

Design and Development of CubeSat Solar Array Deployment Mechanisms Using Shape Memory Alloys

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Abstract

The Advanced eLectrical Bus (ALBus) project is a technology demonstration mission of a 3U CubeSat with an advanced, digitally controlled electrical power system capability and the novel use of Shape Memory Alloy (SMA) technology for reliable solar array (SA) deployable mechanisms. The ALBus CubeSat deploys four SAs in addition to the body-mounted arrays on each side of the CubeSat. A goal of the mission is to utilize the SMAs being developed at the NASA Glenn Research Center to deploy these SAs. The use of SMAs allows for the ability to test and reset the flight deployment mechanism prior to flight, which reduces the risk of in orbit deployment failures common to CubeSats. As a result, an SMA-driven Retention and Release (R&R) mechanism and an SMA-driven hinge were designed, developed, and integrated for flight. This paper summarizes the development of these mechanisms, types and functionalities of the SMAs used, as well as the lessons learned throughout the process.

Introduction

CubeSats are a high-risk, usually secondary payload, mission. They conform to the CubeSat Design Specification [1] and come in standard “U” sizes. A 1U CubeSat is a spacecraft with dimensions of 10 cm³. The Advanced eLectrical Bus (ALBus) spacecraft is a 3U size CubeSat roughly measuring 10 cm² by 30 cm long. The main mission goal of ALBus is to act as a technology demonstrator with an advanced, digitally controlled electrical power system capable of distributing 100 W of power. Typically, CubeSats operate in the 5 to 20 W power range. A higher power distribution capability opens more opportunities for CubeSat mission payloads, experiments, and functions, including propulsion and advanced communication. ALBus is not capable of generating 100 W continuously, so it uses SAs to store electrical power in batteries until enough power has been stored to test distributing 100 W of electrical power. To reduce the amount of time to charge the batteries, additional deployable SAs were added to the design. This drove the second mission goal, which is to leverage the SMAs being developed at Glenn as a way to deploy the SAs.

Flying and operating CubeSats have been a risky endeavor with a 40% failure rate of university class CubeSats [2]. Of those failures, less than 10% can be attributed to the mechanisms, however, 33% fail for unknown reasons [3]. A way to improve on this failure rate is to increase the reliability of the deployment mechanisms. Common deployment methods consist of nichrome burn wires to burn through a strap or tether [4]. This can fail by the burn wire shorting out prior to burning through the release strap or the strap getting tangled upon deployment. Another technique comprises of breakable links made of plastic retaining bars that are heated and burned [5]. While the latter is advantageous in securing the hardware from vibration damages, both methods employ consumables and do not allow direct testing of the actual flight hardware since parts are destroyed during the deployment and new hardware is needed to reconfigure the spacecraft into the stowed configuration. The deployment mechanisms designed for the ALBus are an attempt to eliminate all deployment consumables (or even human factors like winding strap wire) to allow a reliable and resettable means to deploy structures on a CubeSat. In this work, SMAs are used to deploy SAs and allow them to be functioned and tested on the ground with the same hardware that will be used during the flight mission.

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SMA have been used in various applications in the past, including in space. CubeSats are a great way to verify and increase the capabilities of state-of-the-art SMA technology. SMAs have many advantages that can be utilized by CubeSats. In addition to being lightweight with a small footprint, SMAs are not pyrotechnics, produce low shock, do not create debris, and can be designed to be resettable. As part of the ALBus CubeSat technology development, two SMA forms were used. First, novel thermally activated SMAs with higher transition temperatures (compared to commercially available counterparts) were used for the R&R mechanism. Second, novel mechanically-activated SMAs (superelastic alloys) were used as deployment springs to specifically deploy ALBus' SAs and transmit the electrical power from the arrays. Reference [6] discusses more details of SMA functional behavior and types.

This paper will discuss the design and development process of the ALBus CubeSat deployable SA R&R and hinge deployment mechanisms. This includes the mechanisms' final design and capabilities, details on the SMAs, requirements of the design, design evolution and reasons for the design changes, analysis methods used, and the final flight hardware assembly and testing activities.

Design Requirements

The design requirements for the mechanisms are divided up into three categories: CubeSat standards, requirements specific to the ALBus mission and design, and mechanism specific requirements. The CubeSat specific requirements come from the CubeSat design specification [1] and the CubeSat deployer interface control document [7]. These requirements provide several sizing constraints such as keep-in zones for exterior dimensions, mass, and center of gravity. Other constraints include restrictions on creating space debris and use of pyrotechnics. These specifications also provide guidance on design environments. For example, they require using the launch random vibration environment in GSFC-STD-7000A if environments from the launch service provider are unavailable or if the launch provider is unknown while designing the CubeSat.

The ALBus mission's needs, goals, and configuration drove several of the SA deployment mechanism's performance and design requirements. The ALBus design is configured to use four deployable SA panels with seven of the ultra-triple-junction type solar cells installed on a FR-4 Printed Circuit Board (PCB) substrate. These deployable SAs run the length of the 340-mm-long CubeSat and are to be deployed along one of the short 100-mm sides of the CubeSat. This deployment configuration was chosen since the ALBus does not have an attitude control and determination system. It is designed to utilize gravity gradient masses installed on the ends of the deployable SAs to eventually point the CubeSat radiator down toward Earth. The final deployment angle was determined to be 135° from the stowed configuration for optimal power generation. However, a power analysis has shown that a 90° deployment angle is sufficient to recharge the batteries with acceptable power generation degradation.

The underlying goal for the ALBus mission is to design improved and reliable SA deployment mechanisms to reduce mission failures. This drove the design goals for the mechanism to be resettable in order to test and retest the actual flight hardware prior to launch. Reliability also drove the design goal to release all four SAs with one mechanism to minimize failure points. The ALBus mission chose to use new SMAs being developed at the NASA Glenn Research Center over traditional deployment methods. Finally, as the mechanism designs matured the desire to pass the electrical power from the solar cells on the deployable arrays through the SMAs was added in an effort to save the mass of a wiring harness.

The final mechanism's design converged on a two-stage SMA actively driven pin-puller type mechanism used to retain the arrays during ascent and release them in orbit (R&R mechanism). Once released, a passively driven SMA hinge mechanism, one for each of the four arrays, deploys each array to the desired deployment angle. To complete the designs, several specialized requirements were added specific to the R&R and hinge to ensure the desired functionality. NASA's mechanism design and development requirements specification, NASA-STD-5017 revision A [8], was used as a design guide and drove several of the performance requirements on the force and torque margin, mechanism design, and material

selection. Table 1 provides a summary and more detail on some of the key requirements that drove and constrained the mechanism's design.

