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Big Deployables in Small Satellites

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ABSTRACT

The concept of utilizing small satellites to perform big mission objectives has grown from a distant idea to a demonstrated reality. One of the challenges in using small-satellite platforms for high-value missions is the packaging of long and large surface-area devices such as antennae, solar arrays and sensor positioning booms. One possible enabling technology is the slit-tube, or a deployable "tape-measure" boom which can be flattened and rolled into a coil achieving a high volumetric packaging efficiency. Common design constraints however relate to the need for complex deploying mechanisms to manage the stored energy of the metallic slit-tube coil as it is unreeled, the deployed non-axial stiffness and strength, positional stability and wire-harness management. In this paper, we discuss the design, analysis and fabrication of a High Strain Composite (HSC) slit-tube boom system under development in support of the DARPA Phoenix effort. The utility of HSC materials enables a highly tuned structure resulting in a slit-tube which is stable (i.e., no stored energy) in both the stowed and extended configurations and hence reducing the deployment mechanism complexity and volume. In addition, composites enable the ability incorporate thermally invariant materials and to embed wire harnessing/antenna feeds directly into the boom.

INTRODUCTION

The use of large deployable structures dates back to the pioneering days of space exploration and has played a crucial role in enabling a robust spacefaring industry. Today, deployable structures are found on most spacecraft missions to support basic satellite functions such as unfolding solar arrays, positioning antennas and offsetting sensors. Despite the healthy supply of readily available off-the-shelf deployable technologies, the demand for higher performing hardware is pushing the suppliers to seek new and innovative design approaches. Several notable high performance deployable structures currently under development are supporting unique spacecraft architectures with wide footprints to provide thermal [1] and optical [2] shields, 100kW class solar arrays [3] and asteroid encompassing / capture mechanisms [4].

In parallel, the emergence over the last fifteen years of the small satellite concept has set a new paradigm for spaceflight in two distinct ways, the first by creating a new market for miniaturized spacecraft system technologies and second by enabling the capability to rapidly test hardware in space at a low, standardized cost [5]. Beyond the widespread utility of individual small satellites, this form factor also enables several new mission architecture concepts such as distributed sensing where hundreds of small satellites take measurements around the globe simultaneously or fractionated spacecraft where several small satellites of varying capabilities aggregate together to form a larger, more versatile spacecraft.

The work discussed in this paper focuses on the design and utility of incorporating rollable high strain composite structures into small satellites. In the following sections, the benefits and applications of rollable structures and the subsequent enabling technologies of incorporating HSC materials are identified. Next a discussion is given about the current work underway by the DARPA (Defense Advanced Research Projects Agency) Phoenix program to build and test an aggregate spacecraft in space. Finally the paper discusses efforts underway by ROCCOR, LLC, and Altius Space Machines, Inc., of Louisville, Colorado to design and build large deployable structures in a small satellite form factor for aggregate spacecraft.

ROLLOUT HIGH-STRAIN COMPOSITE BOOMS

One type of deployable structure is the rollout boom, also known as a “slit-tube” or a Storable Tubular Extendible Member (STEM). The boom functions in a mechanically similar fashion to a tape-measure where a metal strip can be stored on a coil and rolled out into a rigid member. Metallic slit-tube booms have been widely utilized on spacecraft as the structural members for telescoping booms, truss components, extending antennas, and solar array deployments among others. Their primary benefits include a high packaging efficiency, ability to be retracted and relatively low cost. A common design constraint however relates to the need for complex deploying mechanisms, consisting of rollers, guides, and bearings to unravel the metallic device evenly without binding or disrupting the stored spring energy of the coil. A method which simplifies this issue and thus reduces the volume of the deployment device would incorporate larger, more capable booms into small satellites to support the growing demand for higher performing hardware.

The ROCCOR team, based in Louisville, Colorado is currently developing a High Strain Composite (HSC) slit-tube boom that uses the non-isotropic material properties of Fiber-Reinforced Polymer (FRP) to reduce the stored energy of the coiled boom. This optimized structure results in a slit-tube laminate, -composed of traditional space-qualified materials,- which is completely stable in both the stowed and extended configurations shown in Figure 1 below. 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, the nature of FRP composites enables the tailoring of the lamina plies to improve stiffness across specified axes of the boom. The result is the ability to use a simple, reliable, lightweight, inexpensive and most importantly small deployment devices for large scale space structures.

