Development of Compact Mechanically Driven Systems for High Strain Composite Slit-Tubes

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Abstract

Since the pioneering days of space exploration, large deployable structures have played an important role in expanding satellite capability and performance. Perhaps one of the more prominent and simplistic building blocks of deployable structures is the rollable slit-tube boom, or a “Storable Tubular Extendible Member” [1,2]. This device functions in a mechanically similar fashion to a tape measure where a long metallic cross-section is rolled into a coil, providing a high packaging efficiency and the ability to deploy to various lengths. This technology has been commonly employed in space for 50+ years due to the simple nature of the design and the limited number of mechanical components required to deploy in orbit. Moreover, the industry has long known and applied a wealth of lessons learned from early flights of these simple devices [2]. Examples include using the slit-tube as a standalone structure to offset sensors or cameras from a spacecraft body to more fully integrated systems such as the primary drive mechanisms for telescoping booms used to deploy the sunshade on the James Webb Space Telescope. Despite the extensive use, this technology is limited when the deployable structure requires high precision or is subjected to large structural loads. For these cases a complex set of mechanisms consisting of rollers, guides, and bearings to unravel the metallic slit-tube becomes necessary in order to contain its considerable stored strain energy in the coil and properly manage its deployment. Conversely, the use of High Strain Composite (HSC) slit-tubes [3,4,5] can allow greatly increased boom strength and stability.

Roccor LLC, based in Louisville, Colorado is currently developing a series of HSC slit-tube deployers that take advantage of the non-isotropic material properties HSC materials to reduce their stored energy. Specifically, Roccor is developing HSC slit-tube laminates composed of traditional space-qualified materials, which are highly structural in the extended configuration but also have a relatively low stored strain energy in the stowed configuration. As a result, the need for a complex set of rollers and constraints on the coil are eliminated and the deployment device volume is reduced. In addition, these laminates provide near zero coefficient of thermal expansion (CTE) and/or the opportunity to embed internal conductors, which can act as an RF element or to transfer power/data without a standalone harness. The Roccor team has developed a series of integrated HSC slit-tube boom deployer systems that vary in size, performance and application. In this paper, a design review of four selected systems is outlined with a focus on the mechanical components enabling deployment/retraction while also ensuring structural rigidity. In addition, the best practices for ensuring adequate boundary conditions are also identified.

Roccor’s High Strain Composite Boom Deployer Family

The four unique deployer systems discussed in this paper are identified in Figure 1. Each of these systems was designed for a specific application with a series of performance and operational requirements. A brief description of design considerations for each system follows below:

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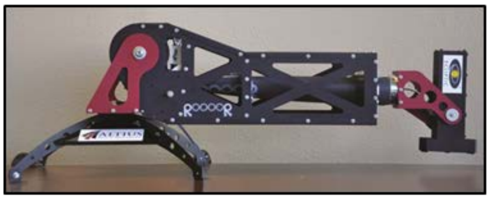
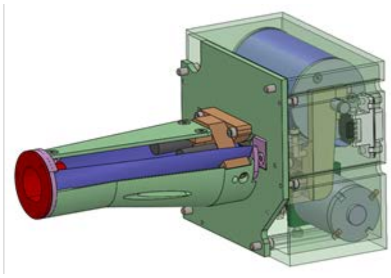
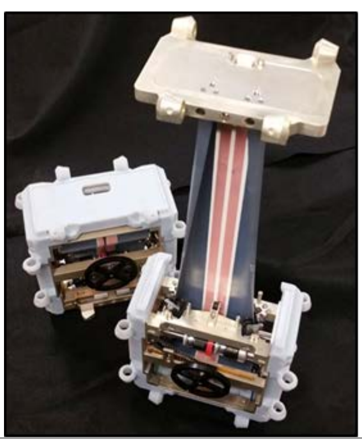