Table 1. Mechanisms Key Driving Requirements Summary

Category	Requirement Text
CubeSat	No space debris shall be created at any point in the mission.
CubeSat	Pyrotechnics shall not be permitted.
CubeSat	The 3U CubeSat shall be 100.0±0.1 mm wide. (X and Y dimensions) and be 340.5±0.3 mm tall. (Z dimensions)
CubeSat	The only CubeSat structure that can contact the deployer are 8.5 mm wide rails and nothing can cross them.
CubeSat	Components shall not exceed 10 mm normal to the surface of the 100 mm cube sides.
ALBus	ALBus mechanisms are to be designed to increase reliability; e.g. releasing all four deployable SAs simultaneously.
ALBus	The ALBus mechanisms are to be designed using SMAs.
ALBus	The ALBus mechanisms shall be resettable so the flight hardware can be tested prior to flight and without disassembly of the CubeSat.
ALBus	The ALBus mechanisms shall be designed to structurally retain the deployable SAs during all mission phases prior to being commanded to release.
R&R	Upon command receipt, and only when desired, the R&R shall release the deployable SAs.
R&R	The R&R shall be designed to accept and operate by electrical power provided by the ALBus electrical power system which is 6 volt limited and 3.0 amps maximum.
Hinge	Upon command and only when desired, the hinge shall deploy the deployable SAs to the deployed state and prevent any detrimental damage to the deployable SAs, any other CubeSat structure, or to mission operations.
Hinge	The hinge shall allow the deployable SAs to deploy to 90°-135° from the stowed configuration.
Hinge	The hinge shall be designed to structurally support the deployable SAs during all mission phases.
Hinge	The hinge shall allow two separate paths to conduct power from the deployable SAs to the spacecraft.
Mechanism	The ALBus mechanisms are to use NASA-STD-5017 rev A as a guide to design the mechanisms.

Final Design

Figure 1 shows the overall architecture of the ALBus CubeSat which illustrates the mechanisms' location.

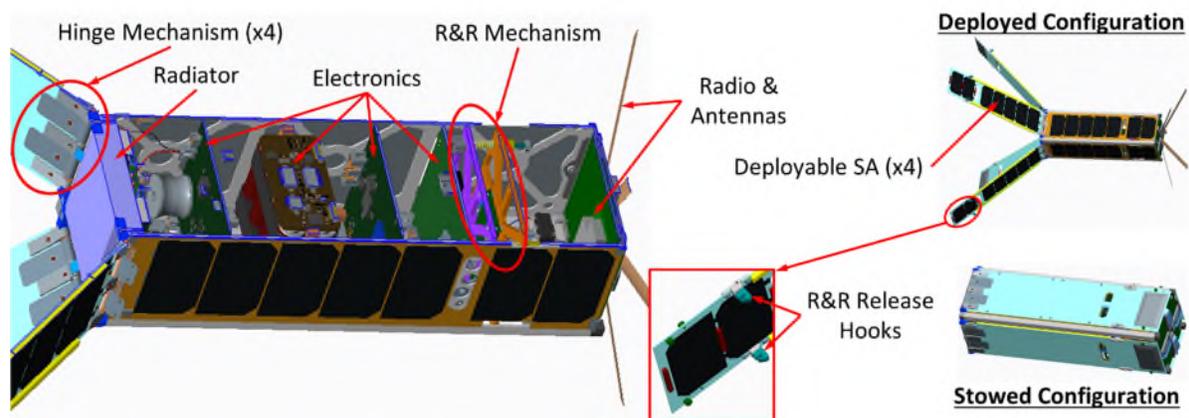


Figure 1. ALBus CubeSat Architecture

Design Summary of the R&R

The R&R final design consists of a two-stage activated mechanism. The first stage is a pin-puller device driven by an SMA linear actuator. The second stage is a hook and pin design that is released by a compression spring loaded plate riding on plain bearings. The operation and design of the mechanism is discussed in the following paragraphs. Figure 2 and Figure 3 illustrate details of the R&R component parts

that go along with the description. Table 2 summarizes the functional performance capability specifications and requirements. These specifications are driven to have positive margins per design guidance from NASA-STD-5017 [8].