Figure 1: Example Fiber-Reinforced Polymer slit-tubes in various stages of deployment.

Design of High Strain Composite Slit-Tubes

The incorporation of non-isotropic materials into slit-tube enables a wide range of design flexibility to suit a particular application. The slit-tube laminate is composed of several layered fiber laminas that are adhered together with a polymer matrix. The material and ply orientation for each layer is selected to determine the desired structural performance of the slit-tube. Slight modifications in the laminate design can have dramatic effects on the performance of the slit-tube. As an example, tailoring the lamina fibers that are furthest offset from the laminate central axis plays a key role in determining the stable configurations of a slit-tube allowing for the structure to either passively deploy, remain neutral or coil. The flexibility of composite design also allows for the structure to be stiffened in critical areas. One known issue with the slit-tube structure is the presence of buckling along the exposed edges and is commonly seen when subjected to a bending load. This concern can be mitigated by tailoring the fiber architecture and laminate thickness at the edges and by the development of reliable simulation and test methods. Another known issue with the slit-tube geometry is its limited resistance to torsional deformation, especially upon comparison with a standard tube. Many approaches whereby the free edges are brought together and interlocked have been proposed and consist of various interlocking teeth for metallic slit-tubes. Ultimately this approach has not been viewed as unreliable as the interlocking teeth cannot be guaranteed to properly mesh with a high degree of probability as they are fragile. In addition, these teeth add parasitic packaging width to the slit-tube system. To resolve this issue, ROCCOR has developed a Seam-Lock technology which is composed of a series of self-guiding interlocking tabs that are embedded into the HSC surface. The deployment sequence is displayed in Figure 2 below. It is predicted later in the paper that the Seam-Locks, in combination with the edge strengthening technique will improve the buckling capacity of a representative slit-tube by more than a factor of 4.

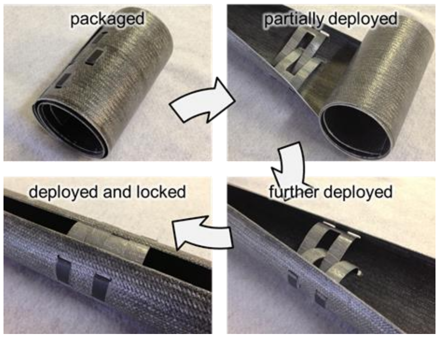


Figure 2: ROCCOR’s Seam-Lock technology
(Patent Pending)

Slit-tube booms are not limited to only single member deployment systems; for large scale structures it is more efficient to add hierarchy into the design. ROCCOR has developed a ROllable Composite-Truss or ROC-Truss technology shown in Figure 3 below. The ROC-Truss is a multi-longeron truss that is able to collapse or flatten into a plane before being rolled for packaging. Upon deployment, body-diagonals (tension members spanning diagonally through the truss cross-section) are utilized to further rigidize the deployed section. The longerons are continuous length (no joints or splices) and the battens and diagonals are axially stiff segments with non-articulating joints that can be bonded or joined under high preload. Each segment (longerons, battens and diagonals) can be made from tailored slit-tubes providing axial and bending stiffness to improve local buckling.

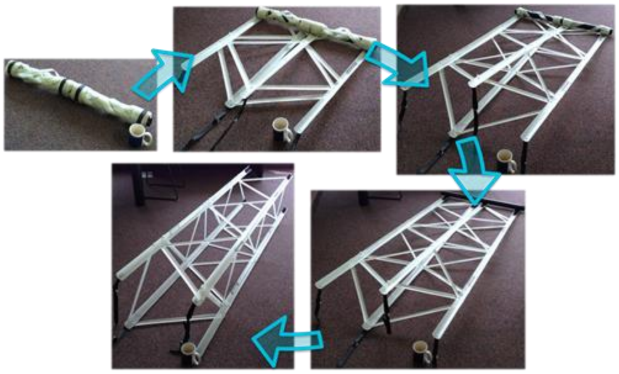


Figure 3: ROC-Truss Prototype (Patent Pending)

