52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference<BR> 19th
4 - 7 April 2011, Denver, Colorado

AIAA 2011-1731

# Design and analysis of a meter-class CubeSat boom with a motor-less deployment by bi-stable tape springs

Sungeun K. Jeon*

*CSA Engineering, Albuquerque, NM, USA*

Thomas W. Murphey†

*Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, NM, USA*

**The increasing demand for greater CubeSat mission capabilities has led to the need for more complex deployable mechanisms within the limited packaged volume. This paper presents a meter-class deployable boom featuring a single burn wire release mechanism and motor-less deployment actuation by the stored strain energy of bi-stable tape springs. Bi-stable tape springs are rolled about two independently rotating central hubs, where the unique and controlled release of strain energy unrolls the hubs and drives boom deployment linearly outward with a nearly constant torque. At the end of deployment, the tape springs lock-out to remove the deployment degree of freedom from the structure while providing structural stiffness, derived from the two inwardly facing and offset bi-stable tape springs, spanning from end to end. The presented device has stowed dimensions measuring 5.0cm by 3.8cm by 3.8cm, well within the packaging requirements of a 1-U CubeSat. The mechanical design and deployment properties are investigated and presented.**



## Nomenclature

| | |
|---|---|
| $A$,$B$,$D$ | Laminate $ABD$ matrices |
| $R$ | Radius of tape spring cross-section |
| $\beta$ | Arc angle of tape spring cross-section |
| $\kappa$ | Principal curvature |
| $U$ | Strain energy |
| $\theta$ | Hub rotation magnitude |
| $L$ | Length of tape spring |
| $\tau$ | Deployment torque about hub |
| $F$ | Deployment axial force |

*Subscripts*

| | |
|---|---|
| $s$ | Secondary Stable State |
| $h$ | Hub |
| $r$ | Roll |

## I. Introduction

In recent times, CubeSats and other nano-satellites have been continually garnering interest due to their low-cost, low-profile ability to be used as an experimental and research platform for industry, military, and academia. As a result, the demand for greater capabilities within their limited packaged volume has led to the need for highly compact deployment mechanisms to allow for more on-board power collection, larger antennas, and longer booms.

*Project Engineer, CSA Engineering, 1451 Innovation Pkwy Suite 100, Albuquerque, NM 87123, and AIAA Member.
†Lead Engineer, AFRL/RVSV, 3550 Aberdeen Ave. SE, Albuquerque, NM 87117, and AIAA Associate Fellow.

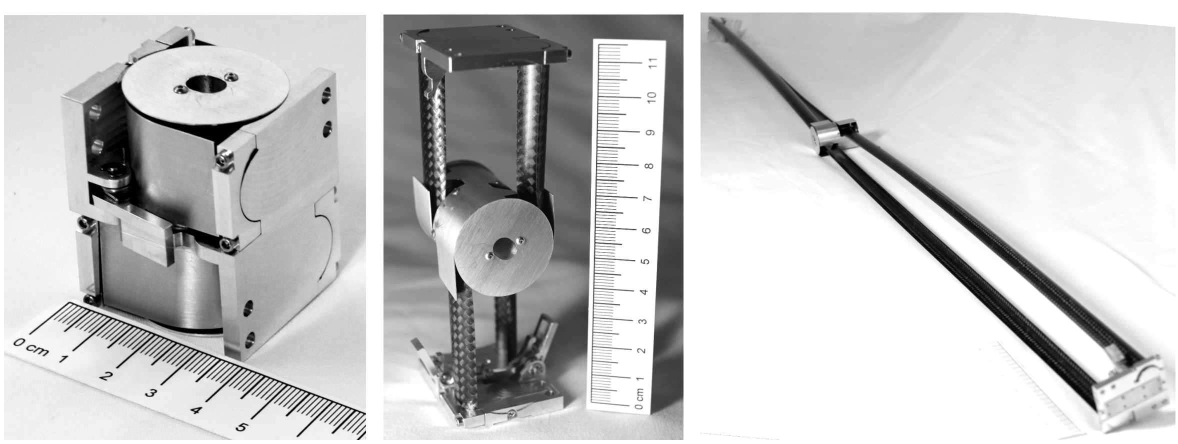
Due to their packaged volume efficiency, strain energy-based deployment devices have been commonly the focus of current research in deployable mechanisms for CubeSats. An example for a deployable antenna would consist of coiled rod or folded solar panels with spring-loaded hinges.[1 2] In many cases, the deployment mechanisms involve large kinematic, unconstrained rotations when deployed, leading to risk of spacecraft strike-back[3] and imparting rotational energy to the spacecraft.

