Development of a Compact, Planar, Spring Finger Latching Hinge for Small Satellites

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Abstract

Janus and Lunar Trailblazer are unique missions in the Lockheed Martin Curio™ SmallSat line intended to achieve critical advancements in planetary and lunar science on a low budget, with rapid development and the accompanying higher risk tolerance. Janus is a planned mission designed to send two carry-on luggage sized spacecraft to observe near-earth binary asteroids. Lunar Trailblazer (LTB) was an orbiter mission to map the distribution of water on the surface of the moon. The Lunar Trailblazer spacecraft is larger than Janus, being similar in size to a mini-fridge and has solar arrays that are approximately one-third larger than those of the Janus spacecraft.

These missions required a low cost, size-limited, latching hinge mechanism with uniformly low friction/drag throughout its range of motion for their deployable solar arrays. The need for a novel hinge design arose when we discovered issues with the baseline solar array hinge design on the Janus program. The baseline solar array hinge utilized a pop-over, integral spring latch that yielded high end-of-travel parasitic torque. The baseline hinge struggled to guarantee latching because of this parasitic torque combined with the dynamics of the deployment event. Modifying the baseline design was determined to be infeasible, and a search for existing solutions did not uncover any options that would meet the size-limitations and mission requirements. Thus, a novel design was required.

We developed a compact, planar, spring finger latching hinge to meet this need, hereafter referred to as the spring finger latching hinge. This spring finger latching hinge was inspired by similar liner lock mechanisms common in some pocketknives. These designs are characterized by a deflected spring finger that drags across the face of the opposing hinge half, then drops into a pocket to lock into the deployed state.

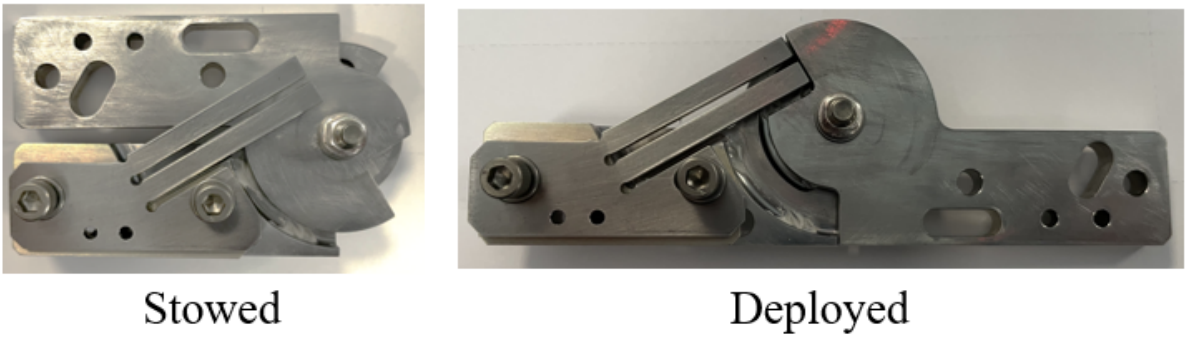

Figure 1: Compact, Planar, Spring Finger Latching Hinge

Our spring finger design features two identical hinge halves and a part with two spring fingers. During deployment, a torsional spring drives the upper hinge half to rotate relative to the lower hinge half. As the upper hinge half rotates, the spring fingers slide across the hinge half surface, then drop into place and

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latch after 180 degrees of rotation. This spring finger latching hinge was fabricated and integrated on the Janus and Lunar Trailblazer spacecraft.

Hinge development challenges were primarily caused by spring finger drag friction during deployment. This created negative static torque margins at the end of travel. This issue was primarily uncovered during the development of Lunar Trailblazer as the arrays on Lunar Trailblazer are larger and heavier, creating a more sensitive deployment. Additional analysis and testing were conducted to better characterize these performance phenomena and validate the design for Lunar Trailblazer.

This paper presents the driving requirements, design, integration, testing, issues encountered, and lessons learned from the planar spring finger latching hinge development.