Additional Benefits of HSC Slit-Tubes

Beyond the structural improvements and greatly simplified spooling characteristics associated with HSC slit-tubes, there are several additional benefits that enable further spaceflight capability. One such advantage is the ability to design a laminate with a near-zero Coefficient of Thermal Expansion (CTE). Existing slit-tube deployment systems flown in space use metallic members consisting of stainless steel or beryllium-copper. These materials are known to have a significant, unchangeable CTE values; a problem that is exacerbated for very long booms. Many composite materials have very small or even negative CTE properties and can be incorporated into the laminate design to make a structure that is invariant to temperature along the longitudinal axis. As a result a new capability has been created to deploy precision components that do not fluctuate with temperature.

Another benefit of incorporating HSC slit-tubes is the ability to embed electrical wire harnesses inside the material as shown in Figure 4. Existing space qualified slit-tubes are metallic which forces wire harnesses to be either externally pulled-out with a separate device or adhered to the surface of the boom. In the latter case, the adhered wires must have strain relief to avoid wire fatigue during the coiling process and results in significant added complexity, poor packaging efficiency and reduced reliability. In the case of HSCs, the embedded wires can run along the centerline of the boom laminate and hence will experience significantly less strain during the coiling process. In addition, HSC materials can be designed in a way to include the embedded wires without effecting the laminate thickness and hence may not add parasitic packaging width to the coil. A related benefit is the ability to including antennas inside the HSC material.

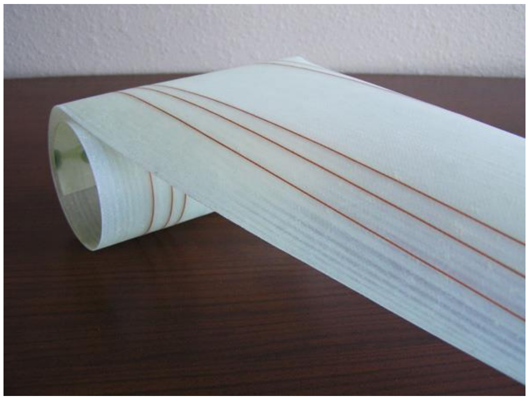


Figure 4: HSC slit-tube with embedded wires

Analysis of HSC Slit-Tubes

A major challenge to analyzing HSC slit-tubes is the prediction of instabilities of long, large diameter systems. Many buckling mode shapes are possible and the particular instability induced is a function of many parameters. Slit-tubes may buckle under typical Euler column buckling modes or due to local buckling of the slit-tube edges. The ROCCOR analytical tools include first-principles and Finite Element Methods (FEM). In the case of FEM, Abaqus and FEMAP/NeNastran which are noted for their composites emphasis are utilized. Both codes can employ Helius: MCT Theory (MultiContinuum Theory which treats the laminate as constituent fibers and matrix instead of a “smeared” stack of plies). This software in conjunction with Classical Laminate Theory (CLT) and empirical correlating parameters has enabled the ROCCOR team to model slit-tubes with a high degree of confidence.

To show the effects of the edge stiffening and Seam-Lock design innovations discussed above, a simple finite element study was done on a standard structure. A 200 inch long slit-tube with a 6 inch diameter and a 0.026 inch thick laminate utilizing [0°/±45°/±45°/0°] IM7 plies (the 0° plies are unidirectional and the ±45° plies are woven fabrics). The tip is unconstrained and has a 100 lb lateral load applied that will put the slit into compression due to bending. The root is optimally constrained with a fixed region at the top (0 degree orientation opposite the slit), two fixed line of nodes at the +90 and -90 degree location to represent an articulating support clamp, and below that region is a radial constraint assuming the slit-tube is preloaded against a cylindrical support bracket. This root configuration presents a challenge for buckling because it forces the thin slit-tube edge to carry compression into the root fitting and often creates a local free-edge buckling mode as shown in Figure 5. Figure 6 shows a substantial increase of the buckling capacity by incorporating a Seam-Lock every 17 inches along the span and utilizing the optimized edge treatments. The Seam-Locks were modeled with 0.020 x 1 inch shallow beam elements with the same laminate properties as the boom. This buckling mode also suggests additional improvements can be made by shortening the Seam-Lock spacing at the root. These improvements combined with other obvious boundary condition and laminate improvements could likely improve the buckling capacity even further.

