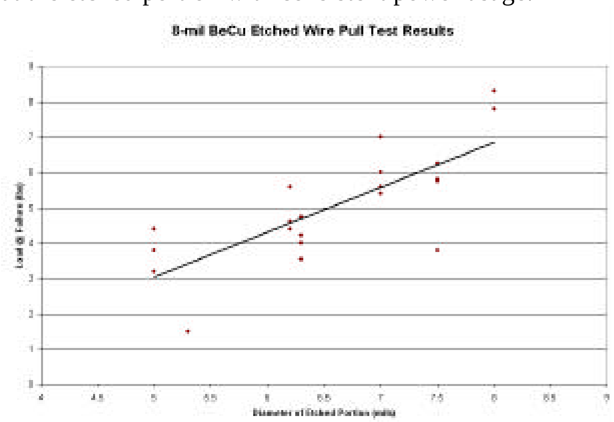


Figure 15. Strength Tests of Etched Wire

Recommendations for Future Development

Use Non-Conducting Housing and Retainer Materials

Shorting of the wire over to an instrument is not good and several shorts occurred during tests. The retainer could be made from a ceramic to give it the strength and isolation needed. The housing could be made from Torlon or other thermoplastic which would provide a low friction sleeve to hold the retainer.

Automate Fabrication and Assembly Processes

Automation was not a goal in this project. However, miniaturized components are very difficult to handle with manual machining and hand assembly processes. Automated or tooled processes are needed to hold the tighter tolerances and improve consistency with assemblies.

Improve Plug-and-Play Design

The housing can be redesigned to make this mechanism truly a plug-in item to make testing easier. A package similar to a bus fuse could be designed. Handling of .060 diameter screws should be avoided because of how fragile they are and how easy it is to loose them within an instrument.

Design a Miniature Connector

For this prototype, the bare wire ends were used to make electrical connection. A high reliability electrical connection will need to be addressed in the future.

Miniaturize the Packaging Further

In order to hand machine and hand assemble the prototype, standard fit and tolerances were used. Alternative fabrication process should be considered to take the mass and volume another step towards being a "micro" sized mechanism.

The prototype burn wire mechanism has been shown to have excellent reliability and possibility for further miniaturization. It is simple in design and the burn wire tests have shown very consistent results. It meets the criteria for current miniature instrument covers, but has possibility for use in numerous applications on a micro-satellite program. The mini burn wire release may develop into a key mechanisms device for the APL MicroSat program.

Mini Linear Actuator

Linear actuators are prevalent in satellite programs as triggers or switches for mechanical devices. There is a definite need for a miniaturized version of this type of mechanism for future micro satellites. The mini linear actuator developed at APL is designed to provide a quick acting, low shock linear motion. This mechanism is in a very early stage of development, with a single test unit built. Characterization and testing of the mechanism is just getting started and shows a lot of promise.

Design Approach

This prototype mechanism utilizes SMA wire to actuate a high force low shock pin puller that can trigger a number of latch devices on instruments shutters or covers. It is self-resetable using a bias return spring (as shown in Figure 16) and can operate in-flight for numerous actuations.

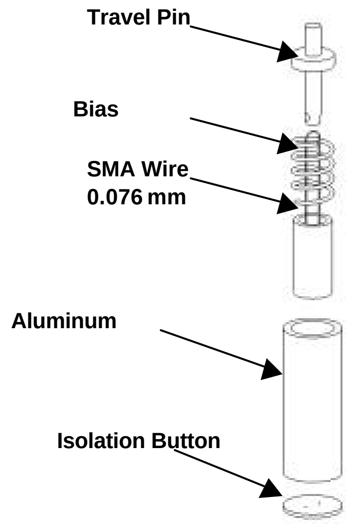


Figure 16. Mini Linear Actuator

The motion (or strain) of typical SMA materials is limited to 8% of the amount of material. A nominal design for this mechanism would limit strain to 2% to ensure adequate fatigue margin. Therefore the stroke of this mechanism is limited. For a wire length of 20-mm (0.8 inches), the stroke would be 0.4 mm (0.014 inches). Larger stroke length can be achieved if room is available across a cover or down the side of a telescope for a longer SMA wire. Redundancy can be designed into the system with dual wires that can be individually powered and singularly operate the device. Nickel-Titanium wire is heated in this device by running current through the wire. The current heats the wire directly via resistance in the wire. Response time is very quick, (~1/10 sec), and the device is not too sensitive to its external thermal environment. Through a strain recovery process in the material, the wire contracts when heated and returns when cooled using the compression bias spring. It is a self-latching device that is fully testable. The assembled concept is shown in Figure 17.

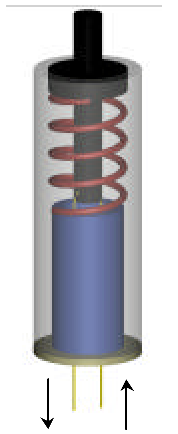


Figure 17. Assembled Mini Linear Actuator

Recommendations for Future Development

Testing needs to be conducted

Initial testing on the prototype mechanism has shown consistent operation over several cycles. Further testing will be conducted to fully characterize the device. Lifetime testing is necessary due to concerns of overstrain on the SMA wire. Tests at temperature extreme will provide useful data for determining maximum power requirements and to determine the effect of temperature on the stroke distance.

Design a range of stroke and force capabilities

One of the best features of this device is its capability to be easily changed to add a heavier wire or longer wire to provide additional force or stroke capability.