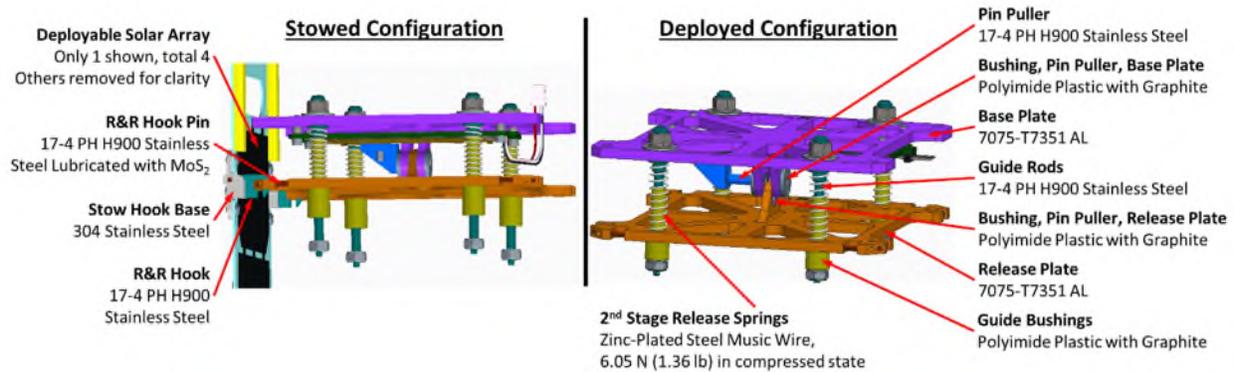


Figure 2. R&R Component Parts and Design

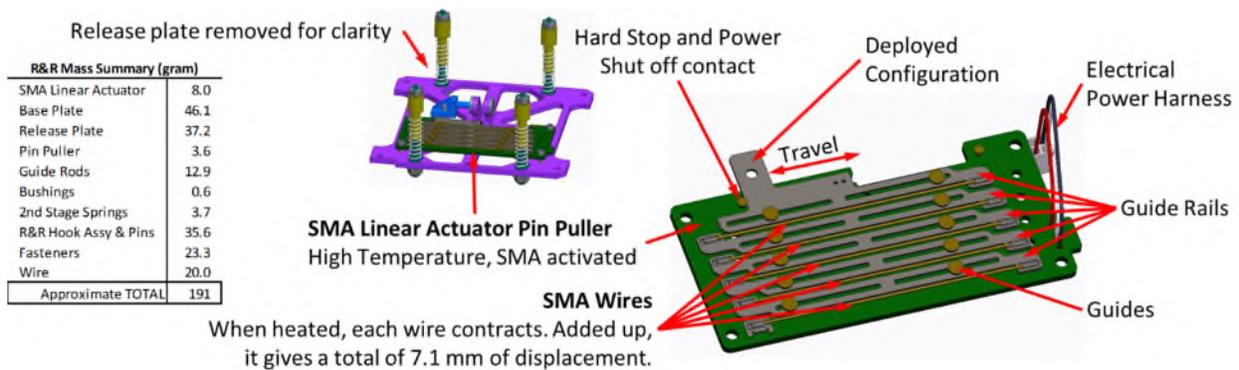


Figure 3. R&R Mass Estimate and SMA Linear Actuator Details

ALBus's initial temperature requirements for a safe SA deployment were set to be $>100^{\circ}\text{C}$, which exceeded any commercial alloy capability. Therefore, the linear actuator consists of an alloy with an atomic composition of $\text{Ni}_{19.5}\text{Ti}_{50.5}\text{Pd}_{25}\text{Pt}_5$ resulting in high transition temperatures above 100°C , work output exceeding 15 J/cm^3 [9], and capability to process into small diameter wire. Thus, rods were drawn into a 0.508 mm diameter wire which was trained, cut into segments, and then installed on a custom linear actuator produced by MIGA Motor Company [10]. A total of five SMA wires are connected to guide rails. Once heated past the transition temperature using direct current (joule heating), each SMA wire contracts to pull its associated guide rail. The summation of the five SMA wires yield a cumulative displacement of 7.1 mm travel to pull the pin and release the second stage.

The pin-puller consists of a 17-4 PH H900 stainless steel pin put in a double-shear configuration between three bushings. The bushings are made of a polyimide plastic that has impregnated graphite.

Once the pin-puller releases the release plate, four compression springs move the plate, unlatching all four deployable SAs. The compression springs were installed concentrically over linear guide bushings. These bushings are made of the same polyimide plastic as the pin puller bushings. The guide bushings ride on guide rods that are made of 17-4 PH H900 stainless steel. The release plate unlatches the arrays using a hook and pin latch. There are two latches per SA panel for a total of eight hooks. Both the hooks and pins are made of 17-4 PH H900 stainless steel. A thin film of a MoS_2 lubricant is applied on the hooks and pin to mitigate any binding concerns from friction, although the joint is lightly loaded and lubrication is probably not needed.

Design Summary of the Hinge

The final design of the hinge consists of two aluminum hinge knuckles that pivot over a hinge pin, two superelastic SMAs, and a latch to keep the SA in the deployed state. The operation and design of the mechanism is discussed in this section. Figure 4 and Figure 5 illustrate details of the hinge component parts that accompany the description. Table 2 summarizes the functional performance capability specifications and requirements. These specifications are driven to have positive margins per design guidance from NASA-STD-5017 [8].