For a more controlled deployment, linearly deployed booms, commonly used in the large deployable space structures, is the Storable Tubular Extendible Mast (STEM).[4] This structure uses a motorized reel mechanism to roll a highly stressed metal or composite ribbon that once deployed, overlaps itself and forms a tube, which is its stress-free state. However, in the stowed configuration, the highly stressed ribbon stores a significant amount of strain energy and outwardly applies pressure against a substantial containment device to constrain the unstable roll, also known as blooming. In addition, deployment must be controlled and mechanized to limit the release of strain energy and prevent damage to the spacecraft. Both the substantial containment and corresponding deployment mechanisms may prove to be too large and cumbersome for use in nano-satellites.

This research presents a *s*elf-contained l*i*near *m*eter-class de*p*loyab*le* (SIMPLE) boom with a motor-less self-deployment by the unique controlled strain energy release of bi-stable tape springs. The presented boom design has a deployed length of 1-meter with highly compact stowed dimensions of $5cm$ by $3.8cm$ by $3.8cm$, for a total stowed volume of $72cm^3$, and only requires a single burn-wire to release and initiate deployment. The deployment actuation is effectively constant force, separating the two spacecraft end masses linearly in opposite directions with little to no rotational energy imparted to the overall system and with a low risk of strike-back.

The presented boom is highly compact due to its application of composite bi-stable tape springs to act simultaneously as the deployment mechanism and deployed structural element, while not requiring a stowed constraint mechanism. Bi-stable tape springs has the unique property of having two stable states, and, most significantly, the stored strain energy is only released in the transition between stable states. This transitional strain energy release allows for a nearly constant, deterministic source of deployment energy. Also, due to the two stable states, bi-stable tape springs avoid the use of a substantial containment and deployment mechanism by being self-contained in a higher energy stable state. For the SIMPLE boom, the tape springs are designed to have the high strain energy state in a rolled cylindrical configuration and the low or zero-energy state in a straight structural tape spring configuration. The boom consists of two concentric, counter-rotating cylinders, each with two bi-stable tape springs wrapped about them. Only a light-weight shroud is required to assist in guiding the unrolling of the the tape springs during deployment.

## II. Mechanical Design



(a) Stowed configuration (b) Initial Deployment (c) Deployed configuration

**Figure 1. General dimensions of the SIMPLE boom.**

The SIMPLE boom has a packaged dimensions of $5.0cm \times 3.8cm \times 3.8cm$, as shown in Figure 1(a) and a measured mass of $86gm$, well within the one liter volume and 1kg mass requirements of a 1-U CubeSat.

In the deployed state, the boom measures 1 meter in length and the end plates rotate roughly 35° relative to each other, as shown in Figure 1(c). The 35° relative end rotation is due to the change in roll diameter from the stowed state to the deployed state.