‘DARPA Phoenix Camera Boom’	‘NASA CubeSat Magnetometer Boom’
• 2.5” (6.35-cm) diameter, circular cross section • 60” (1.5-m) deployed length • Embedded wires allowing power and data transmissions for distal camera • External motor	• 0.75” (1.9-cm) diameter, circular cross section • 50 inch (1.3-m) deployed length • Near-zero CTE design, high precision distal end knowledge • CubeSat form factor • Magnetically clean

‘DARPA Phoenix *HIMast* Boom’	‘NASA Asteroid Redirect Mission’ (ARM)
• 1” (2.5-cm) diameter with extended cross section • 180” (4.6-m) deployed length • Low CTE design, high precision distal location • Embedded high current power supply wires • Fits the *NovaWurks* ‘*HISat*’ envelope with an external drive motor	• 1.4” (3.6-cm) diameter, circular cross section with overlap • 80 inch (2-m) deployed length • Low CTE design • Internal motor



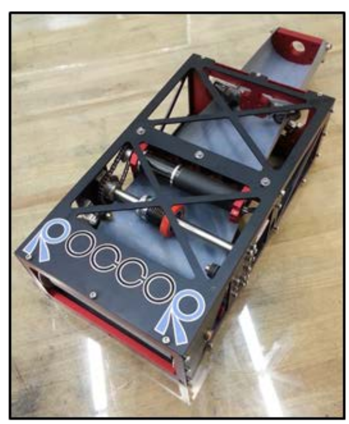


Figure 1. The Roccor High Strain Composite Slit-Tube Deployer Family.

DARPA Phoenix Camera Boom

This boom was designed to deploy and retract a camera (hundreds of cycles) in support of the DARPA Phoenix program. This boom utilizes a thin carbon fiber HSC laminate and was designed to be neutrally stable (same strain energy in deployed and stowed configurations) upon rolling. As a result, during operations the spool passively rolls / coils without requiring additional constraints. The boom geometry is circular with a 2.5” (6.35-cm) diameter with roughly a 300º included angle. The deployer volume is set so that the boom geometry is near fully recovered prior to exiting the front of the box to maximize structural efficiency. This system also utilizes a preloaded friction drive-wheel to deploy and retract the boom as well as radial roller supports to enable rigid boundary conditions of the deployed boom. Finally, thin copper wires are embedded into the composite material to allow for power and data transmission to a camera located at the distal end. A slip-ring is implemented into the spool to electrically connect the boom wires with the deployer. This feature eliminated the need for a separate, pull-out wiring harness.

DARPA Phoenix *HIMast* Boom

This boom was designed as a deployable building block element for re-configurable satellites, and provides improved structural performance, power transmission and deployed stability/precision as compared with the *‘DARPA Phoenix Camera Boom’*. In addition, this system was designed to fit within the mechanical envelope of the ‘*HISat’*, a low-cost, modular satellite architecture that allows for rapid reconfiguration and on-orbit assembly under development by *NovaWurks* of Los Alamitos, California. The options for reconfigurability and potential to use multiple ‘*HIMast’* deployers in tandem led to the development of a unique, non-circular cross sectional shape shown in Figure 2. This shape is also convenient as it enables a flat surface to embed large copper wire traces to supply power at the distal end. This boom is composed of a combination of carbon and glass fiber materials to enable high strength, precision and thermal stability.