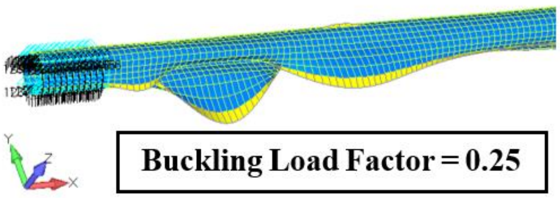


Figure 5: Buckling mode of baseline slit-tube without edge treatment or Seam-Locks. (full mesh not shown)

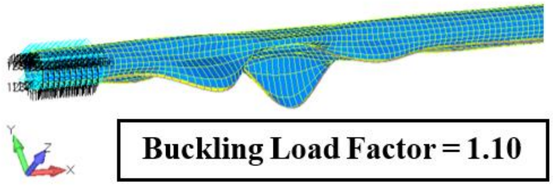


Figure 6: Buckling mode of slit-tube with effective 0.5 inch edge treatment and 11 Seam-Locks along span. (full mesh not shown)

Fabrication of HSC Slit-Tubes

Slit-tube structures undergo relatively high strain levels during packaging and deployment. Consequently, the HSC laminates are very sensitive to manufacturing consistency and quality. The typical aerospace manufacturing goal of obtaining the highest possible fiber volume fraction is not necessarily optimal for slit-tubes since consistency and toughness are primary concerns. Due to the high sensitivity to processing quality, the processing and manufacturing design are key to the success of the design-analysis-optimization loop. At ROCCOR the fabrication technique most commonly utilized is a single vacuum bag process. Here the fiber material is layered onto the mold and a vacuum bag is employed to consolidate the laminate and remove trapped air during the high-temperature oven cure. The matrix is infused into the laminate either via the use of prepreg materials or added through a Vacuum Assisted Resin Transfer Molding (VARTM) process.

Since the vacuum bag consolidates a prepreg-based laminate when it is evacuated, some amount of air is trapped between the compressed plies. To resolve this, ROCCOR is currently implementing a double vacuum bag system shown in Figure 7 below. This process uses an autoclave to evacuate air from the oven volume and vacuum bag simultaneously as a 1st step. Once all air has escaped, the vessel is vented to atmospheric pressure which begins to consolidate the laminate and, finally, pressurized. From this point forward, the process is equivalent to typical autoclave processing. Double-vacuum composite fabrication ensures minimal processing variability necessary for flight articles while the non-autoclave, single vacuum bag processing saves significant time and cost.

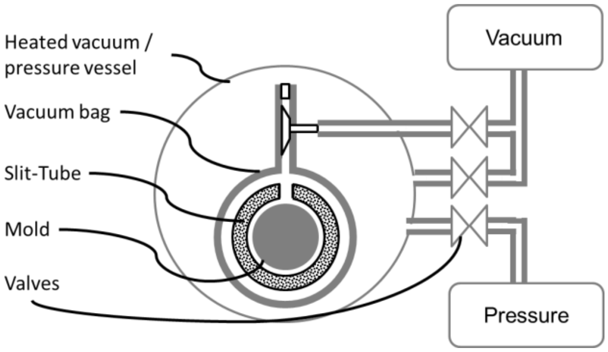
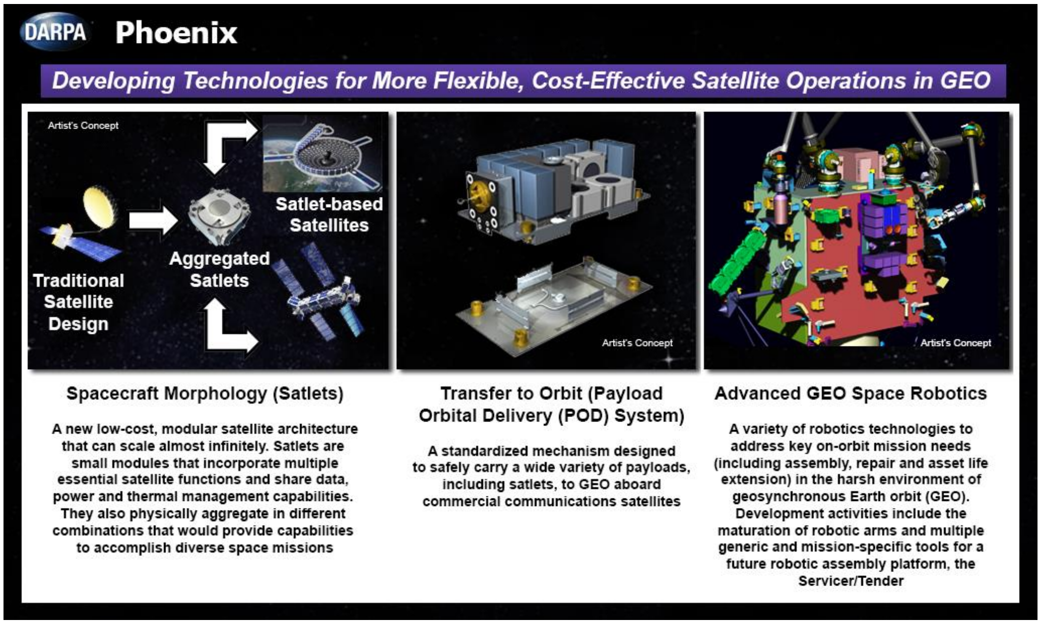