Introduction

Class D SmallSats provide a unique opportunity for designs with strict packaging requirements for launch and flight operations. NASA Class D, defined by NPR 8705.4a, warrants a more risk tolerant posture to keep overall spacecraft costs low while adhering to accelerated spacecraft assembly, test, and launch operations. Lockheed Martin (LM) has developed the Curio™ SmallSat product line to meet this need while leveraging heritage experience on larger and more costly Class A and B mission architectures. Janus and Lunar Trailblazer are the first of their kind within the Curio™ line which required development of many unique structures and mechanisms to support the mission needs. Late in Janus development, the solar array hinges responsible for guiding array deployment and latching at the end of travel required redesign to provide a lower parasitic torque profile through the range of motion of each hinge, as the baseline hinge utilized a pop-over, integral spring latch that yielded high end-of-travel parasitic torque. This effort led to the development of the spring finger latching hinge. The new hinge utilized a self-locking design like those used in ”liner lock” pocketknife designs. As a result, the hinge is intended to experience a nearly constant friction torque during deployment.

Originally designed for the smaller Janus spacecraft, the spring finger latching hinge was baselined on the larger Lunar Trailblazer vehicle at risk to meet cost and schedule constraints. Further testing and analysis subsequently indicated that hinge design modifications were required on LTB to ensure successful array deployment. Once these modifications were made, the spring finger latching hinge was capable of successful deployment of the Lunar Trailblazer arrays.

Design

The spring finger latching hinge was inspired by liner lock mechanisms common in pocketknives. These designs are characterized by a deflected spring finger that drags across the face of the opposing hinge half, then drops into a pocket to lock into the deployed state.

This design provides a low complexity and compact design with a near-constant parasitic torque through the range of motion. A key advantage of this design is that it eliminated the increase in parasitic torque at the end of the travel that plagued the previous design, since the spring finger requires no additional deflection over a catch pawl and it simply drops into a pocket to an undeflected state. Once latched into the pocket, the spring finger cannot escape the pocket without a large buckling force to deflect it up and over the shelf.

Our design features two PH 17-7 stainless steel spring fingers that travel across a lubricated stainless-steel surface. We utilized two spring fingers for redundancy in the latching action and to distribute buckling loads on the spring fingers once in the deployed state. A single large spring finger would be suitably stiff to loading in the deployed state but would make latch reset difficult due to the larger forces required to deflect it out of the pocket. Shims are used to ensure proper hinge-line alignment and reduce undesired parasitic torque caused by eccentric loading on the hinge.

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The sliding contact surfaces between the hinge halves were minimized using machined pocket features to further reduce the friction during deployment. These hinge halves were pinned about the pivot point using a long fastener and a locking nut. A mandrel and torsion spring were then installed on the remaining fastener shaft and secured with an additional locking nut. Once assembled, an individual hinge can be fixed to the top and bottom edges of a panel to create one hinge-line.