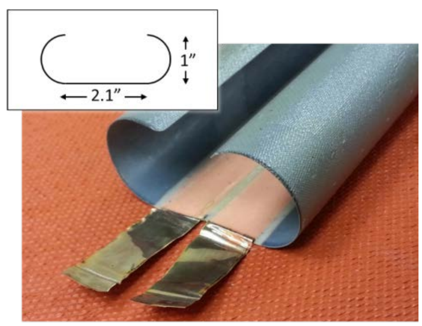


Figure 2. ‘*HIMast’* Slit-Tube Cross-section

Perhaps one of the most challenging aspects of the ‘*HIMast’* design was the 20x20x10 cm mechanical envelope available for the deployer mechanism. This coupled with the required structural performance of the deployed boom forced this design to have component-level proportions not typically seen in slit-tube systems. For example, a large spool was required that occupied roughly 1/3rd of the available volume which was not fully compatible with the natural spooling diameter of the composite. As a result, a preload on spool was required during retraction to ensure proper coiling. In addition, in order to ensure that the boom deployed perpendicular to the box, the composite had to be back-bent as it came off of the large spool. This required additional focus on the laminate design to ensure high strain levels and robustness. Another example of the high compactness of the system relates to the drivetrain design. Here the ‘*HISat’* architecture enabled external motor driving which eliminated the need for a dedicated motor. However this created several subsequent requirements such as the need to pass this mechanical power to adjacent ‘*HISat’ / ‘HIMast’* boxes as well as the need to mechanically sequencing the systems. This led to a drivetrain design consisting of multiple gears, chains and slip-clutches shown in Figure 3. Here the mechanical input/output is shown as black wheels on the top and bottom while the elastic wheels interfacing the composite are shown in orange. Further details on this system designed are available within the literature [8,9].

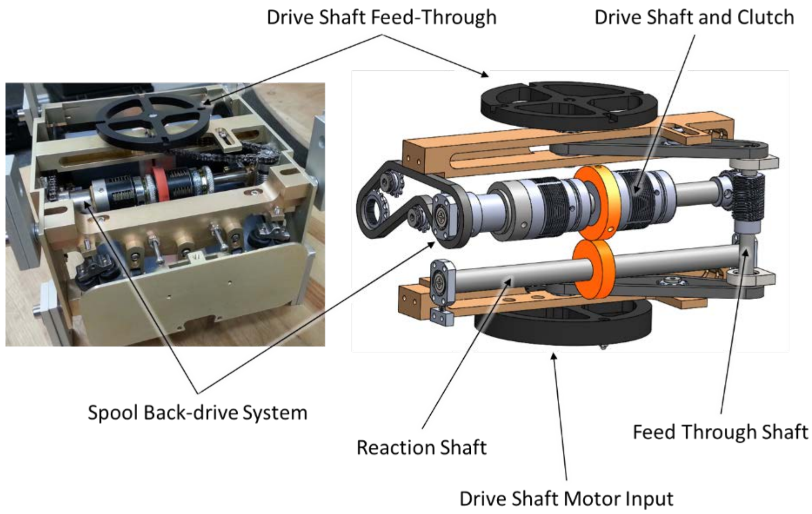


Figure 3. '*HIMast'* Drivetrain Design

<u>NASA CubeSat Magnetometer</u>

This effort is currently under development with the NASA Goddard Space Flight Center in Greenbelt, Maryland. This project builds upon Roccor's previous experiences in fabricating high precision, thermally stable booms with a new focus of miniaturization into the CubeSat form factor, use of magnetically clean materials and need for low-cost hardware. This boom is 0.75" (1.9 cm) in diameter, has an included angle of 350º and a deployed length of 50" (1.3 m). This boom utilizes a thermally stable laminate design consisting of both carbon and glass fibers. Unique to this design are a series of roller-free boom support boundary conditions to reduce the number of moving parts and to maximize the available volume. In addition to meet precision, this system contains a highly geared-up drive train to ensure fine deployment resolution as well as a pin-latch mechanism and a composite insert to lock the boom at the desired deployed length. This boom also contains a hybrid elastic friction wheel and mechanical toothed interface to improve deployment length knowledge.

<u>NASA Asteroid Redirect Mission</u>

This boom system was developed in conjunction with a commercial group working to fabricate ground demonstration hardware in support of NASA's Asteroid Redirect Mission. This system closely resembles the '*DARPA Phoenix Camera Boom'* deployer design outlined above however utilizes a higher fidelity laminate design, contains an internal motor and utilizes a new edge roller constraint scheme. The laminate design consists of a 1.4" (3.6-cm) diameter boom with a 400º overlap and a deployed length of 80" (2 m). The overlap strengthens the boom along the generally weaker bending direction where the open portion of the slit-tube is in compression. The internal motor is directly connected to the boom shaft and is capable of supplying an axial deployment force in excess of 20 lbf (89 N). The edge supports depart from earlier approaches where a wheeled interface is replaced with a hard metallic interface. Here the composite rubs against the surface enabling a stout boundary condition while eliminating additional moving components.

