Mechanism Design & Flight Build of Furled High Strain Composite Antenna for CubeSats

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Abstract

In August of 2016, Roccor was tasked to develop a CubeSat antenna mechanism that deploys four 20 x 5 inch (51 x 13 cm) radial petals from a small, 2U stowed volume. It was determined that High Strain Composites (HSC) coupled with a copper-beryllium alloy enabled a simplistic furled solution utilizing few mechanical parts. A two-stage mechanized deployment scheme was developed to first expose the wrapped petals to the outside of the spacecraft via a hinged joint and then separately trigger a dynamic unfurling of the petals with a tether. This paper describes the initial trade study and detailed design of this deployment mechanism as well as the lessons learned during the flight qualification. In May of 2017, Roccor delivered two, low-cost flight qualified units to the customer after a design, prototype, build and test campaign lasting a total of nine months. The hardware is slated to fly in late 2018.

Introduction

The emergence of the small satellite platform and subsequent ease of access to space has created high demand for advanced, yet compact spacecraft systems serving a range of science, commercial and defense applications. Furthermore, the industry-wide embrace of the CubeSat standard, establishing both spacecraft form factor and consistent launch requirements, has established investment in off-the-shelf spacecraft components and high quantity production within the field [1,2]. Across the community, one of the largest hurdles to developing a successful CubeSat system is the challenge in miniaturizing the technology to function within the desired form factor. This is especially challenging when designing deployable structures such as large antennas or solar arrays, where common physical components such as fastened interfaces, articulated joints and actuators are not efficient in the miniaturized form factor. Furthermore, structural performance does not often scale linearly in size causing the need to embrace different architectures at smaller scales to enable a desired deployed stiffness and precision. One such technology receiving increased attention within the CubeSat community are High Strain Composites [3,4] (HSC) or materials that deform from one shape to another during deployment. A commonly known high strain device is a slit-tube, or a deployable “tape-measure” boom that allows the cross section to be flattened and rolled into a coil reaching a high packaging efficiency [5,6]. Although the metallic slit-tube device has extensive flight heritage, a controlled deployment requires complex mechanisms to control the strain energy of the wrapped coil. When fabricating a slit-tube boom with a HSC material, the ability to tune the composite laminate to control the strain energy of the furled structure offers a new level of simplicity while enabling adequate control to deploy and retract the device. The use of HSCs offer an improved level of mechanism simplicity over architectures utilizing traditional moving mechanisms such as rotational joints, springs, dampers and latches.

In August of 2016, Roccor LLC was approached by an advanced CubeSat payload provider to design a mechanical system that would house and deploy a series of co-planer RF elements on orbit. This customer required a rapid system development ranging from early requirements definition to the delivery of multiple flight units over the course of a nine-month period. To add to the challenge, this effort was bounded by a relatively small budget, driving the need for mechanism simplicity. These desired elements consisted of four petals, each measuring roughly 20 in x 5 in (51 cm x 13 cm) in length and height respectively that would be aligned radially about a central hub. These petals would also need to be folded into a 2U CubeSat

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The geometry of this antenna system is shown in Figure 1 with the four petals shown in the deployed state. Here the co-planer petals are shown in green, and the desired stowage volume of 10x10x20 cm is shown in purple. The remaining 6U CubeSat volume is identified with a semi-transparent box.

Structurally, the deployed petals needed to maintain a stiffness requirement above 0.5 Hz, a lateral precision of ±4 in (±10 cm) at the petal distal edge and a twist precision of 1 in (2.5 cm) measured with respect to the top/bottom of the outer ends. It was found that the simplest approach was to wrap the four petals around a central hub and utilize strain energy to deploy upon the release of a circumferential restraining band. The petals, consisting primarily of a copper to enable RF performance, were reinforced with high strain composite lamina to control the stowed strain energy and deployment dynamics. The added lamina also protected the metallic RF element while stowed, assist the deployment and finally to improve the deployed structural performance. In a recent publication [7], the end-to-end development process of the petal design is discussed at length; this includes the architectural trades, laminate fabrication, early challenges such as delamination and creep effects, and finally the integration efforts of this system into the spacecraft deployment mechanism. This current paper focuses on the mechanism specific design aspects of this system that secured, exposed and triggered the petal radial deployment within the CubeSat form factor. Challenges in design as well as lessons learned during initial fabrication and flight qualification are detailed at length as well as the challenges of integrating high strain composite deployables.