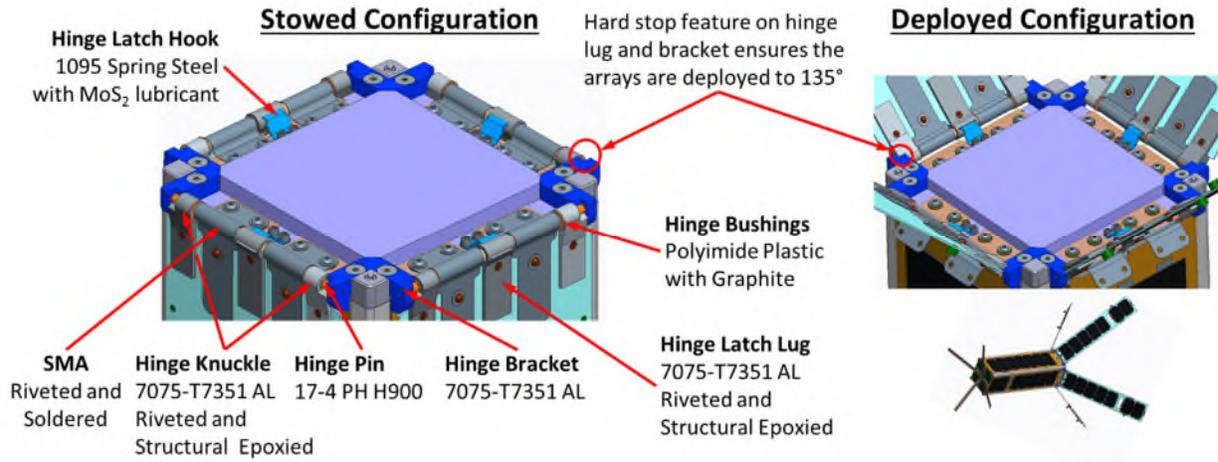


Figure 4. Hinge Component Parts and Design

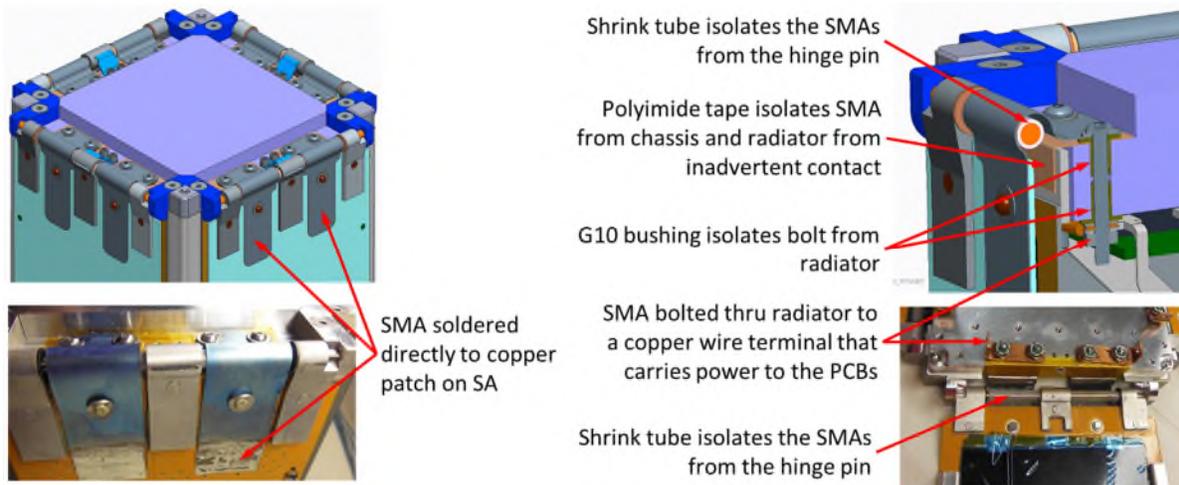


Figure 5. Hinge Component Electrical Interfaces and Design Details

After the R&R releases the SAs, they are free to rotate and each array is driven open by two preloaded superelastic SMAs per array. In this design, a Ni-rich Ni_{50.7}Ti_{49.3} (atomic %) superelastic alloy was selected to serve a dual purpose of (i) a spring load to open the arrays and (ii) a current carrying conductor to transmit power from the SAs. The superelastic material was rolled into a 0.2-mm-thick sheet with a transition temperature (i.e., martensite start temperature) below 0°C. At room temperature, the sheets exhibited a superelastic plateau between 200 and 300 MPa, depending on the heat treatment used. This superelastic plateau denotes the effective start of the materials' stress-induced transformation from the stiffer phase known as austenite to the more compliant phase known as martensite. The superelastic sheets were machined into a flat-shape profile and then shape set to a specific U shape with a custom jig. After several

iterations, shape-setting parameters were selected to be 550°C for 2 minutes followed by water quenching, which yielded the best form in terms of stiffness and reversibility after deformation.

Table 2. R&R and Hinge Mechanism Performance/Functional Specifications and Requirements

Specification Description	Value	Requirement (with margin)
R&R Pin-Puller, Pull Force	13.34 N	≥ 12.19 N
R&R Pin-Puller Stroke Length	7.1 mm	≥ 6.14 mm
R&R 2 nd Stage Compression Spring, Spring Rate	0.701 N/mm	0.235 – 0.736 N/mm
R&R 2 nd Stage Compression Spring, Stowed Force	6.05 N	2.03 – 6.35 N
R&R 2 nd Stage Travel Distance	7.62 mm	≥ 5.87 mm
R&R Operating Power Rating	6 volt limited, 3.0 amps	6 volt limited, 3.0 amps max
R&R SMA Transition Temperature	150 to 160°C	> +50°C*
R&R Temperature Operation Range	-51 to +61°C	-40 to +50°C
R&R and Hinge Maximum Random Vibe Exposure**	14.1 gRMS, 3 minutes, 3 axes	10.0 gRMS, 1 minute, 3 axes
Hinge SMA Stowed Spring Torque (1 spring)	0.190 N•m	0.140 – 0.282 N•m
Hinge SMA Transition Temperature***	-20°C	> -40°C
Hinge Temperature Operating Range***	-20 to +61°C	-40 to +50°C
Other R&R Features	High temperature SMA, resettable, one mechanism releases all four SAs	
Other Hinge Features	Utilizes SMAs in a new application to advance the technology and SMAs transmit power from the SAs.	

* Initial R&R SMA transition temperatures were set above 100°C

** The development unit was exposed to 14.1 gRMS; the flight unit was only exposed to 10.0 gRMS

*** The hinge SMA transition temperature is known to not meet the low-temperature requirement and starts to soften around -20°C. This is handled through operational controls. When the CubeSat is in sunlight, the SMA springs will heat up beyond the transition temperature and the SAs will deploy.

From an operation standpoint, the U-shaped form is rotated by an amount of ~270° while in the stowed configuration and by ~135° while in the deployed configuration. When stowed, the material with the chosen thickness and form is designed to exist in the end of the superelastic plateau (i.e., martensitic phase) to provide enough force but no material damage. In the deployed state, the material partially unloads and exists in a multiphase region to continue providing some load in order to keep the arrays open, since the load-free state is the U shape.

In addition to the SMA springs, the hinge design consists of two lugs with bushings made out of the same polyimide plastic with graphite as used in the R&R. The lugs and bushings rotate around a precision ground, 17-4 PH H900 stainless steel hinge pin, constrained by aluminum hinge brackets on either end of the pin.

Upon deploying the arrays, a hard stop on the hinge brackets was designed to prevent the array from going beyond the required deployment angle, since the superelastic springs continue to apply a force. Once in the deployed state, a latch engages to act as a failsafe to keep the arrays in the deployed state should an unknown or unexpected environment cause the springs to become too cold and temporarily lose their spring stiffness. The design of the latch is a pin and detent type design. It converged on using a piece of spring steel lightly preloaded on a bare aluminum cylindrical surface. When the array rotates open, the latch falls into a slot locking the array in the deployed configuration. The latch to cylindrical surface has a thin film of a MoS₂ lubricant applied to ensure low friction and smooth deployment.

The hinge design also transfers the electrical power from the SAs to the power management system. This is done by conducting electricity through the superelastic springs. To ensure a good electrical path and strong structural stiffness accommodations, the superelastic springs were riveted and directly soldered to the SA panel and then attached to the radiator with screws. On the radiator end, the fasteners used to attach the superelastic springs also conduct the electricity to a copper lug. Wiring harnesses were soldered

directly to the copper lug, which takes the electrical power to the power management system. Isolating the various electrical paths from one another involved adding a shrink tube to the hinge pin, polyimide tape to various surfaces on the radiator and chassis (in case the superelastic springs inadvertently contact those surfaces), and G10 fiberglass laminate composite bushings around the fasteners used to attach the springs to the radiator.

Design Evolution, Development Issues, and Solutions

The following section discusses the design evolution, development issues, and solutions of each mechanism, starting with the R&R and followed by the hinge.

The mechanism's development started with proof of concepts tests. These involved building several early low-level hardware models to test out the design ideas and options. The R&R was subjected to several three-dimensional (3D) printed designs, which aided in choosing the design features to use and to discover issues with the concepts. The hinge also used 3D printed hardware to prove out the concepts. In particular, several of the latch concepts were tested quickly using 3D printed hardware. This proved to be advantageous since conventionally machined designs can be more expensive and time consuming.