Lessons Learned in High Strain Composite Boom Deployer Design

During the development of the four boom systems outlined above, several best practices and lessons learned were established by the Roccor team. In this section several of these details are outlined and design features that incorporate these best practices are discussed.

<u>Designing HSC Slit-Tubes to be Neutrally Stable</u>

The utilization of neutrally stable HSC materials offers an opportunity to fabricate unique structures with a wide range of performance properties. The design space ranges from one extreme where the neutrally stable laminate slit-tube architecture passively deploys into an extended beam when unrestrained to the other extreme where the boom passively retracts into a compact coil. With proper tuning, a hybrid laminate design can be implemented that is *neutrally stable* – possessing equal strain energies in the stowed and deployed configurations. This attribute allows for the slit-tube to be manipulated between its stowed and deployed configurations without managing a significant change in strain energy and thus enabling a simplistic deployer system. The concept was first analyzed by Murphey and Pellegrino [10] and later by Shultz, Hulse, and Keller [11]. Figure 4 shows an example of a fiberglass composite slit-tube that is neutrally stable and remains partially coiled without external constraints.

Although it may seem ideal to tune the laminate design to be neutrally stable, often this can be challenging to achieve practically while balancing with other competing laminate requirements such as thermal stability or structural performance. For the case of the *'DARPA Phoenix Camera Boom'* and *'NASA ARM Boom'* deployers, these two designs had the flexibility to enable a neutrally stable boom. This resulted in deployer systems that contained fewer mechanisms and an overall lower unit cost. In the *'DARPA Phoenix HIMast Boom*' and *'NASA CubeSat Magnetometer Boom'* cases, this was not possible whereas the laminate design required added features to ensure tight packaging on the spool. Without this assistance, the coil diameter naturally grew to be ~50% larger than what was ultimately desired. For both of these cases, this was relatively easy to overcome by either adding a small retraction spring inside the spool or in the case of the *'DARPA Phoenix HIMast Boom*' system, a chain and slip-clutch coupling to apply a desired and constant spool preload during retraction.

Figure 4. Example of a Neutrally Stable Boom (Glass Fibers)

Boom Formation Region

As the HSC material is rolled off of the spool, there is a 'formation' region where the boom transitions from a flattened geometry on the spool, to a fully formed cross section that is capable of supporting loads. It is the responsibility of the deployer to guide the boom through this transition and when enough depth has been established, create a stout boundary support to enable a rigid deployed structure. In practice, it has been found that the length of this formation region for a neutrally stable boom is approximately 9x the diameter of the coiled boom or the *envelope form factor*. Note that this length is substantially shorter than the factor 8π analytically predicted 50 years ago by Rimrott for isotropic slit-tube booms, which illustrates a further advantage of neutrally stable laminate designs [12].

In ideal systems, the deployer envelope would fully encompass this *envelope form factor* to ensure that the boom exits the box with its fully formed cross section established and to provide adequate structural support to the base of the boom once deployed. However it has been Roccor's experience that most practical spacecraft envelope constraints do not allow for this "luxury." For the Roccor deployer family, the portion of the boom formation region covered by the deployer varies widely from the '*DARPA Phoenix HIMast Boom'* system of 2x to the *'DARPA Phoenix Camera Boom'* system of 6x. The optimized deployer length depends upon the design loads. High axial loads can be sustained with a relatively short deployer length while bending loads necessitate a relatively long deployer length. In the case of '*DARPA Phoenix HIMast Boom'* the system design and requirements were able to close with the *envelope form factor* of x2 due to the mission architecture where multiple units would be used in tandem to form a hierarchal structure. For the cases where the boom deployers are less than x4 in length, additional considerations such as the distal end attachment method (see the *Distal End* section below) and the boom structural knockdowns must be considered.