Figure 7: Double Vacuum Chamber Fabrication Process.

THE DARPA PHOENIX CAMPAIGN

The primary goal of the DARPA Phoenix program is to foster on-orbit servicing technologies to enable more flexible and cost-effective geostationary spacecraft. Several tasks identified to fulfill these objectives include: the ability to execute orbital corrections for existing spacecraft, perform inspections and regular maintenance, transport spacecraft components to GEO at a lower cost and assemble new spacecraft in-orbit from small low-cost modular components [6]. The Phoenix program is currently divided into three focus areas with the goal to increase TRL of key technologies; a short review of these efforts are described below and are summarized in Figure 8.



Phoenix

Developing Technologies for More Flexible, Cost-Effective Satellite Operations in GEO

Spacecraft Morphology (Satlets)

A new low-cost, modular satellite architecture that can scale almost infinitely. Satlets are small modules that incorporate multiple essential satellite functions and share data, power and thermal management capabilities. They also physically aggregate in different combinations that would provide capabilities to accomplish diverse space missions

Transfer to Orbit (Payload Orbital Delivery (POD) System)

A standardized mechanism designed to safely carry a wide variety of payloads, including satlets, to GEO aboard commercial communications satellites

Advanced GEO Space Robotics

A variety of robotics technologies to address key on-orbit mission needs (including assembly, repair and asset life extension) in the harsh environment of geosynchronous Earth orbit (GEO). Development activities include the maturation of robotic arms and multiple generic and mission-specific tools for a future robotic assembly platform, the Servicer/Tender

Figure 8: Summary of the three technology areas under development for the DARPA Phoenix Phase II Program. [7]

The first area focuses on changing the morphology of spacecraft from the current monolithic construction method utilizing expensive custom components to a cellular construction of low-cost repeat-units. The repeat-units or cells are termed *Satlets*. Spacecraft are then formed from a series of interconnected Satlet units along with additional hardware components that are harvested from retired geostationary assets. The most central Satlets in the Phoenix program are those that have bus-like functionality. The bus-like Satlets were developed by NovaWurks and are termed *HISats*. Each HISat has a form factor near a 4U cubesat and contains a level of independent functionality to maintain attitude control, power, command & data processing, networked communications and thermal management. Depending on the mission, some HISats perform a dedicated role such as a solar array management or providing system level attitude control. The configurability of these HISats coupled with the ability to harvest retired hardware enables a near infinite collection of Satlet architectures and capability. One configuration previously studied is called the Aperture Satellite, (i.e. ApSat), in which a large antenna reflector from a retired cooperative asset is harvested and repurposed by a series of HISats for high performance communications with the ground.