When the designs were finally matured, an engineering design unit (EDU) of each mechanism was fabricated and tested to prove out the designs for flight. The EDU was built to be as flight-like as possible. The test program was conducted in the summer of 2016 and included subcomponent testing such as measuring performance parameters of the hinge SMA springs, R&R linear actuator pull force, and other data used to correlate to analysis. The subcomponents were then combined into a system and subjected to environmental testing. This included a random vibration test to 14.1 gRMS for 3 minutes in three axes and in extreme cold and hot environments with margin. The EDU functioned successfully before and after the vibration test and in the extreme thermal environments. This testing program was very successful. It proved out the designs and discovered issues that were corrected in the final build. Though the EDU and flight builds differed slightly, the EDU essentially acted as a qualification unit. After the EDU test campaign, a critical design review was held to present the final design that incorporated all of the changes discovered in the EDU tests.

R&R: Early Concepts

The final R&R in the ALBus design was the product of several iterations. Three main concepts were initially investigated. The first was a piston design using antagonistic SMA springs where one pulled and the other pushed to release the SAs when activated. This design never made it past the conceptual phase as it was determined the unrestrained condition of the SMA spring in one of the directions would mostly likely be detrimental under launch vibrations and possibly cause a premature deployment. The second concept involved a collet design and used an SMA to free up the collet fingers. A plastic 3D printed prototype was created and the design was moving toward development of a fully functional engineering unit. While this concept was very promising, the mass budget and forecasted development time stopped this concept from continuing. The mass of the entire CubeSat needs to be kept at or under 4 kg. A critical thermal issue demanded the addition of a radiator for the primary mission objective, which reduced the available mass for the R&R. At this point in the development of the mission, there was not enough time to redesign and reduce the mass. This led the design toward the third and final concept described in this paper.

The final R&R design was based on prior SMA work developed at Glenn and is an SMA linear actuator device that can be quickly procured and modified. Leveraging the second-stage loaded spring concept of the collet design and this SMA linear actuator, the SMA driven pin-puller design was created for the ALBus CubeSat. The moving pin frees up a secondary release plate used to constrain the deployable SAs through two hooks on each deployable array.

R&R: Development Issues and Solutions

The design of the R&R started by using the linear actuator in its originally designed configuration given our budgetary and time constraints. However, it became apparent that the linear actuator needed some modifications to meet our mission's application.

One of the most critical changes was the SMA material. Initial requirements listed a thermal environment that may have exceeded the activation temperature of commercially available SMAs. This would cause a premature activation and release of the SAs, which could cause the CubeSat to jam inside the deployer. Fortunately, an SMA wire with a higher phase transition temperature had already been developed by Glenn. This wire was incorporated into the design and alleviated the thermal concerns. However, this wire had never been tested or used in other flight applications and therefore, the ALBus mission was the first opportunity to use it.

Another change to the existing SMA linear actuator was the location of the pin-puller attachment point (output stage). The existing actuator caused the pin-puller to be off-center from the four guide rails. This was due to packaging the actuator in order to physically fit inside the CubeSat chassis. To install the linear actuator so the pin-puller would be centered, it would have to be offset so much that it would protrude outside of the walls of the chassis. The off-center pin-puller was clearly not ideal, however, that configuration was attempted nonetheless to identify potential issues and solutions. A plastic 3D-printed prototype was created and the concept worked. A metal prototype followed and was also shown to work, however, it was prone to occasional binding from the off-center pin-puller. Since the R&R is a mission-critical mechanism, this anomaly was unacceptable. The linear actuator was then modified to move the pin-puller attachment point to allow the actuator to be mounted in the R&R and align the pin-puller on center. This substantially reduced the observed binding, but did not remove it completely.

The R&R was still prone to binding occasionally when the release plate tilted. This led to the next change, which added guide bushings made out of a polyimide plastic. Prior to the bushings being added to the design, the thin 3.17-mm-thick aluminum release plate only had holes drilled in it so it could travel on steel guide rods. NASA-STD-5017 [8] provides guidance and recommends a length ratio of 2:1 for plain bearings that are used in this guide rod type configuration. For the ALBus, this is a physical impossibility as the bushing and resulting guide rails would become too long and take too much space inside the CubeSat. If this ratio cannot be met, as it is in this case, the specification recommends taking into account several potential binding-causing issues. It also suggests to perform an analysis based on report work by J.R. Schroeder [11]. This analysis was performed and a compromise between overall length of the guide rails and bushings to the physical packaging limitations of the CubeSat was made. As a result, the bushings were made as long as possible toward the base plate and extended toward the releasing direction. This change significantly reduced the observed binding, but did not prevent all of the binding occurrences.

The final change made to remove binding, also learned from the EDU, was to free up the guide rods. When the guide rods were fully installed by tightening the installation nut, the R&R was still prone to binding. When the nuts were loosened to allow the rails some freedom to move, the mechanisms released smoothly and consistently. Therefore, the final design allowed the guide rod to float. This was designed into the flight mechanism such that the guide rod diameter to the through hole in the base plate has a diametral clearance gap of 0.229 to 0.381 mm (0.009 to 0.015 in). When the installation nut was installed, it was preloaded onto a collar of the guide rod that extended past the base plate. As a result, the nut did not lock out the guide rod to the base plate, allowing each of the guide rods to float a small amount. All of these design modifications allowed the mechanism to consistently function during the development tests.

Hinge: Early Concepts

There was one previous concept for the hinge. This design consisted of solar cells on both sides of the SA, which complicated the assembly and design. This concept used one large blade-like hinge knuckle with smaller hinge brackets. However, three superelastic springs were needed to provide the power from both sides of the SA. The concept had solar cells installed onto PCBs that sandwiched the hinge and SMA springs. The difficulty with this design was getting the electrical power from the solar cells to the SMAs and

isolating those electrical paths from each other. A non-electrical conducting coating needed to be applied because this was a metallic blade hinge. Eventually, the requirement to have solar cells on both sides of the SA was deemed unnecessary and removed. This allowed the design to evolve into the final concept with reduced complexity.

Hinge: Development Issues and Solutions

From this initial concept, the hinge design still had several design, interface, and assembly issues to overcome. The design evolved to reduce the effects and risk of friction-causing issues. One was changing the large hinge knuckle in favor of two smaller knuckles at the corners in order to limit the contact area of the knuckle on the pin. The other change was to add a bushing made out of a polyimide plastic with impregnated graphite between the hinge knuckle and pin interface. This provides a low-friction interface on the rotating parts' surfaces without the need for grease or liquid lubricants.