Figure 1. Basic geometry of deployed CubeSat antenna

Architectural Trade & Mechanical Design

The challenge of deploying a series of large, furled flat panels within a small CubeSat form factor was broken down into several targeted areas for the Roccor team to work through. The first consisted of designing a laminate that could withstand the high strains while stowed, ensure sufficient energy for a robust deployment and finally provide adequate stiffness and precision once exposed. Important considerations such as defining the furled geometry of the petals were a central focus, especially in the transition region between the furled panels and the central petal supporting structure. The second category focused on the mechanics for how to stow, package and protect the furled petals within the CubeSat volume during launch, and upon activation, release the petals in the space environment. This area had the added complexity of physically moving the stowed petals from the cocooned volume to the outside of the spacecraft prior to petal unfurling. In addition, the deployment synchronization and analysis of the petal unfurling were prime focus areas within this group. The final category consisted of the electrical considerations such as the incorporation of the actuation device, integration of the RF electronics, wire harness management and finally, providing sensory feedback indicating a successful deployment.

Petal Laminate Design
The first step in the design of the petal, was to define the key geometric constraints imparted by the CubeSat envelope and central hub structure. This latter component, supplied by the payload provider, consisted of two interlocking plates forming a cross, with each of the petals bonded to the exposed outboard surfaces.
This rigid structure had a diameter of 2.6 in (6.6 cm) and contained finely tuned RF elements and electronic components, requiring delicate care. This geometry is shown as the light green components in Figure 2. The RF petals extended beyond the interlocking plates and were geometrically required to sustain a ~0.25-in (6.4-mm) bend radius as they transitioned from the central hub structure to the larger, wrapped geometry required of the 2U CubeSat form factor. This immediate region, defined as the transition area, contained the highest strain within the system design. Finally, the petal length and spacecraft envelope of ~3.1-in (7.9-cm) square required each petal to be wrapped just over two full rotations around the central supporting structure with a maximum petal thickness of 0.020 in (0.5 mm). Further considerations were imparted to maximize volume such as a non-circular wrapping geometry and the clocking of the central hub with respect to the space envelope to maximize the transition area bend diameter as seen in Figure 2.

The initial petal laminate design consisted of a homogenous approach where the central RF conducting element was sandwiched with reinforcing lamina across the entire petal length. Here the RF element was baselined to be Copper Beryllium (CuBe) due to its excellent electrical conductive performance and ability to withstand high strains. Several lamina materials were considered, however, E-glass was set as the baseline due to the material's high strain capability, availability and low cost. Upon early modeling and coupon fabrication, it was quickly determined that a variation of laminate designs across the length of the petal was required to optimize performance. For example, it was found that reinforcing the outer 1/3rd of the petal geometry did not increase deployed stiffness as the added mass of the lamina at the distal end overpowered the benefits of the improved localized stiffness resulting in an overall lower frequency. It was also found that this added distal mass reduced the 1g buckling resistance, a property that made ground testing more difficult. The finalized petal architecture of the petals is shown in Figure 3 with the R0-R3 regions representing different levels of high strain composite reinforcement. The R3 region is exposed CuBe while the R2 and R1 regions have one and two layers of glass reinforcement respectively. The R0 region is in the transition area, per Figure 2, experiences the highest strain during packaging and hence maintains only a single layer of reinforcement. This reduces the overall deployment energy and effects of creep. The length of each region, $L_A$, $L_B$ and $L_C$ were optimized to increase the petal’s deployed frequency and 1g buckling resistance. The images on the bottom of Figure 3 show an early prototype of the petal design in the deployed and furled states.