The second DARPA Phoenix focus area is centered on creating a delivery system of small payloads to geostationary orbit. These devices are integrated into the launch vehicle as secondary payloads utilizing available excess mass and hence are inherently low-cost. The contents of this Payload Orbital Delivery (POD) system includes cargo such as: fuel tanks for resupply, Satlets and an assortment of tools for the on-orbit spacecraft assembly / GEO servicing.

The final DARPA Phoenix focus area is aimed at advanced robotics which will perform a slew of on-orbit activities pertaining to the servicing, refueling, repurposing and assembly of the cellular spacecraft in geostationary orbit. This division involves a series of high dexterity robotic arms working in tandem to perform the servicing needs. The robotic arms are contained within a platform called the *Servicer/Tender* (i.e., S/T) and houses a series of tools (grappling devices, cameras, etc), Satlets and fuel tanks to accomplish its mission. The S/T is capable of moving from one cooperative asset in GEO to another and is designed to function for long duration spaceflight.

Within the Phoenix program, the need for a structural repeat unit, or Satlet to enable the construction of large structures has been identified. One method of assembling large structures using the cellular morphology is to stack HISats like “Legos” to accommodate offset hardware such as solar arrays or cameras. This approach, however, requires a large volume of HISats to construct capable structures. Taking the ApSat mission concept as an example, the size of the reflector array is on the order of several meters in diameter and an efficient structure is required to enable the feed horn offset capability without the Satlet aggregate interfering with the RF transmission. Roccor LLC, and Altius Space Machines of Louisville, Colorado are currently working with the developers of the HISat system to create a variant module called the *HIMast* which contains a deployable slit-tube HSC structure. While maintaining the same volume and some of the electrical functionality as the HISat, the HIMast is capable of extending the slit-tube structure with a prescribed extensional length, precision and stiffness. The HIMast expandable structure enables a new range of cellular morphology spacecraft concepts without wavering from the modular form factor. Several of these architectural concepts are summarized in Table 1 below.

Table 1: Summary of HIMast enabling Satlet architectures.

Science	• Offsetting Sensors (i.e., Magnetometer) • Moiré Optical Support
Power	• Deployable/Retractable Solar Array • Variable Length Radiator
Enabling Devices	• Capture / Rendezvous • Robotic Arm Extension • Camera / Situational Awareness
Attitude Control	• Gravity Gradient Micro-Thruster Moment Arm • De-orbit Device
Comm.	• Yagi Antenna • Dipole Antenna • RF Dish Support Structure

HIMAST CAPABILITIES

The DARPA Phoenix concept utilizes a series of modular HISat and HIMast units to assemble an aggregate spacecraft on-orbit. The grouped set of HISats provides the general functionality of a common spacecraft bus while the HIMast provides a structural element to support components such as solar arrays, radiators, antennas and offset sensory devices. An example of a hypothetical aggregate spacecraft is shown in Figure 9. Each HISat box has a physical envelope of 0.2 × 0.2 × 0.1 meters that roughly corresponds to a 4U cubesat.

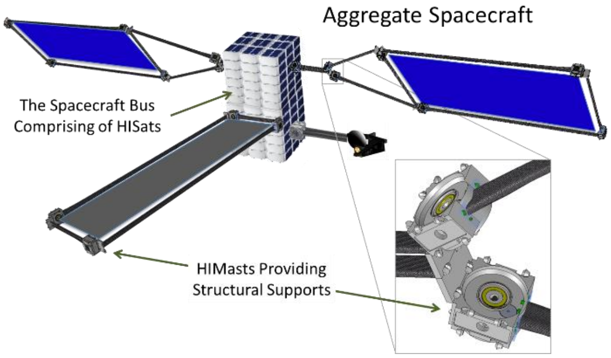


Figure 9: Hypothetical concept of an on-orbit assembled aggregate spacecraft containing both HISats and HIMasts.