Transmitting the electrical power through the SMAs and isolating them from each other required many design solutions. The SMA needed to be isolated over the steel hinge pin, chassis, and through the radiator. Isolating the hinge pin from the SMAs was solved by adding a polyimide tape layer covered by a heat shrink sleeve. The SMA was isolated from the radiator using G10 composite bushings, which isolated the terminal bolts from the metal radiator. These isolation solutions work in the stowed configuration. However, when deployed, the SMA bends and folds into a different shape that can contact the radiator and chassis in other areas, causing an electrical short. This was solved by adding the polyimide tape to the radiator and chassis in areas where the SMAs may make contact.

Designing the SMA to provide enough torque to open the array and transmit the electrical power required many considerations. The final shape of the SMA was driven by the required torque and the available room for installation onto the SA. The torque drove the width of the SMAs, however, that width was wider than the available footprint to install the SMAs to the PCB and keep them isolated. This was solved by maximizing the width of the SMA where it attaches to the radiator and over the hinge pin where the torque is generated. Then, the SMA's width narrows down at the installation location on the PCB. Some issues arose during mechanical tests. The SMAs were soldered to the PCB copper substrate and the torque generated by the SMA to open the array was enough to delaminate the copper layer from the rest of the PCB. This issue was solved by adding a rivet close to the edge of the PCB. However, installing the rivet caused the SMA and PCB to crack. This issue was solved by adding a washer to both sides of the rivet to spread out the load when driven. Lastly, the design decision on how to install the SMA to meet the SMAs' torque requirement was made. The initial SMA location was inboard under the hinge pins. This did not work because it prevented the array from fully deploying. The final configuration chosen was to install the SMAs outboard of the pin.

The hinge latch is provided as a backup to keep the SAs in the deployed configuration if the SMAs fail. The latch evolved from several different concepts, but was kept as a simple hook and detent latch. Overall, the latch worked well, although there were some special considerations performed during assembly for proper functionality. Initially, the latch had some issues staying latched. The hook would jump out of the detent when the array hit the hard stops and then rebound. Several mitigation methods were used to prevent this. Proper installation of the hook is key to ensure that it is preloaded with enough force. This is done by installing the hook in the deployed configuration. The latch design is a steel on aluminum surface. The loading is light enough that a thin film of a MoS₂ lubricant applied to the contacting rotating surfaces is enough to mitigate the friction concerns. However, the lubricant has to be limited to a thin film and cannot go onto the latching surfaces in the detent or the mating surface on the hook. If it does, the hook can slip out of the detent.

Analysis of Mechanisms

The analysis of these mechanisms was divided into three main areas: structural strength, mechanism tolerances (critical primarily to the thermal environments), and dynamic and kinematic analysis. The structural strength of the parts was primarily driven by the random vibration environment during ascent.

Loads from this environment were generated from a finite element random vibration model using Finite Element Modeling And Postprocessing (FEMAP) as the pre and post processor and MSC NASA Structural Analysis (NASTRAN) as the solver. These loads were applied to the various parts as appropriate to show positive margins using factors of safety of 2.0 on ultimate and 1.5 on yield strength. Overall, the stresses were low enough from the random vibration environment such that fatigue analysis was not necessary.

In both the R&R and hinge mechanisms, the thermal environment needed to be considered. Due to the coefficient of thermal expansion mismatches between parts, the mechanism may bind at the temperature extremes if enough dimensional tolerance is not accounted for in the design. The extreme hot and cold environment of 61°C to -51°C was evaluated on all of the moving parts. The analysis was also done by assuming the worst case tolerance stack that would result in the tightest fit at the installation temperature of 22°C. The analysis results showed the critical case is the cold environment and a gap of 7.6 μm (0.0003 in) between the hinge pin and the hinge bracket.

The critical analyses for these mechanisms, kinematic and dynamic analysis, were performed to ensure the mechanisms would have enough torque and force to release the arrays and deploy them at the appropriate angle. NASA-STD-5017 [8] was used as a guide to perform the analysis and calculate the margins.

The kinematics and dynamics of rotating the arrays to the deployed state via the preloaded SMAs formed the main analysis for the hinge mechanism. This analysis considered both design criteria of (i) sufficient torque to open the SA and (ii) minor impact force as to not damage the solar cells when the array deployed to the open configuration and contacted the hard stops. This was done by hand sketching free-body diagrams and developing the equations of motion. The free-body diagram listed the driving forces (the torque supplied by the SMA) and the resistive forces and torques (friction from the bushings to the hinge pin, friction from the latch hook, and the inertia of the SA that is needed to be deployed). The friction from the latch hook was difficult to quantify since it is a unique design and required building and testing hardware. Early attempts to approximate it did not align well with the test data. The bushing friction was easier to approximate since it is a cylinder on a pin and the manufacturer's suggested friction coefficients were used for estimating friction. The normal force on the bushings was conservative because it used the weight of the array from 1g of acceleration even though the deployment occurs in orbit. The inertia resistive torque was approximated by using the equation of motion, the known final deployment angle of 135°, and assuming a reasonable deployment time of 1.0 second (based on test observations). The equation of motion is a 1 degree of freedom rotation and derived using Eqs. 1-3. The torque supplied from the SMA was also difficult to approximate due to the hinge mechanism's unique springs. This also required building and testing the hardware. These values were then entered into the torque margin calculation from NASA-STD-5017 [8] with appropriate factors for whether it was an analysis or test value.

$$\text{Angular acceleration} \quad \alpha = \frac{T}{I} \quad (1)$$

$$\text{Angular velocity} \quad \omega = \omega_0 + \alpha t \quad (2)$$

$$\text{Angular displacement} \quad \theta = \omega_0 t + \frac{1}{2} \alpha t^2 \rightarrow \frac{1}{2} \frac{T}{I} t^2 \quad (3)$$

where: T = SA inertia resistive torque, I = SA mass moment of inertia, ω_0 = initial angular velocity is 0,
 t = time

The R&R required analysis of the mechanisms to ensure the two-stage concept would release the SAs. Starting with the first stage, the linear actuator, two aspects of the design were considered. These were the pin-puller activation force and the stroke margin. For the activation force, the linear actuator needed to pull the pin to disengage the release plate. To do this, the SMA linear actuator needed to overcome the pinching friction force that came from the 2nd stage compression springs. An analytical estimate was originally done based on the friction coefficient and geometry, however this proved to be inaccurate. Once the hardware

was built, the force to move the pin was measured directly. This measured force to move the pin and the available pull force from the SMA linear actuator, along with the appropriate safety factors, were used to calculate the force margin using NASA-STD-5017 [8] and ensure that it was positive. The other analysis evaluated the stroke margin of the linear actuator to ensure that it would move enough to clear the middle lug in the release plate and therefore release it. This was calculated using the geometry of the design, the total available stroke of the linear actuator of 7.1 mm, and assuming 10% extra for a positive margin as suggested by NASA-STD-5017 [8].