Distal End

The distal end, (i.e. the boom end fitting) is a complex component of any deployer system as its attachment method plays a large role in ensuring boom rigidity. Perhaps the most challenging aspect to this component is an attachment method that ensures boom torsional rigidity. Additional complexities arise for deployer systems that do not exit the box with a fully formed cross section. For these cases, the distal end must accommodate changes in the cross section geometry and lock into place once the boom reaches beyond the 9x *envelope form factor*. An example of this case is illustrated in Figure 5 and shows the closeout feature utilized for the *'DARPA Phoenix HIMast Boom'* system. Here as the numbers in the figure ascend, the boom is deployed out and the cross sectional geometry wraps and closes around the distal plate.

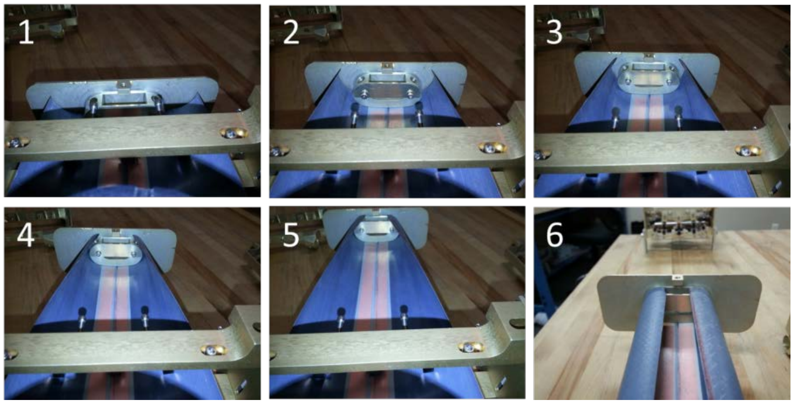


Figure 5. Distal End Closeout, Roccor '*DARPA Phoenix HIMast Boom'* System

For this case, it was found that the best distal closeout method was to use a series of kinematic mount interfaces that preloaded boom front edge against the distal plate to enable torsional rigidity. Other practices were trialed for additional improvement including the use of magnets, springs, etc., however with the large closeout length for this architecture, significant benefits for these added features were not realized. For Roccor's other deployers, the *'NASA ARM Boom'* system (with an envelope form factor of 4x), a distal plate was adhered and fastened to the end of the boom, as shown in Figure 6, and worked very well however minor, non-destructive edge buckling was noticed upon full retraction. Further design changes to the front roller supports relieved this effect. For the *'DARPA Phoenix Camera Boom'* deployer (envelope length of x6), a system utilizing a long, thin sheet metal plate adhered to the composite surface was incorporated without any observed issues.