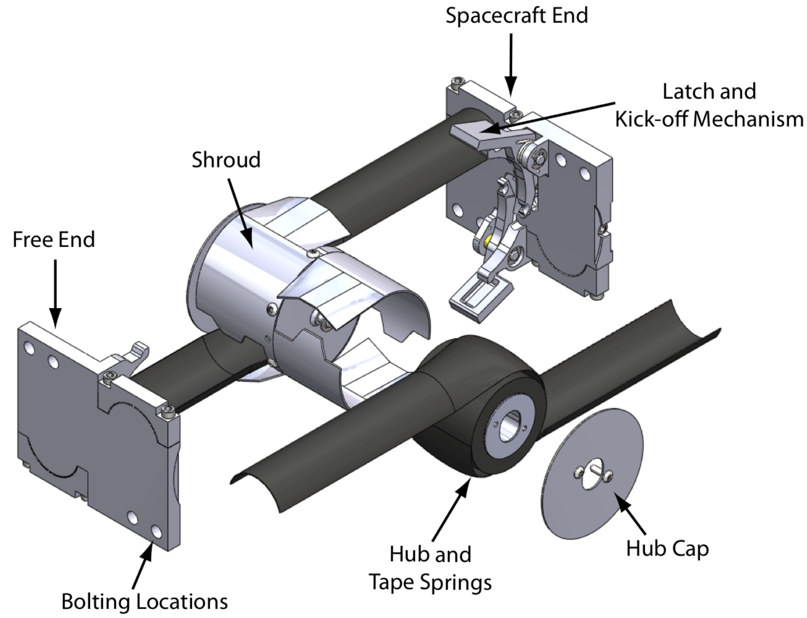



**Figure 2. Exploded hub view of the SIMPLE boom in initial stages of deployment.**

Figure 2 illustrates and identifies the major components of the device, consisting of two end-plates and a central spool, each spanned by two inwardly facing and offset bi-stable tape springs. The spacecraft end-plate features a spring-loaded latch, designed to interface the free end-plate about the central spool and securing the three major components to each other, while providing structural rigidity to the stowed configuration. The latch arms hinges near the base of the end-plate and are actively preloaded with an unlatching force by torsional springs. The latch arms continue to extend beyond the hinge and through the underside of the spacecraft end-plate, where they are restrained by a single nylon monofilament line with a burn wire release mechanism. To assist in overcoming initial deployment friction, the latch lower arm extensions also act as a kick-off mechanism, continuing to rotate and contacting the central spool, once the latch successfully releases. To further reduce internal friction, the internal components of the central spool are coated with a dry-film lubricant. The central spool consists of a rigid center plate and a shaft with two independently rotating hubs attached on both ends. On each hub, two bi-stable tape springs are wrapped about and affixed to the hub, where the tape spring ends are oriented to deploy in opposing directions. A light-weight shroud, bolted about the circumference of the center plate, and two hub caps act as guides to ensure a linear deployment by constraining the relative movements of the tape springs. Finally, there are four bolting locations on each end-plate, positioned to allow mounting the device to the spacecraft after it has been stowed, latched, and armed.

From the stowed state, the deployment sequence begins when the spacecraft initiates release by activating a burn wire to sever the nylon monofilament line restraining the latch. The two latch arms rotate to release the free end-plate and central spool, then continuing to rotate, kicking off the central spool from the spacecraft end-plate. The bi-stable tape springs unroll, releasing their stored strain energy in a controlled manner due to their unique properties, and push the end-plates and spacecraft masses linearly apart. At the end of deployment, the bi-stable tape springs lock out at the hubs, effectively removing the rotational degree of freedom of the hubs from the deployed structure. The four bi-stable tape springs, two about each hub, now structurally act as two long tape springs with the central spool out of the deployed load path.

The SIMPLE boom bi-stable tape springs are stowed with an initial transition between the two stable states. Each of the bi-stable tape spring ends are clamped to the end-plates in their lower strain energy state, providing the initial transition, while the rest of the tape springs are rolled about the hubs in their higher strain energy state. Hence, once the SIMPLE boom is unlatched, the boom will have an immediate deployment force. By kinematics and the clamped end conditions, the four bi-stable tape springs simultaneously unroll to provide a nearly constant torque about the hubs, pushing the end-plates outward. In addition, the counter-rotation of the co-axial, unrolling hubs cancel out and minimizes the rotational energy imparted to the overall spacecraft.

The SIMPLE boom is simple by design and does not feature a damping mechanism to restrict deployment velocity, except for the already existing internal friction and material hysteresis in the tape spring. Since deployment is not controlled, the velocity of the deploying ends of the spacecraft may continually accelerate and suddenly stop when deployment completes. The impact may lead to a risk for boom failure or spacecraft damage. However, in the following section, the deployment force produced by the bi-stable tape springs may be tuned to mitigate impact risks and reduce deployment velocity.

## III. Bi-Stable Tape Spring Model

The properties of bi-stable tape springs have been studied in-depth, such as investigating the behavior and construction when composed of isotropic materials[5] and composite materials. Composite bi-stable tape springs have shown to be versatile due to the freedom of creating unique laminate layups by pre-stressing layers and creating neutral bi-stability[6].[7] Galletly[89] and Guest[10] investigate the boundary effects and twisting behavior of bi-stable tape springs and alternative laminate layups, not captured by other models. In this research, the bi-stable tape springs used in the SIMPLE boom consist of a single layer of a plain-weave, carbon-fiber fabric, cured at a 45° bias relative to the major axes of the tape spring. The plain-weave fabric is balanced and does not exhibit any twisting deformation modes. Hence, the fabric is modeled as an equivalent, anti-symmetric unidirectional-ply laminate by Naik,[11] for which the model by Pellegrino[12] is applicable.