The 2nd stage mechanism's analysis evaluated the force margin of the compression springs, stroke margin of the release plate, and bearing analysis for linear-guided bearings. The force margin of the compression springs was calculated by adding up the resistive and friction forces and ensuring that the springs would overcome these forces, along with the appropriate safety factors. The resistive forces are from the eight deployable array hooks, friction between the guide pins, and other parasitic drag forces such as manufacturing misalignments, which were approximated. Additionally, to show the 2nd stage was failsafe, the margin for a one spring out case was calculated. For the stroke margin analysis, the release plate needs to clear the eight hooks used to hold the SAs in the stowed position. This analysis was done using the geometry of the hooks and ensuring that the release plate could move enough with at least 10% more distance than required. Finally, NASA-STD-5017 [8], gave guidance on how to analyze the four guide rails and plain bushings used in this mechanism to ensure that it would not bind and the stick-slip phenomena would not occur. The general rule of thumb is to assume a 2:1 ratio of allowable moment arm length to bearing length, which would cause the mechanism to become unrealistically long to fit in the CubeSat, so the bearing length was reduced. To ensure the design would not bind, an analysis was conducted using guidance from J.R. Schroeder [11], which essentially is a statics analysis of the design.

To aid in verifying that the mechanisms would deploy the SAs in orbit, an Automated Dynamic Analysis of Mechanical Systems (ADAMS) kinematic model was generated. The goal of the ADAMS model was to validate the design by showing all four SAs would deploy without adverse effects on the dynamics of the free-flying CubeSat. Moreover, the analysis was also used to evaluate some off-nominal pre-deployment rotations to see if there is a state when the arrays would not deploy or cause adverse effects on the dynamics of the free-flying CubeSat. This analysis also provided a way to support a test-like-you-fly exception, which is the inability to test the full deployment of all four SAs at the same time. The SMA hinge springs are designed to open the arrays in the freefall environment in orbit and the SMAs cannot open the arrays against Earth's gravity. Therefore, the fully assembled CubeSat's SAs are deployment tested with the array's gravity offloaded on its side, which results in only being able to test two SAs at one time. The ADAMS model was created to deploy all four arrays at the same time to learn about the full system's response and dynamics from a deployment in orbit. Additionally, the model was used to analyze other extreme initial conditions since it is unknown what state the CubeSat will be in before the deployment occurs. It could be tumbling and rotating, which would be impossible to test. Other off-nominal deployments were investigated, such as learning what would happen to the dynamics of the CubeSat if the arrays impact at different times or if one of the arrays became hung up then suddenly released. The ADAMS model was critical in observing the dynamics of a deployment from these various initial conditions.

The ADAMS analysis can retrieve other important data that can be difficult to generate from a ground test or analyze by hand such as deployment impact and latching forces. This information would aid in the structural design of subcomponents. An attempt was made to correlate impact load test data to the ADAMS model. However, the test data was significantly smaller than the ADAMS values. A very involved analysis and testing program is required to get the values to correlate better. This was deemed impractical and not necessary for this CubeSat project. However, it is important to be aware of the effort needed to capture these data for large projects.

The ADAMS model that was generated focused on the hinge mechanism and not the R&R since it can function completely on its own and against Earth's gravity. The model was useful early on in the development of the mechanism to give an idea of the required torque needed to deploy the arrays. However, many unknowns exist with analysis methods alone and it is pivotal to also build hardware to correlate to the

analysis model. The process for building the ADAMS model was the crawl, walk, run approach. A single-array model was generated first, which was correlated to single-array proof of concept tests. Data from those tests were used to adjust the ADAMS model so the observed test dynamics correlate to the model. This proved to be a very iterative process while the design matured. The key data that was correlated was the time from first motion to full deployment and the settling time for the deployed array to dampen out and stop moving. A complete model with four SAs was generated from the single-array model.

The analysis of the four-array model verified that the dynamics of the deployment in the microgravity environment should be successful and not detrimental to the dynamics of the CubeSat from either the nominal case, off-nominal cases, or any of the various initial conditions also analyzed. The various initial conditions analyzed included a no-rotating and free-floating case, moderate rotations (5, 20, 5 deg/s), high rotations (19, 80, 19 deg/s in the pitch, roll, and yaw directions respectively), and a hung-up array that impacted at a later time. These cases were sufficient for this CubeSat project, but for a more critical project, a full Monte Carlo analysis should be performed to capture more cases that may exist. An interesting result from the analysis was for the case when the CubeSat was tumbling or rotating; the deployment will somewhat reduce the rate of rotations while stabilizing the spacecraft.

Flight Assembly and Test

Building and testing the flight hardware started in February 2017. A number of unexpected issues arose during the assembly, which emphasized the need for schedule margin to work through those issues. Several of the hardware components required rework upon receipt from manufacturing. The R&R failed during subcomponent testing, primarily due to incorrectly-sizing the linear actuator and not fully understanding the friction forces in the pin-puller. This resulted in redesigning the R&R's 2nd stage compression springs and reducing their spring rate and stowed compression force. During the hinge assembly, one of the SMA springs fractured and had to be replaced. Then, during a critical time of final CubeSat integration with only a month left before the project was scheduled to be completed, multiple SMA hinge springs fractured and failed prematurely as seen in Figure 6. All of these issues did not occur during the EDU assembly and test.