Figure 2. Basic geometry of deployed CubeSat antenna

The initial petal laminate design consisted of a homogenous approach where the central RF conducting element was sandwiched with reinforcing lamina across the entire petal length. Here the RF element was baselined to be Copper Beryllium (CuBe) due to its excellent electrical conductive performance and ability to withstand high strains. Several lamina materials were considered, however, E-glass was set as the baseline due to the material's high strain capability, availability and low cost. Upon early modeling and coupon fabrication, it was quickly determined that a variation of laminate designs across the length of the petal was required to optimize performance. For example, it was found that reinforcing the outer 1/3rd of the petal geometry did not increase deployed stiffness as the added mass of the lamina at the distal end overpowered the benefits of the improved localized stiffness resulting in an overall lower frequency. It was also found that this added distal mass reduced the 1g buckling resistance, a property that made ground testing more difficult. The finalized petal architecture of the petals is shown in Figure 3 with the R0-R3 regions representing different levels of high strain composite reinforcement. The R3 region is exposed CuBe while the R2 and R1 regions have one and two layers of glass reinforcement respectively. The R0 region is in the transition area, per Figure 2, experiences the highest strain during packaging and hence maintains only a single layer of reinforcement. This reduces the overall deployment energy and effects of creep. The length of each region, $L_A$, $L_B$ and $L_C$ were optimized to increase the petal’s deployed frequency and 1g buckling resistance. The images on the bottom of Figure 3 show an early prototype of the petal design in the deployed and furled states.
Mechanical Exposure and Deployment of Wrapped Wings

The initial mechanical deployment concepts consisted of a single-phase process whereas the unfurling and translation out of the enclosed envelope happened simultaneously. This approach however was deemed high risk due to uncertainties of blooming / binding of the petals during initial release. In addition, risk reduction testing of this highly coupled and dynamic deployment would require detailed analysis and a complex offloading setup. As such, a two-phase deployment was baselined where the wrapped assembly would initially move out of the stowed volume as a rigid body and then as a separate function, unfurl the wings. It was determined that the best way to restrain the wrapped system was with a single circumferential band applied at the mid-plane of the system. Upon exposure of the wrapped petal assembly outside of the spacecraft, the band could be released with a pin allowing for a dynamic unfurling of the four wings. Alternative approaches such as utilizing radial pins or a breakable wire that would penetrate through the wings, to provide continuous or sequential wing deployments, were deemed as technically feasible however not within the schedule or budget of this program.

To expose the wrapped petal assembly, several architectures were traded with the two strongest candidates focusing on 1) a linear sliding deployment and 2) a pivoting architecture, shown in Figure 4 & Figure 5 respectively. The linear translation approach utilized a sliding mechanism to shoot the wrapped petal assembly out in an axial fashion. This system was restrained with two release doors and triggered by a single hold down release mechanism. Once the petals were cleared from the cavity, the restraint band would be released and captured by a single tether. This architecture had several advantages such as the co-alignment with the spacecraft envelope, ease of the wiring harness management and similar design to mechanisms associated with p-pod deployment canisters. The challenges however were identified such as the complexity of multiple sliding interfaces, limited space at the region near the door where release device was housed and the opportunity of binding along the winged surfaces with particular concern focused on the restraint strap. The pivoting architecture consisted of a single door that preloaded the wrapped petal
assembly within the canister. Upon release of the door via pin puller, the petal assembly would pivot out, via torsional springs, a full 180 degrees in the opposite direction with respect to the door and hard stop outside of the spacecraft. Half-way through this rotation, the restraint band would be triggered and captured via tethers. Unique to this architecture is the load path and intentional contact of the wrapped petals and the spacecraft envelope. This allowed the petals to be further compressed and preloaded when stowed, forming a more direct and benign load path to the structure. This architecture was ultimately selected due to the simplistic nature of the rotational mechanism, the clean preload between the furled wings / stored envelope and lower concerns of petal binding.