HIMast Requirements

The top-level requirements of the HIMast system are to fit within the structural shell of the HISat box and to provide a length adjustable, structural member with a specific stiffness, stability and precision. Based on the HISat mechanical envelope and the needs of the various hypothetical aggregate spacecraft outlined in Table 1, the boom is sized for an extension length of 4.5 meters and an initial deployed positional accuracy of 8cm. Once deployed, the system is designed to have a low, near zero response to changes in temperature and mechanical disturbances such that the combined positional stability is <1cm. In addition the boom is designed to maintain a deployed stiffness greater than 0.13 Hz with a freestanding mass of 20kg offset at the tip axially by 0.25 meters and laterally by 0.1 meters. Finally, the system must contain embedded wires to supply 8 amps at 28 volts to the distal end with a voltage drop less than 5%.

To deploy the HSC slit-tube, the HIMast relies on a rotating mechanical interface provided by the HISat system. This unique feature within the HISat is a universal motor capable of providing mechanical motion to the aggregate spacecraft supporting functions such as HISat layout manipulations, mechanical deployments and solar array tracking. The rotating mechanical interfaces are located along the top and/or bottom surfaces of each HISat, are circular in nature, and are referred to as “carousels”.

HIMast System Design

The leading constraint on the structural design of the slit-tube boom is the undeployed coil size that must fit within the HISat envelope. The coil geometry is dictated by the number of wraps on the spool, which corresponds to the boom length, and the minimum allowable inner coil radius necessary to maintain a neutrally stable HSC structure, which corresponds to the maximum cross sectional diameter of the deployed slit-tube. Given these restrictions, the optimal geometry was found to contain two 180°, 1 inch diameter slit-tubes that are offset by a flat bridge measuring 2.1inches in length as shown in Figure 10. This shape has a similar geometry to a standard ‘C-section’ beam which is commonly used in structural engineering. As an additional advantage, the small diameter of the 180° slit-tubes enables a shorter transition region near the coil which allows a stronger root-support roller interface within the HIMast box. In addition, the bridge section provides ample room to run multiple embedded conductors along the length of the boom.

Figure 10: HIMast HSC test coupon with selected cross sectional geometry

The modularity of the HISat boxes allows the units to be stacked upon each other to increase capability and performance. In the case of the HIMast system, there is a need to stack two units vertically in order to dynamically support the distal end shown in Figure 11. This is driven by the worst case, large lateral offset of the mass at the tip in which a single slit-tube does not have the rigidity to provide adequate stiffness. The dual HIMast system provides a wider footprint for root support and greatly improves the integrity of the structure. The modularity of the HISat boxes also extends to the mechanical rotation which drives the deployment of the slit-tube. As a result the deployment of the conjoined HIMast units are mechanically linked eliminating the need for multiple HISat motors and synchronization methods.

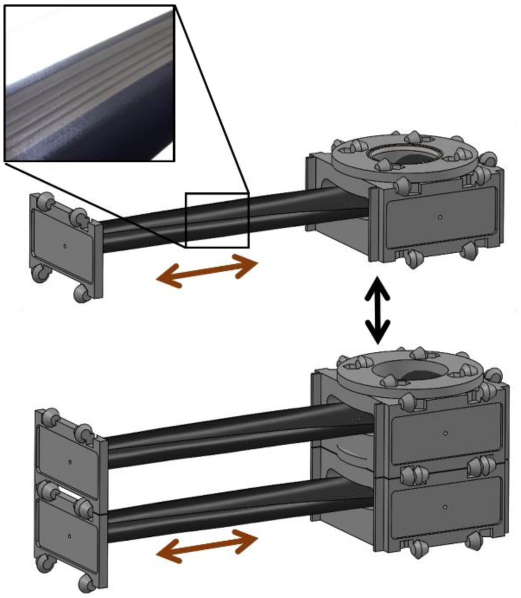


Figure 11: HIMast systems in both the stand-alone and stacked configurations. The embedded electrical conductors are highlighted.

HIMast System Layout and Key Features

The HIMast box consists of three major components, the external structure embodying the HISat shell (supplied by NovaWurks), the HSC slit-tube with supporting rollers along with the drive wheel plus spool/coil assembly (Roccor), and the gear train (Altius Space Machines) which transfers the mechanical input from the HISat to the slit-tube drive wheel and adjacent HIMast boxes. An overview of the HIMast layout is provided in Figure 12 below.