Figure 6. SMA Hinge Spring Failed Flight Attachment

The failure of the SMA hinge springs during the final moment of integration proved to be a major issue and adversely impacted the schedule. From the failure investigation, it was determined that the failure occurred due to fatigue and over constraining the SMAs at the attachment point on the deployable SA panel. The EDU was cycled several times and this failure never occurred, making this failure even more unexpected. Further comparing the EDU and flight hardware, the issue was determined to be the SMA's attachment method to the panels. In the EDU version, there was a gradual bending slope in the SMA sheet where it attached to the deployable panel. In the flight version, a washer under a rivet head was added to prevent the process of driving the rivet from potentially cracking the SMA sheet, and the SMA was soldered more firmly past the rivet head toward the hinge pin. It was intended to solder the EDU hinges following the same procedure used in flight hardware. However, the EDU never adhered to the deployable panel near the rivet, and testing was conducted in that manner. This was corrected in the failed flight version by having a trained technician perform the soldering procedure, which was thought to have made the attachment better. The result actually caused the SMA to bend and crease at a very sharp corner when in the deployed

configuration as seen in Figure 6, which should be the lowest stress state. This was verified by attempting to perform 15 wear-in cycles on the flight design, which resulted in more SMA spring failures in early cycles.

The SMA hinge springs needed to be disassembled, redesigned, and replaced. The corrective action consisted of moving the solder attachment to cover the bottom half of the SMA hinge spring only and away from the rivet. The SMA was redesigned to remove a narrowed-down region that was no longer needed since the solder is only being applied at the very bottom edge. This increase in area was estimated to reduce the stress on the part by more than 20%. Finally, the washer under the rivet, which was still needed to prevent the rivet from potentially cracking the SMA, was bent upward to allow the SMA to have a smoother curve onto the PCB. These changes can be seen in Figure 7. New SMAs were then fabricated with the same processes that were conducted on the original batch such as torque testing each new spring. The new design was then installed onto the EDU and underwent a 4-times cycle life test (130 cycles) to gain confidence that the changes would correct the issue, which it passed. The redesign was then reinstalled on the flight hardware and underwent a 15 cycle wear-in test to ensure good workmanship and no other issues. Figure 7 shows the new SMA spring design and attachment method.

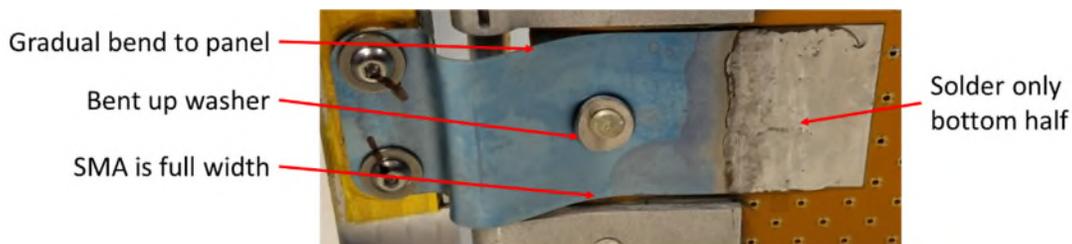


Figure 7. SMA Hinge Spring Flight Design Change, Attachment Corrective Action, and Repair

Once assembled, similar to the EDU testing, the flight subcomponents underwent functional and performance testing to ensure they were functioning correctly. Then, the units were integrated into the flight CubeSat assembly and underwent environmental testing. This included a random vibration test to 10 gRMS for 1 minute in three axes and a thermal/vacuum bake out. The CubeSat was functional before and after the vibration test and after the thermal/vacuum test. It was then stored for shipment to the launch service provider with a target launch date of April 2018. Images of the flight hardware are provided in Figure 8.

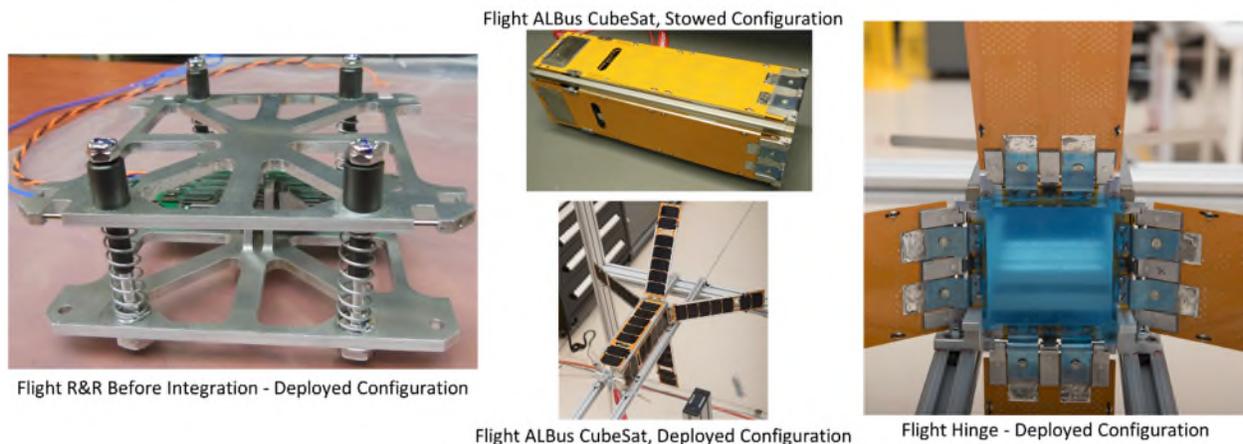


Figure 8. ALBus CubeSat R&R and Hinge Mechanisms Flight Hardware

Conclusion and Lessons Learned

The ALBus CubeSat mechanisms are an attempt to advance CubeSat technology by reducing mechanism risk from deployments of SAs. They also advance SMA technology by demonstrating the use of custom, unique, and high-temperature SMAs in the space environment. The project illustrates the potential of SMAs in CubeSat applications where space and weight are limited. This work is also a simplified example of the steps needed to develop a new design or technology from concept to final product and all of the common development challenges that occur along the way. Lessons learned include:

- Friction forces are difficult to quantify without validation from hardware tests.
- Sizing analyses such as loads, mechanisms, and kinematics should be done early on along with the design concepts even if firm inputs are not available. Do not focus only on the CAD design aspects.
- Building an EDU or 3D printing hardware to test is key in any new development to quickly uncover assembly issues and evaluate actual functional performance. Do not only rely on analysis only.
- Even though it can be easy to create dynamic and kinematic models for mechanisms, it may be very difficult to get meaningful correlations with the actual test data.
- SMA applications should be evaluated from a system level. For example, although the hinge mechanism uses simple SMA sheets, the integration process which involved bolting, riveting and soldering proved to be very difficult.

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