A closed-form strain energy solution for fiber reinforced plastic (FRP) bi-stable springs, by Pellegrino, assumes that the bi-stable behavior stems from the interaction between in-plane orthogonal bending of the laminate. Classical laminate theory[13] shows for certain laminate layups the laminate $ABD$ matrices, bending and twisting are decoupled. Furthermore, the strain energy of the bi-stable tape springs can be approximated by assuming flat laminate plate theory applies to an initially curved tape spring and enforcing curvatures, defined by Figure 3. The model assumes a uniform distribution of internal forces and edge effects are ignored. The strain energy is computed by enforcing $k_x$ and $k_y$ curvatures and ignores twisting of the tape spring. The initial condition has zero-strain and is defined by cross-section radius $R$ and cross-sectional arc angle $\beta$.

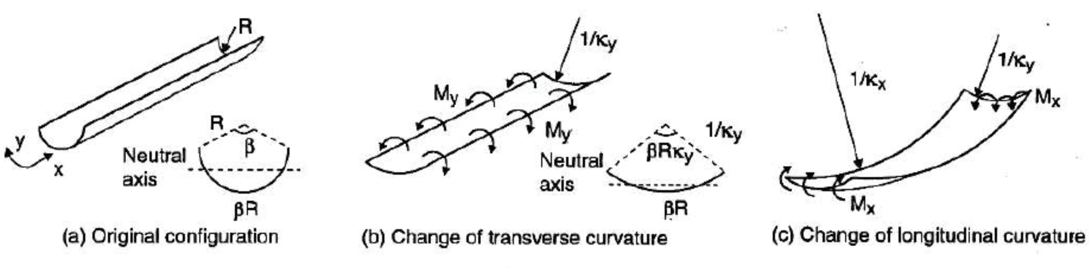



**Figure 3. Orthogonal bending definition of a cylindrical shell (Pellegrino)**

Eq.1 and Eq.2 define the stored strain energy per unit length in a bi-stable tape spring by flattening and wrapping, respectively. The total stored strain energy per unit length of a bi-stable tape spring is defined in Eq. 3, by applying superposition.

$$\frac{dU_x}{dL} = \frac{1}{2}\beta R\left[D_{11}\kappa_x^2 + 2D_{12}\kappa_x(\kappa_y - \frac{1}{R}) + D_{22}(\kappa_y - \frac{1}{R})^2\right] \tag{1}$$

$$\frac{dU_y}{dL} = \frac{A_{11}}{2}\left[\frac{\beta R}{2}\left(\frac{\kappa_x^2}{\kappa_y^2}\right) + \frac{\sin(\beta R\kappa_y)}{2}\left(\frac{\kappa_x^2}{\kappa_y^3}\right) - \frac{4\sin^2(\beta R\kappa_y/2)}{\beta R}\left(\frac{\kappa_x^2}{\kappa_y^4}\right)\right] \tag{2}$$

$$\frac{dU}{dL} = \frac{dU_x}{dL} + \frac{dU_y}{dL} \tag{3}$$

Expanding on the strain energy model, the gradient vector field of the strain energy equation Eq.3 is computed by the partial derivative in terms of the orthogonal curvatures, shown in Eqs. 4 and 5. The gradient equations may used to compute the minimum strain energy path between stable states, assuming the coupling of internal forces along the length are negligible, as well as, leading to other useful insights of the mechanics of the SIMPLE boom, which is discussed later.

$$\frac{\partial}{\partial k_x}\frac{dU}{dL} = -\beta D_{12} + \beta R(D_{11}k_x + D_{12}k_y) + \frac{A_{11}}{2}\left[\frac{\beta R k_x}{k_y^2} + \frac{k_x \sin(\beta R k_y)}{k_y^3} - \frac{2k_x \sin^2(\beta R k_y/2)}{\beta R k_y^4}\right] \tag{4}$$

$$\frac{\partial}{\partial k_y}\frac{dU}{dL} = -\beta D_{22} + \beta R(D_{12}k_x + D_{22}k_y) + \frac{A_{11}}{4}\left[\frac{\beta R k_x^2(\cos(\beta R k_y) - 2)}{k_y^3} - \frac{7k_x^2 \sin(\beta R k_y)}{k_y^4}\right] \tag{5}$$