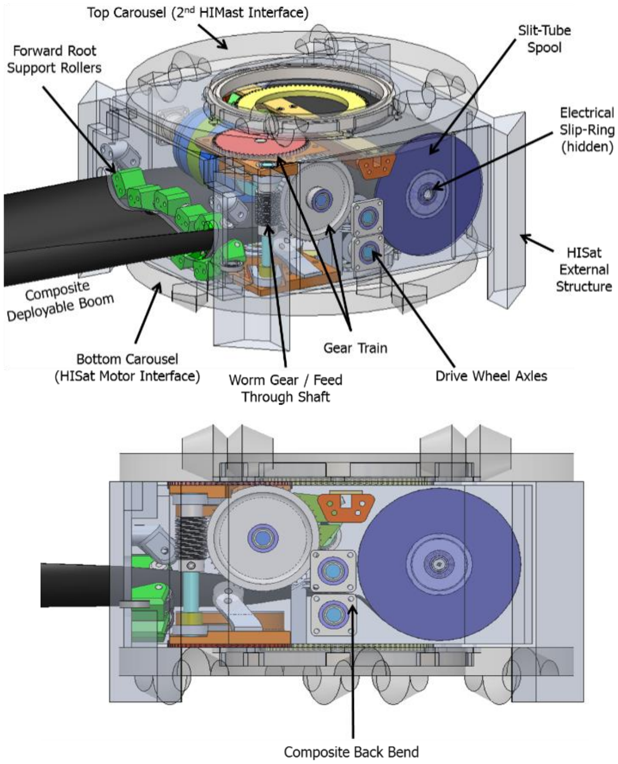


Figure 12: HIMast Layout, dimetric view (top) and side view (bottom).

The external HIMast shell consists of a box with two rotating carousels on the top and bottom surfaces. Three of the four remaining surfaces each contain a removable electronics box which provides basic functionality such as thermal control, command & data handling and an electrical interface to the attached HISat. The remaining surface is the exit port for the slit-tube and meshes with the distal plate in the undeployed configuration. Externally, the HIMast and HISat box both have a series of interlocking features that enable the two to be joined on-orbit in multiple configurations.

Internally, the slit-tube HSC booms extend along the entire length of the HIMast box and coils adjacent to the rear wall. The fully wound coil encompasses the entire height of the available volume and contains an electrical slip-ring interface to connect the embedded wiring harness in the HSC boom with the box electronics. Several series of rollers run along the remaining length of the HSC boom to provide a robust support. An additional function is of the internal rollers is to guide the formation region of the slit-tube and prevent any buckling modes that may appear when not fully shaped. The drive wheel, which functions as the mechanical interface enabling the slit-tube deployment, is located next to the spool. Due to the limited volume and the desire to allow the slit-tube to exit the box in a perpendicular direction, the HSC material is back-bent (i.e., reverse or opposite sense bent) as it comes off the spool. This creates new design parameters on the HSC boom to ensure that the strain limits are not exceeded and that the material does not creep.

The gear train connects the two rotating carousels on the top and bottom surfaces of the HIMast via a feed through shaft that is located along the front corner of the box. This shaft interfaces with the drive wheel axle and incorporates a worm gear as a passive axial mechanical-brake within the system. In addition, the gear train is designed to include an optional electro-mechanical clutch which gives the ability to disconnect the gear trains of two conjoined HIMast units for fine tune tip adjustments and pointing.

CONCLUSION

In this paper the utility of using High Strain Composite (HSC) slit-tubes was described as an alternative to metallic-based systems. The benefits stemming from this improved technology was outlined to include better structural performance, mechanical simplicity and reduced volume of the deployer system. In addition, new applications pertaining to this technology were introduced such as the ability to tailor the laminate properties to be invariant to large changes in temperature or the ability to embed electrical conductors and antennas directly into the material. This innovative technology was discussed in the context of enabling higher performing deployment devices within spacecraft with a focus on the small satellite community that depends on miniaturized and simplistic devices.

This paper also described the efforts of the DARPA Phoenix program that is supporting the development of a HSC slit-tube boom for an upcoming aggregate spacecraft mission. Currently, a 4.5 meter HSC slit-tube boom deployment system is under development and expected to be completed for ground testing by the end of 2014. This effort to build large scale booms within small packages empowers the space community to design more sophisticated and technological innovative spacecraft.

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