Characterization and Analysis

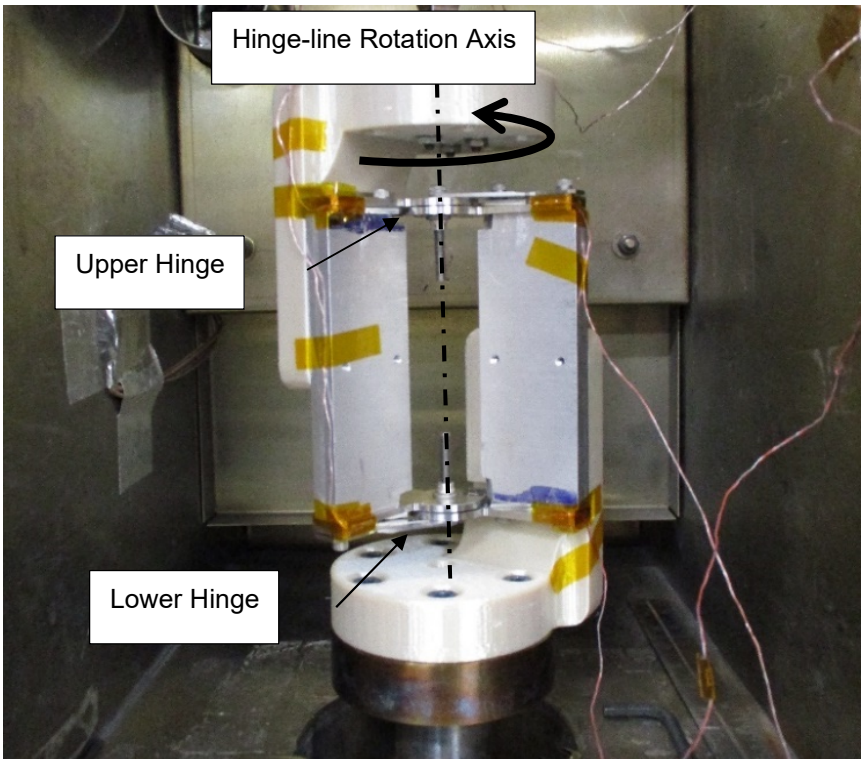

Figure 2. Hinge-Line Parasitic Torque Test Configuration.

Parts were fabricated and integrated to make a complete hinge-line assembly comprising two individual hinges, and a test was conducted to quantify hinge-line friction. To obtain bounds for friction and stiction, the test was run at ambient temperature, 4.4°C (40°F), and -40°C (-40°F). The test setup is shown in Figure 2 and results for the hot and cold measurements are reported in Figure 3. This test validated that the compact spring finger latching hinge design operates with relatively low torque losses. The initial increased torque at the beginning of travel is due to the initial static friction present in the hinge, which is not of concern for this application because the initial torque provided by the hinge deployment torsion springs is highest when the hinge is stowed. Additionally, the solar arrays include a kickoff release mechanism to impart additional energy into the system to overcome the higher required torque at the beginning of travel.

Data from this test was used in analysis and deployment simulations. For the Janus spacecraft, a Monte Carlo deployment analysis was conducted. In this case, the varied parameters were hinge friction, drive spring force, temperature and many other parameters. For Janus, 531 cases were analyzed and the results showed successful deployment in every case. At this time, the Janus program moved forward with the design and procured hardware to meet schedule needs.

Early in the test phase of the Janus program, Lunar Trailblazer began and its solar arrays needed a similar low part count, compact, latching hinge design as the panel construction was nearly identical to Janus. However, the Lunar Trailblazer spacecraft required arrays 33% larger than Janus with no additional hinge volume. Given that both programs were Class D and featured a rapid development schedule, it was decided

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to reuse the Janus spring finger latching hinge design on LTB. This decision was made with the acknowledgement that LTB was accepting a risk that the hardware may have some margin challenges with the slightly larger arrays. The program would not be able to retire this risk until analysis and testing could be performed with the LTB configuration. This reuse, however, maintained part commonality allowing LTB to take advantage of expedited delivery of the hinge hardware that was previously procured for Janus.

The hardware delivery allowed for the program to proceed toward solar array deployment testing in parallel with preparing a Monte Carlo analysis. This analysis revealed that due to the larger panels, hinge latching was not guaranteed in all cases. It was concluded that the larger panel momentum aids certain hinge-lines in the array stack but hinders others based on the alternating accordion-fold configuration of each array wing. This resulted in a predicted failure to latch in 78% of the Monte Carlo cases, which was far outside of our earlier risk assessment.