![Figure 4. Translational architecture showing: 1- the stowed system, 2- post translation of the wrapped petal assembly outside of the storage volume, and 3- post petal unfurling](image)

![Figure 5. Pivot architecture showing: 1- the stowed system, 2- the door fully opened and rotation of the wrapped petal assembly, part way through the 180-degree motion and 3- post petal unfurling](image)

**HDRM, Electrical and RF Considerations**

The system deployment was initiated by a 067-011 Pin Puller provided by GlenAir of Glendale, California. This hold down release mechanism (HDRM) restrained the door during launch and upon command, enabled free motion of the door and subsequent wing assembly. The door and wing were preloaded with torsional springs sized to enable swift motion to ensure unobstructed rotation of the wing assembly. While the release of the wing assembly preload provides a strong kick-off, the motion of these two components

NASA/CP—2018-219887 341
are dominated by springs along the hinge axes. Hard stops on both the lid and wrapped wing assembly were placed to prevent bounce-back and potential re-contact during deployment.

The GlenAir Pin Puller operates via a fuse-wire system whereas an electrical current causes a preloaded wire to fuse, enabling a pre-loaded mechanical bolt to translate under considerable force. For this effort, the GlenAir team fabricated and qualified a custom size, delivering a series of flight mechanisms within three months of the request shown in Figure 6.

![Figure 6. GlenAir 067-011 pin puller hold down release mechanism](image)

The wing assembly required a rigid coaxial cable that would need to dynamically deploy with the system. To resolve this, the cable was laid along the base of the canister with a series of bends incorporated. During the full rotation of the wing assembly, the bends would allow for the cable to flex and twist with modest parasitic force. The clean nature of the canister walls eliminated potential snag hazards of the cable.

**Detailed Flight Mechanism Design**

An early prototype was fabricated in November of 2017 for design feedback and risk mitigation. The focus of this effort centered on verifying the stowed petal assembly shape and ensuring clearance during rotation. It was found that the wrapped, square-like shape shown in Figure 2 was hard to achieve and instead the petals, upon an application of preload from the system, formed an oblong shape with a defined and consistent elastic response. This result was built into the design of the flight system. Other details pertaining to the strap, tethers, incorporation of foam and wire harnessing are described in further detail below.

**Strap and Tether Design**

The stowed petals are held into a cylindrical shape with a circumferential restraint strap, this is shown in Figure 7 and as the pink component in Figure 8. The strap has clasp features bonded on either end which is temporarily held together with a removable release pin. This pin is connected to a tether that removes the pin from the clasp as the system deploys allowing the antenna elements to unfurl.
The restraint pin pull tether works in tandem with two other tethers designed to restrict the location of the deployed strap assembly and to capture the hardware post deployment to prevent interference with the hardware and orbital debris. The sequence of system deployment can be seen in Figure 8. Phase 1 shows the system in the stowed configuration with everything constrained and preloaded by the door (green). Once the release is initiated, the door begins to open which allows the stowed hub assembly to begin exiting the stowed volume. Phase 2 shows how the door opens faster than the hub assembly to prevent contact. Both items are driven by torsion springs which are sized to provide adequate torque and sequence the deployment. The detail view of phase 2 shows the release tether (left side of image in turquoise) attached to the release pin. During this phase the tether is still loose. This view also shows the band tether (right side of image in turquoise) in a slack state.

Phase 3 shows the release tether becoming tight which is accomplished by the cam shaped feature near the root pivot of the hub assembly (bright yellow). As the hub assembly deploys the distance between the release tether and base increase, thus providing a pulling motion on the release pin. Once the hub assembly rotates a few degrees beyond the position shown in Figure 3 the release pin will be removed. It is important to note that the system was carefully sequenced such that the petals on the stowed hub would not begin to deploy until there was no chance of contact with the spacecraft. The springs are also sized so that the pin will be removed in the absence of kinetic energy.