The secondary stable configuration of a bi-stable tape spring exists at a clear local strain energy minimum when $k_y \to 0$. A closed form strain energy solution may be computed for the location of the secondary stability configuration by solving where the gradient vector is zero in the area of interest, or when Eq.4 and Eq.5 are both zero near $k_y = 0$. While a closed-form solution is difficult as stated, small angle approximations may be applied to Eq.4, since $k_y \to 0$, resulting in Eq.6.

$$\frac{\partial}{\partial k_x}\frac{dU}{dL} = \frac{\beta}{2R}\Big(D_{22}(k_y R - 1)^2 + k_x R\big(D_{11}k_x R + 2D_{12}(k_y R - 1)\big)\Big) \tag{6}$$

Solving for the zero gradient in terms of $k_x$ and setting $k_y = 0$, Eq.6 reduces to the simple expression in Eq.7, where $k_{xs}$ is the x-curvature at the secondary stable state.

$$k_{xs} = \frac{1}{R}\frac{D_{12}}{D_{11}} \tag{7}$$

Eq.7 provides a quick estimation to determine the secondary stable state roll radius. The solution also states that, for the same laminate properties, the secondary stable curvature is linearly related to the initial tape spring curvature, and is independent of the cross-sectional arclength, $\beta$. In addition, the ratio of the initial and secondary stable state curvatures may be changed by adjusting the ratio of the laminate bending stiffness properties, $D_{12}$ and $D_{11}$. This would be useful for cases such as, if a tape spring design requires a larger initial deployed radius and a smaller secondary rolled radius for packaging requirements, or vice versa. The ratio of the laminate bending stiffness properties may be changed by using different fiber types, resin systems, or creative laminate layups.

The strain energy per unit length at the secondary stable state solution is simply computed by applying $k_{xs}$ and $ky = 0$ to Eq.3, resulting in Eq.8. The equation shows a simple linear and inverse relationship with the cross-section arc angle and the tape spring initial radius, respectively, and a dependency only with the laminate bending stiffness parameters.

$$\frac{dU_{xs}}{dL} = \frac{\beta}{2R}\left(D_{22} - \frac{D_{12}^2}{D_{11}}\right) \tag{8}$$

With the secondary stable state strain energy solution, an expected ideal deployment torque of a SIMPLE boom design may be estimated by the following logic. Neglecting factors such as friction losses and composite creep and hysteresis, the net strain energy released during deployment must equal the work performed on the spacecraft. During deployment, the bi-stable tape spring unrolls in a controlled manner from the rolled state to tape spring boom state with a transitional section between states. If the transitional section is assumed consistent throughout deployment, the net strain energy in this section does not change, because the entire piece-wise length of tape spring must pass through the strain energy saddle point from the secondary stable state at any given point of the deployment. Since the deployment work on the spacecraft is performed by the rotation and unrolling of the bi-stable tape springs, the stored strain energy at a stable rolled state $U_r$ and deployment torque $\tau_r$ may be directly related by Eq.9, where the initial stable state is assumed zero strain.

$$W = U_r = \tau_r \theta \tag{9}$$

Substituting the tape spring length $L$ and roll radius $R_r$ for $\theta$, the partial derivative in terms of the tape spring length results in Eq.10, and written in terms of the expected ideal deployment torque of a bi-stable tape spring in Eq.11. For the SIMPLE boom, the expect deployment torque is computed by Eq.11 and multiplying by the number of bi-stable tape springs actuating the deployment.

$$\frac{dU_r}{dL} = \frac{\partial}{\partial L}\left(\frac{\tau_r L}{R_r}\right) \tag{10}$$

$$\tau_r = R_r \frac{dU}{dL} \tag{11}$$

Furthermore, the ideal deployment separation force $F_r$ provided by a single bi-stable tape spring may be estimated by the same logic. If the moment arm is equal to the roll radius, Eq.11 reduces to Eq.12. This relationship is also independently concluded to by Murphey.[14]