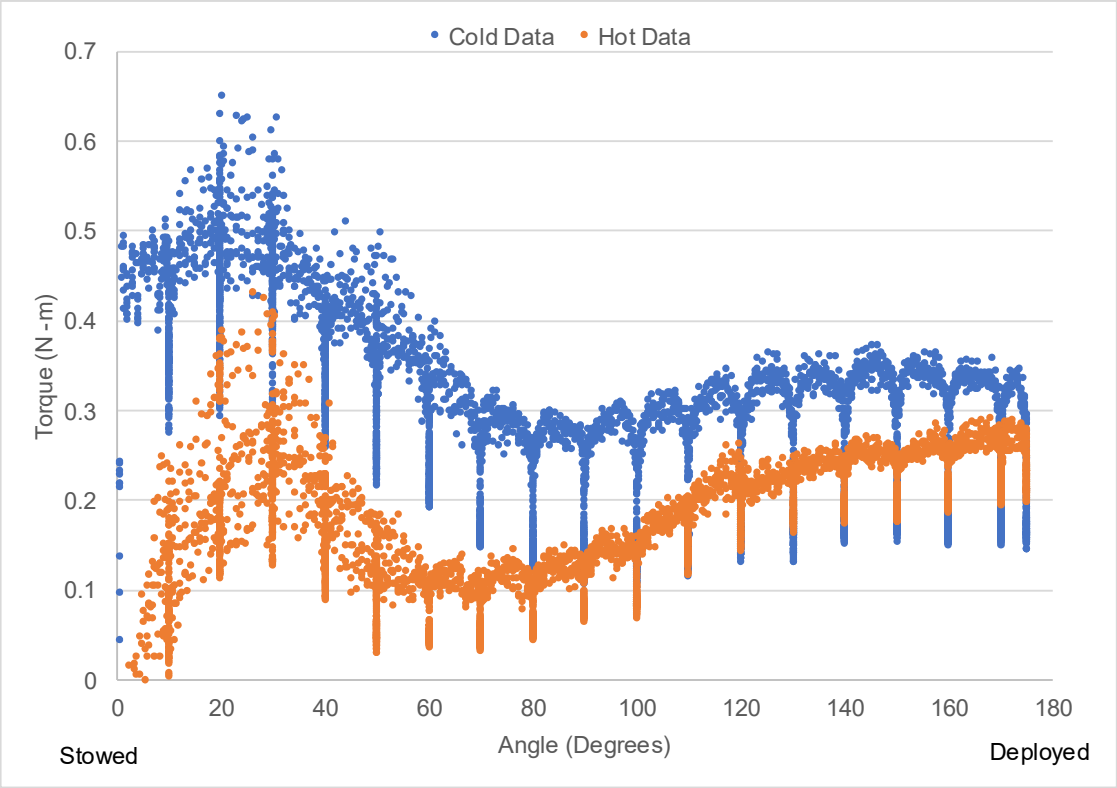

Figure 3. Hinge-Line Frictional Torque Losses through Hinge-Line Range of Motion.

Subsequent inquiry led to the discovery of an issue with this hinge-line design unknown to the LTB team that impacted their application. The deployment torsion springs previously procured for Janus had margins calculated with early parasitic torque measurements taken in ambient conditions at room temperature using prototype hardware which did not have AIAA S-114A-2020 margin factors applied. When testing on Janus showed sufficient margin, more rigorous factors were not included in the analysis by their design team. When the solar array panels were scaled up for LTB, the deployment springs and spring finger latches were not scaled as the hardware was shared between Janus and LTB to satisfy mission schedule and cost constraints, and the LTB team was unaware of the lack of analysis margin. It was concluded that the deployment spring torque could not overcome the LTB hinge-line friction. Figure 3 applies a factor of 2.5 to the measured hinge-line torque data in accordance with AIAA S-114A-2020 and overlays the available deployment spring torque per hinge-line. The plot shows that the mechanism does not have positive static torque margin against the tested performance of the hinge when cold nor hot and nearing the end of travel.