Phase 4 shows the restraint band assembly completely removed from the stowed hub assembly which will allow the petals to begin unfurling. This image also shows how the band tether will restrict the location of the deployed strap assembly. This is critical for the system so that there is no interference in the deployed state. Also notice the release pin is still attached to the strap assembly with a third tether. The length of the three tethers is critical for consistent performance and to prevent tangling. Tether length was set at final assembly by hand deploying the hub assembly in order to guarantee successful performance.
Strap Presence in the Door Window
A key requirement of the design involved verifying that each payload stow process was consistent and would remain in the proper configuration throughout testing and launch. A major concern was the placement of the restraint strap with respect to the hub assembly and placement in the stow volume. As described above if the restraint strap assembly were to shift it could impact the timing of the tethers, increasing risk of binding and/or premature petal unfurling. This risk was mitigated by designing a window into the door which trapped the clasp and release portion of the strap assembly. This entrapment prevents the release pin from shifting and being unintentionally removed from the clasps via direct interference with the door as shown in Figure 9. Once the deployment sequence is initiated, the door swings open first allowing the rest of the system to deploy unimpeded.
Incorporation of Foam
Polyimide foam was placed on the bottom surface of the chassis and inside the door to control the amount of deflection on the stowed antenna, thus generating preload to stabilize the assembly for launch. This style foam was chosen for its low outgassing and damping properties. The foam is also available in various thicknesses which allowed the fine tuning of preload on the antenna by simply scaling the thickness. Preload was measured and fine-tuned in the testing phase of the program.

The foam must be preconditioned in order to function in a reliable manner. To do this Roccor essentially used a large rolling pin to flatten the foam into a consistent thickness. During this process it was noticed that the foam lost roughly 50% of its original height. Once in this state the amount of preload generated remained consistent throughout testing.

The foam was positioned in the deployer and held in place using pressure sensitive adhesive. Due to the likelihood for the foam to generate particulate, it was covered with a polyimide film and seamed around the perimeter, this essentially encapsulated the foam. One small area of the seam was left unsealed to allow venting of the cavity. This layer of foam and polyimide also had the secondary benefit of providing abrasion protection on the antenna elements by preventing direct contact with the aluminum surfaces inside of the deployer.

Wiring Harness Guidance
In order to electrically connect the deployed hub to the spacecraft, careful electrical harness routing was required. Due to the 180-degree rotation of the hub and baseplate, significant slack was allowed in the harness, and epoxy staking locations were limited. The only option for staking was a single location near the top of the antenna. The smooth walls of interior volume prevented any snagging that would prevent deployment. Careful routing also aided in providing deployment force as opposed to developing a parasitic torque.

Flight Development and Lessons Learned
In Q2 of 2017, two systems were fabricated and flight qualified. Due to the fast nature of this 9-month program, many of the design features discussed above were tailored during flight build to ensure the system functioned as expected. This included the exact sizing of tether lengths, implemented foam thickness to control stowed preload, and the final geometric coax cable routing scheme. While numerous minor unexpected issues presented themselves during the testing phase of the program, two were considered significant with the possibility of preventing or degrading successful deployment on orbit. Both of these were addressed with minor modifications to the design and are presented below.
Strap Performance
The first significant find during testing was the release pin jamming in the clevises and not being extracted during deployment. This prevented the restraint band from releasing causing a failed deployment. It was found that this issue was caused by a wedging effect created by the tether pull force on the strap. Figure 11 shows the ideal location of the strap represented by the green line and the as tested location in red.

Upon further design review it was found that the geometry of the machined clasps with the tang offset from center caused wedging when the assembly was under tension. Future designs will incorporate a centered tang which will balance the tensile forces. Figure 12 shows the component names and geometry of the strap assembly to better explain the situation.

Redesigning the parts was not an option due to schedule, so other modifications were implemented. First the sharp edges of the tang were chamfered to prevent them from digging into the pin. This decreased the amount of pull force needed to extract the pin. Figure 13 shows the chamfer added to the upper surface of the hole, this was also completed on the lower surface.
In order to combat the strap assembly taking on the wedge shape in the first place, epoxy was applied beneath the clasps to prevent a downward translation of the assembly. While the original design called for this feature, the location of those epoxy beads did not prevent the restraint band wedging near the clevis. The epoxy bead was therefore moved to provide better support by interfacing directly with one side of the clip while not interfering with the release pin. This epoxy bead also improved the tendency of the strap assembly to slide as a removal force was applied to the release pin. Figure 14 also shows how a second epoxy bead is placed 180 degrees from the first but on the top of the strap. This prevents the rear portion of the strap from sliding upwards which also causes a wedging at the clasps.

![Epoxy bead applied to the black surface. No adhesion to any other components.](image1)

![Backside epoxy bead prevents the rear portion of the strap from translating upward.](image2)

**Figure 14. Epoxy bead placement**

These updates prevented the strap assembly from translating with respect to the hub which allowed for consistent pull forces from the release pin.