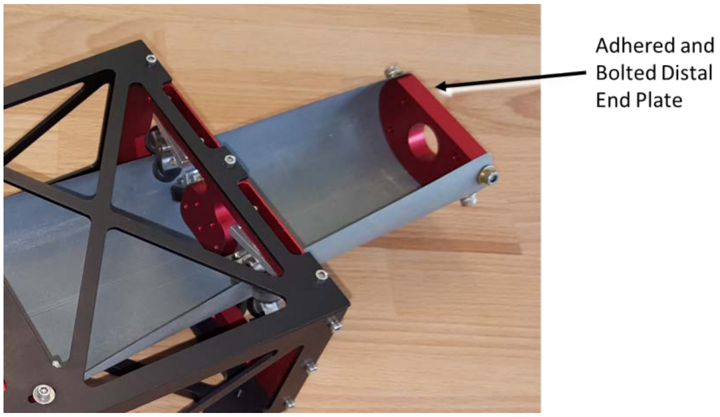


Figure 6. *'NASA ARM Boom*' Deployer, Distal End

Boundary Conditions: The root boundary conditions, along with the distal end, define the structural performance of the entire system. Within the Roccor boom deployer family, a myriad of boundary constraints mechanisms have been incorporated in an attempt to maximize rigidity while minimizing cost and complexity. To date, all of Roccor's deployers contain at least two roller support planes, an aft set near the root end of the formation region and a forward end where the boom exits the box. The roller supports for each plane come in two types, a 'surface' roller that contacts the composite radially around the cross section and 'edge' rollers that guide and preload the open/exposed section of the slit-tube. In Figure 7, two *'DARPA Phoenix HIMast Boom'* units are stacked in tandem with the distal end partially deployed. Here the difference between surface and edge rollers can be clearly seen. Each boom contains a maximum of two edge rollers, while a variable number of surface rollers are placed where the support is needed on both the inside and outside of the open cross section. For all of Roccor's boom deployers, the surface rollers are simplistic Delrin wheels that passively roll against the composite surface to provide support and low parasitic drag. In the case of the *'NASA CubeSat Magnetometer Boom'* the small envelope does not allow volume for these rollers so the composite runs along a smooth, low-friction contoured material interface.

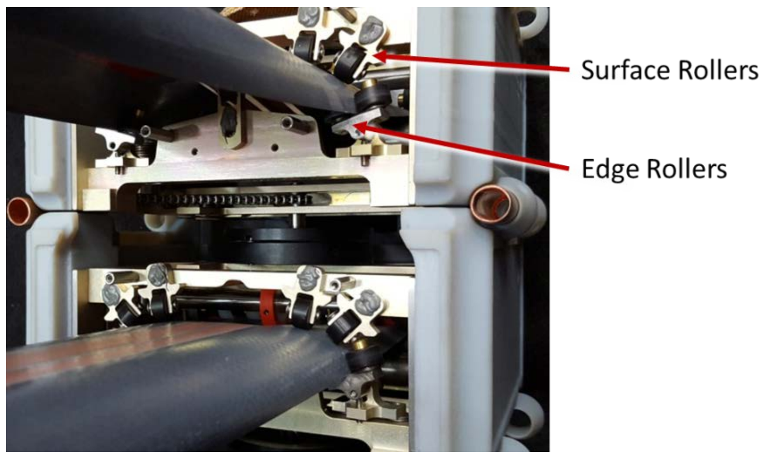


Figure 7. *'DARPA Phoenix HIMast Boom'* Boundary Condition Restraints

The edge rollers within the Roccor family have evolved significantly as a need for deployers with high precision and robustness has been realized. The early design implemented for the *'DARPA Phoenix Camera Boom*' deployer is shown on the left side of Figure 8. Here a ball-bearing pulley was used and preloaded against the composite edge with a spring-plunger system. This design concept worked well however it was challenging to tune the pitch of the wheel in order to align it to the composite edge. Slight misalignments caused the side of the pulley to rub against the composite causing damage and unpredictable performance. Furthermore, during the course of the deployment, slight changes in this angle occurred as the distal end moved away from the deployer box leading to degradation to the composite edge. The magnitude of the edge preload was also very limited in order to prevent composite edge degradation due to the small contact area between the circular edge pulley and the linear laminate edge. In addition, when the boom was subjected to lateral loads, the spring-plunger was in this load path which was often times too compliant and reduced the overall deployed performance.

The most current edge roller design is shown on the right side of Figure 8. This image is from the *'NASA ARM Boom'* deployer system however this concept has been implemented into the *'DARPA Phoenix HIMast Boom'* and the *'NASA CubeSat Magnetometer Boom*' deployers. Here the composite slides directly against a flat, hardened steel block enabling a rigid line-contact interface along a defined length of laminate edge. In addition, two surface rollers are immediately adjacent to align and hold the edge in place. This system is designed to maintain the contact position even as the boom edge angle changes during the boom deployment. In addition, there is no compliance within this system other than a set screw to establish the initial edge preload during tuning (in higher TRL versions, any set-screw adjustors have been replaced with shim adjustment). Instead, the compliance within this interface is transferred into the composite laminate itself and the surface rollers locations are strategically placed to prevent undesired strains and binding. It is important to ensure that the boom edges are properly trimmed to ensure minimal variance – and hence change in edge preload - during the deployment of the slit-tube. In addition, proper edge treatments to ensure smoothness and robustness are paramount when utilizing this method. One consequence of this design is added parasitic drag however the graphite to hardened steel interface is inherently low-friction. It has also been found that this system is robust and that the component receiving the most wear is the hardened steel in which minor <0.001-inch (25-µm) grooves are present after extended use.