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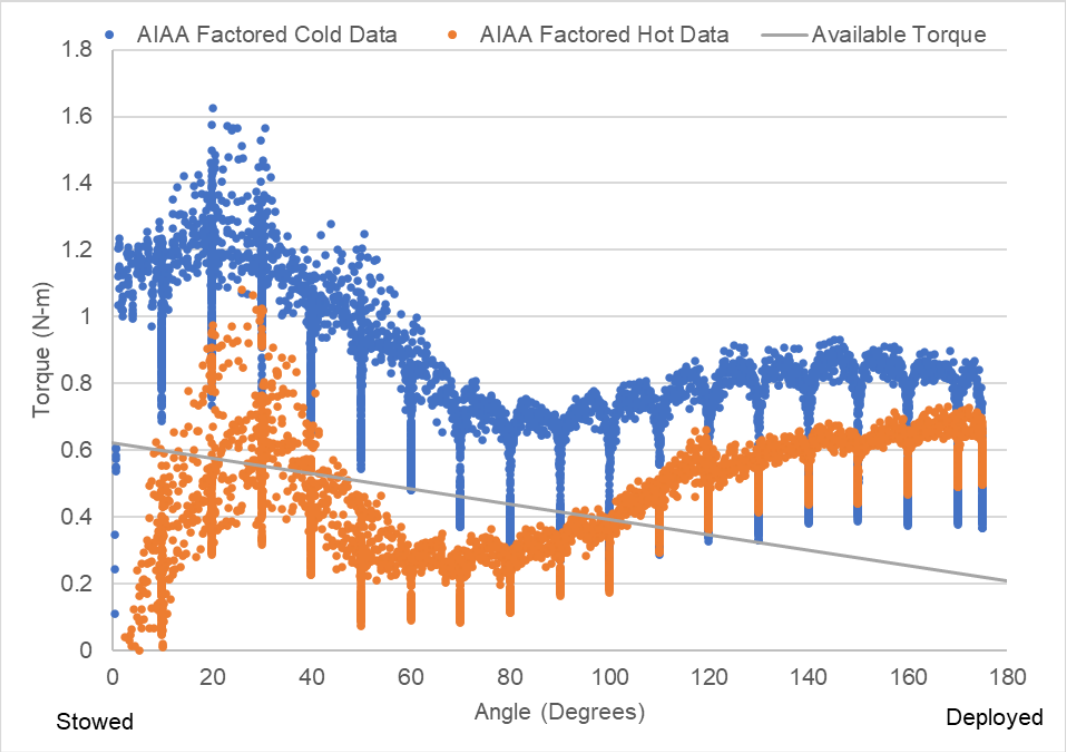

Figure 3. Factored Hinge-Line Frictional Torque Losses through Hinge Deployment Relative to Available Deployment Spring Torque.

This issue was not discovered in the Janus analysis as the smaller arrays had margin and the deployment dynamics did not appreciably hinder unfolding the alternating panel stack, resulting in full deployments in every case. In a case such as Lunar Trailblazer, without a positive energy margin, the remaining drive spring torque must finish the deployment of each panel of the array once the momentum of the array has been damped out. The late negative margin discovery on LTB did not allow sufficient time to redesign and procure new hinges and a program level risk assessment was convened to consider some atypical solutions to allow the vehicle to meet the tight ride-share launch. Subsequent Monte Carlo analysis for the LTB arrays showed that removing a spring finger from the hinge-line that failed to deploy reduced friction during deployment in the hinge-line by 50%, resulting in 100% latching success.

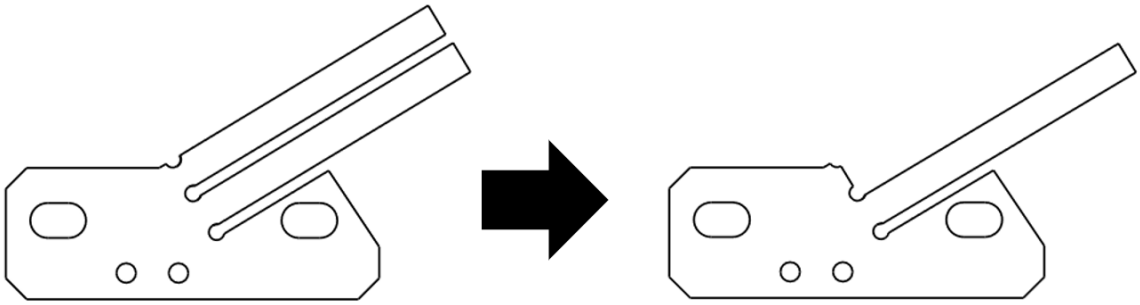

Figure 4. Spring Finger Removal for LTB.

This removal was only permissible at the yoke to first panel hinge-line due to the reduced energy it experiences, only this hinge was able to show positive buckling margin with this change. At other hinge-lines the removal of a spring would have created a negative buckling margin when back driving the latched hinge.