Add a redundant wire

Another SMA wire can be incorporated into this mechanism giving it full mechanical and electrical redundancy. This feature would be very valuable to high reliability programs.

Overall, this SMA driven mechanism shows promise for being easily scalable and highly redundant mechanism. It will be a valuable addition to the tool kit.

Mini Redundant Release Mechanism

This miniature release is designed to provide electrical and mechanical redundancy. Most mechanisms strive for redundancy in the electrical connections but have single points of failure in the mechanical operation. This mechanism provides multiple redundancies with its ability to operate (release a plunger) with two of the three SMA elements operating. The mini redundant release is in a very early stage of development, and one test unit has been built. Characterization and testing of the mechanism is just getting started and shows a lot of promise.

Design Approach

This prototype mechanism contains shaped SMA strips that lock a restraint shaft for an instrument cover, solar array, or other system needing a release device. SMA strips grip the end of the shaft while in a cold state. When powered and brought to a higher temperature, the SMA strips change shape to “open the lock”. Figure 18 shows an exploded assembly view of the mechanism.

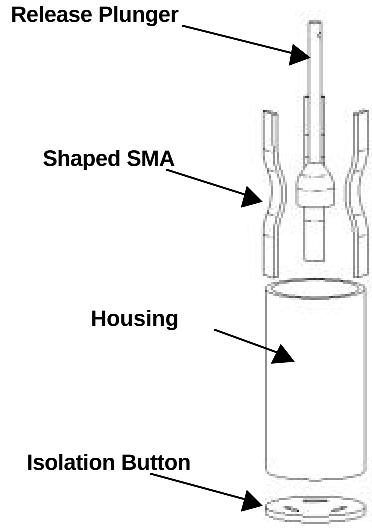


Figure 18. Mini Redundant Release Device

Full mechanical redundancy is achieved because the device still operates if one of the strips fails to open. A resistor heater on the housing provides the temperature control. This design can be converted to direct current heating to increase the response time. Direct current heating will also provide further electrical redundancy. Simple construction lends to miniaturization. This mechanism can be miniaturized much further depending on the holding force needed. The assembled concept is shown in Figure 19.

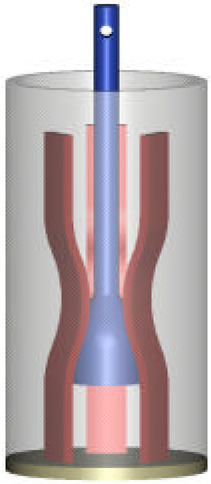


Figure 19. Assembled Mini Redundant Release Device

Recommendations for Future Development

Redesign and rebuild next test article

Initial fabrication and testing on the prototype mechanism showed the need for proper tooling to manufacture and shape the SMA material in a consistent manner. The first prototype used hand shaped SMA material that successfully operates the mechanism, but pullout force changes depending on how well the SMA shaping is performed. Tolerances need to be held tighter with the assembly.

Incorporate heaters directly on the SMA

A higher level of redundancy will be achieved with heater elements on each strip. Also, there will be faster response times for initiation of the release if heaters drive the SMA rather than the entire housing and assembly. APL has applied heaters to similar types of material.

Design a self-reset capability

Leaf springs may be incorporated into the design to provide a reset capability and also to provide a means for having consistent reset.

Investigate alternative SMA sizes and shapes

A range of strip sizes and various ways of restraint on the plunger will be investigated. This could lead to a more optimum approach, higher restraint capability, and greater miniaturization.

<u>Lessons Learned</u>

Designing and developing mechanisms at this scale requires a different approach than most mechanism designers are accustomed too. There are a number of considerations that must be addressed, some of which have been discussed earlier in this paper.

Tolerances on Parts

Working with parts this scale intrinsically leads to tolerance issues. A small dimensional discrepancy on a part can lead to a significant change in mechanism performance. Mechanisms should be designed so that the dimensional variations lead to minimal impact on the overall mechanism performance. Secondary "machine-to-fit" operations may be required to achieve the desired interface between tightly controlled parts.

Manufacture

The manufacturing of these mechanisms will likely require automated machine processes and specialized tooling because of the tight tolerances needed to ensure reliable operation. The amount of distortion in the SMA needs to be set precisely for it to work properly. If the SMA is precisely formed it should work properly every time. If it is set by hand between tests you can't always be sure what you are going to get for the next test.

Shape Memory Alloy

The use of Shape Memory Alloy (SMA) creates a number of considerations that must be examined as part of the design process.

Characterization

It is critical to carefully characterize the performance of the SMA element prior to incorporating it in the design. This will help the designer understand the variations in the behavior of the SMA. Many of the custom shapes or forms are somewhat inconsistent in their behavior. It is important to understand these affect and how they will impact the overall mechanism design.

Control

The control strategy for applying power directly to the SMA must be carefully considered. It is easy to damage or re-anneal the SMA element if power is applied for too long.

Conclusions

During prototype development, the project addressed several problems of miniature mechanism development. Manufacturing of these mechanisms provides a challenge that is being met with micro-machining tools. Assembly is difficult, but can be handled with proper tooling and technique. Using SMA's properly provided the most challenge aspect of the design and development process. As satellites continue to shrink in size, the market for miniature mechanisms will to grow. The design and development of the current designs has been a challenging task that resulted in mechanisms with a strong potential for future satellite applications. The prototype mechanisms fabricated have performed well to date, but they will require further development before they are able to meet all the design criteria and complete qualification for flight.