Figure 8. Edge Roller Design: Pulley Wheel (left), Hard Metallic Stop (right)

As a few final notes regarding the boundary condition restraints, the inclusion of adjustability to add preload to the edges and select surface rollers is a helpful feature. The variability in the composite fabrication process during a system development and the need for tuning can cause tedious tuning where ease of adjustability will help quicken this effort.

In addition, in some cases one can artificially decrease the need for the x4 or greater envelope factor (discussed above) by pinching the boom at the forward roller plane to more closely resemble the fully formed geometric cross section. This can be done within reason however does add additional strain to the composite, handling challenges during integration and increased parasitic drag. Roccor has successfully implemented this practice on the '*NASA CubeSat Magnetometer Boom'* deployer.

<u>Drivetrain</u>

Within the Roccor deployer family, the drivetrain design widely varies due to the requirements imparted for each application. The inclusion of internal motors vs external drives, the need for slip clutches to enable boom synchronization and the ability for mechanical pass-through to adjacent boxes are some examples the Roccor team has incorporated when considering drivetrain designs. A detailed discussion of this area is beyond the scope of this paper however the topic of the drive wheel design and placement is an important area to review. Within the Roccor family of boom deployers, it was found that the best method of driving the boom for deployment and retraction is via a friction wheel interface placed outside of the spool. Many existing systems for metallic slit-tubes incorporate a motorized spool inside the rolled boom as the primary drive mechanism. In conjunction with this, numerous rollers and pins need to be placed around the spool and boom exit point to 1) control the strain energy of the coil prior to applying drive forces, 2) counteract very high forces associated with radial expansion of the rolled boom imparted from the motorized spool and 3) ensure that the flattened boom does not buckle due to the spool drive forces as it exits the spool. When upgrading the system to include HSC booms, the need to constrain the spool is no longer present and hence placing the drive wheel outside of the spool reduces significant complexity and cost. For all four deployers outlined in this paper, a simplistic drive wheel with high durometer elastic material has been used with success as shown in Figure 9. For the case of the *'NASA ARM Boom'* deployer, an axial preload of >20 lbf (89 N) has been successfully demonstrated with this system.

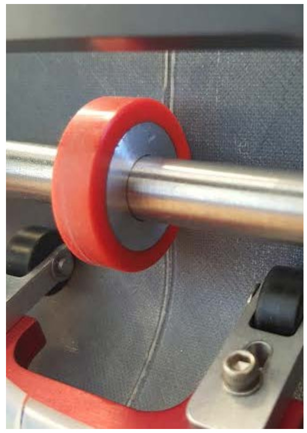


Figure 9. '*NASA ARM Boom'* Deployer Drive Wheel

Modeling the Formation Region

The geometry of the laminate formation region is a function of the material properties, laminate design, thickness, cross-sectional geometry and fabrication processes. These interconnected design features ultimately leads to a cross section that is hard to predict without empirical measurements. As such, it is important to fabricate a fully functional boom prior to initiating detailed deployer design. In addition, the formation region can change over time due to boom degradation, creep and thermal effects and should be fully understood prior to fabrication.

Conclusion

In this paper, the design traits of four unique deployer systems developed by Roccor was presented with the goal to inform the reader of the wide range of design features and applications for High Strain Composite slit-tube deployable booms. In addition, common design practices were presented to provide a flavor for how the designs converged when developing these boom deployers as well as to provide lessons learned and future recommendations for new systems. The use of High Strain Composite structures in spacecraft deployables is an emerging field that offers the opportunity to develop simplistic, low cost systems that can supplant and reduce complexities of established deployable systems.

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