**Door bounce**

The second significant find was the bouncing of the door during deployment. This was not noticed as an issue until a cold thermal deployment test. The door opens quickly and in the original design, a Viton bumper provided damping as the door hit a hard stop at ~90 degrees. At the cold temperature, the Viton did not damp all return motion and during testing, re-contact with the hub assembly was identified. While this did not prevent full deployment, it did have the potential to damage the sensitive RF element edges of the HSC petals, especially since the re-contact location was adjacent to the extrusions of the 'window' feature on the door. It was determined that a better bumper material was needed that would dissipate all energy and prevent door bounce back. Figure 15 shows the contact zone and the motion of the components at the time of contact.

![Contact zone](image3)

**Figure 15. Door bounce back illustration**

The Viton bumpers were replaced with copper mesh to better absorb the energy generated during deployment. These bumpers were a single use item that dissipated energy by crushing when contacted by...
the door. Careful setup was required to ensure that the bumpers would enable full motion of the door eliminating the chance of the bumpers preventing the door from blocking / re-contacting the wrapped petal assembly during deployment. This was done by installing the copper mesh in place and then opening the door to pre-crush the bumpers to the minimum opening angle of the door. Figure 16 shows a pair of crushed bumpers on the left and a pair of partially pre-crushed bumpers on the right. In the left image the layer of copper sheet can be seen with copper mesh below it. The entire stack was encapsulated with Kapton tape. Many tests were conducted to determine the ideal cross section area, height and buildup of these to dissipate the proper amount of energy.

![Figure 16. Copper mesh bumpers](image)

Flight Assembly and Other Considerations
The two flight units were fabricated in March of 2017 and successfully passed qualification testing including vibration and stow / deploy cycles at the extreme operational temperatures. The system was found to be robust after multiple stow and deployment cycles however the high strain composite laminate did show signs of wear-and-tear (abrasion marks, roughening of edges, etc.) after successive deployment cycles. This was mainly due to the difficulty in handling / supporting the petals during the deployment testing and the inter-petal rubbing during the stowage process. As such, the flight units were subjected to a limited number of full unfurling tests as part of the acceptance testing checkout. It was also found that immediately after deployment, creep effects from the high strain composite prevented the wings from deploying in fully straight manner. As per the discussion defined in a separate publication [7], this deflection gradually reduced in severity after deployment due to stress relaxation within the laminate. The Roccor team performed a series of long-duration tests on the laminate architecture and determined that the petals would deploy within the required precision parameters.

![Figure 17. Stowed system during flight qualification vibration testing](image)
Conclusion

In August of 2016, Roccor was approached to develop a CubeSat deployable antenna that would deploy four large radial petals while housed in a small, 2U volume. It was found that High Strain Composites coupled with a copper-beryllium alloy enabled a simplistic furled solution to stow the system with few mechanical parts. A two-stage mechanized deployment scheme was selected to first expose the wrapped petals to the outside of the spacecraft via a hinged joint and then separately trigger a dynamic unfurling of the petals with a tether. This scheme was selected over other two-stage approaches due to the low risk of binding, ease of securing the wrapped wings via external preload and overall mechanism simplicity. The design was triggered by a single commercial GlenAir pin puller and utilized torsional springs to allow rotation. The petals were unfurled via a restraint strap that was triggered and afterwards captured by a series of three tethers. During the flight build, details such as the tether lengths, foam thickness and coaxial wire routing were fine-tuned to ensure the system performed as expected. While there were numerous lessons learned and small tweaks implemented during the flight build, qualification testing revealed two significant issues that required action. The first was a modification to the restraint band clevis and addition of guides to prevent binding during release. The second involved improving the energy absorption to prevent bounce-back of the door and subsequent re-contact with the wrapped petal assembly of the door during deployment. In May of 2017, Roccor delivered two, low-cost flight-qualified units to the customer after a design, prototype, build and test campaign lasting a total of nine months. The hardware is slated to fly in late 2018.

References

5. Storable Tubular Extensional Member Device, US Patent #3434674