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Deployment Testing

Following the analysis and hinge modification, deployment testing began on LTB. Multiple unrelated issues with the deployment fixture were identified and corrected in early deployment runs. The array deployment fixture offloads the weight of the arrays onto trolleys that sit in an angled rail. However, due to the relatively weak deployment springs in the hinge-lines relative to the additional mass of the MGSE, very minor issues in the rail are exaggerated and hindered the deployment. Once test support equipment issues were resolved and MGSE frictional losses were mitigated, the hinge design modifications consistently demonstrated successful deployment of the LTB arrays.

Figure 5. LTB Solar Array Deployment Test and Associated Support Equipment.

Lessons Learned & Conclusions

The development of a spring finger latching hinge with a near-constant torque latch provided many lessons learned. The hinge provided a favorable frictional torque loss profile near the end of travel at hot and cold temperature extremes, resulting in a well characterized hinge-line design for future mechanisms. This spring finger latching hinge met the design requirements for the Janus mission. The parallel reuse of that same hinge hardware on Lunar Trailblazer posed what was initially evaluated as a low risk due to the characterization and analysis work done by the Janus team. However, while LTB accepted what was considered low risk for the larger LTB vehicle; it became apparent that this reuse was really a design creep case and additional analysis and test were crucial to retiring the risk. Though not a new concept, this effort reemphasized the importance of sufficient analysis and test even on hardware reuse where design creep in loads may impact existing designs that were complete but not yet flown.

Additionally, during a temporary reinstall of one solar array wing, one of the spring fingers on a single hinge-line broke. The break was observed near the root of the spring finger, and a thorough investigation was conducted. The other spring finger in this +X hinge line, as well as the two spring fingers in the mirrored -X hinge-line on the other solar array wing were removed and imaged via X-ray. The other spring finger in the +X hinge-line showed signs of cracking, but the parts from the -X wing did not show any issues. Spring fingers from all other hinge-lines were visually inspected in-situ. The spring finger that fractured was part of

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the gimbal-yoke hinge-line which was in an overstressed condition due to the interfacing panel clips being out of tolerance. In correcting the gimbal bracket the stowage load was brought back to nominal, however during the period prior to the rework the stowage load was much higher than design intent leading to increased deflection in the spring finger. This off-nominal deflection cycled and overstressed the fingers which might have resulted in the weakened integrity of the spring fingers leading to the fracture. This overstressed condition was recreated in multiple tests, but the team was unable to recreate the same fracture, leading us to believe the spring finger was further overstressed during latch handling and resetting. The issue with the spring finger breaking off also reveals the need to always have a safe way of stowing without overstressing hardware. The liner lock knife inspiration usually also contains over-travel stops via the knife scales. This design did consider having stops, but space and weight restrictions outweighed the implementation. Since the failure could not be recreated, it is hard to know if the out of tolerance positions caused the failure or if the mechanism was mis-handled during an operation. Regardless, with fragile mechanism components, the design should consider the ease of stowage, and any necessary support equipment or over-travel stops to ensure safe and proper stowage without the risk of damage to flight hardware.

While reuse of heritage, characterized mechanisms is preferred to reduce cost and development schedule, system-level changes should always be properly vetted, even on Class D risk missions the risk and impact of design creep should never be under estimated. The hinge design and specified deployment springs were suitable for Janus, but the increased solar array mass for Lunar Trailblazer meant that modifications were required to ensure successful deployment on Lunar Trailblazer.

Lastly, this mechanism development showcased the importance of testing hardware in a flight-like manner. For mechanisms with large positive deployment torque/force margins, discrepancies in test configurations relative to the flight configuration may be overcome by the overall deployment energy of the system. However, for mechanisms with very low positive deployment energy margin, minor discrepancies in the test support equipment or spacecraft configuration can exacerbate issues resulting in uncharacteristic system performance. The non-scalable effects of deploying in an atmosphere and with fixture friction have a greater impact on small scale hardware. Ideally this effect can be minimized by avoiding the use of mechanisms with low, near zero deployment energy margin.

Lunar Trailblazer was launched on February 26, 2025. Data indicates the Lunar Trailblazer solar arrays successfully deployed and latched shortly after separation from the launch vehicle, validating the compact, planar, spring finger latching hinge design worked as intended on orbit.

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