$$F_r = \frac{dU_r}{dL} \tag{12}$$

In the SIMPLE boom, the two bi-stable tape springs, each $0.5m$ in length with a finite thickness, are rolled about each of the two hubs of fixed diameter. When the bi-stable tape spring are rolled about themselves, the $k_x$ curvature reduces with the outer roll size, where the strain energy of these outer layers no longer exist at the secondary stable state. Figure 5 illustrates the strain energy distribution of the SIMPLE boom bi-stable tape spring. The strain energy well near the secondary stable state is elongated along the $k_x$ axis, with a gradient toward the secondary stable state. This indicates that, when in a bi-stable tape spring is rolled about itself and $k_x \leq k_{xs}$, the roll is self-contained and stable. Unlike STEM booms, bi-stable tape springs will not bloom when simply rolled about a hub and does not require a substantial containment or deployment device to constrain the strain energy. For a more accurate computation of the expected deployment force and torque of these outer roll layers, the strain energy per unit length in Eq.3 should be calculated in terms of the outer roll curvatures for Eq.11 and Eq.12.

The increasing roll radius with deployed boom length also indicates tape spring length is finite. In Figure 5, the path of minimum strain energy eventually departs from the x-axis near the transition saddle point. This results in an unstable roll, where the outer layers begin to prefer a doubly curved shape and show signs of warping. Figure 4 illustrates the progression of roll warping, from a stable roll, the initial onset of instability, and a fully unstable roll. The fully unstable roll, which is taped down for the illustration, exhibits a buckled roll shape, a tendency for blooming, and is no longer self-contained.

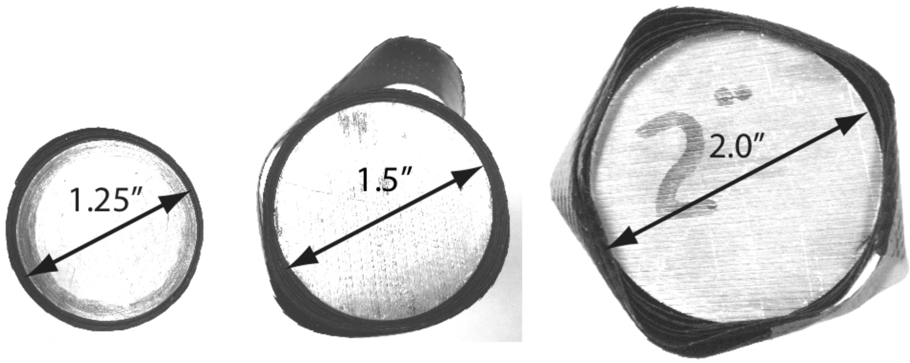



**Figure 4. Wrap instability of bi-stable tape spring about cylinders of varying radii.**

The roll radius $R_r$ of the tape spring may be expressed by an Archimedes spiral approximation, shown in Eq.13, where $R_h$ is the radius of the hub. Eq.13 may also be used to calculate deployed length in terms of packaging requirements. For the SIMPLE boom, the tape spring thickness $t$ would effectively be doubled since there are two tape springs rolled about one hub.

$$R_r = \frac{1}{k_{xr}} = \sqrt{\frac{Lt}{\pi} + R_h^2} \tag{13}$$

Due to the free deployment of the SIMPLE boom, the inertial impact at the end of deployment can cause damage to spacecraft components or cause boom failure. Tape spring designs must concurrently provide adequate deployment force, while limiting the velocity at the end of deployment to prevent spacecraft damage. If the total strain energy stored in the bi-stable tape springs ideally performs work on the mass of the deploying spacecraft $m_{sc}$, then the deployment velocity $v$ may be computed by a kinetic and potential energy relation. The total strain stored in a bi-stable tape spring may be computed by substituting roll radius equation, Eq.13, into the strain energy equation, Eq.3, applying $k_y \to 0$, and integrating over the length. Then, the deployment velocity may be estimated by the classical mechanics kinetic energy equation, assuming the strain energy released performs work only on the end masses and the tape spring and central spool assembly are small in comparison.

## IV. SIMPLE Boom Analysis

The SIMPLE boom bi-stable tape springs are constructed with single-ply, plain weave CFRP fabric at a 45° bias. The pre-preg fabric is supplied by Patz Materials & Technology with a 36.8% resin content and is composed of a 6k tow T300 carbon fiber plain weave fabric with PMT-7 toughened $350°F$ epoxy. The fabric is cured on a $0.25in$ cross-sectional radius cylindrical mandrel and trimmed to a cross-sectional arc angle of 180°. The maximum cured thickness is approximately $0.009in$.

An analytical method, by Naik, is used to model the laminate properties of the composite fabric. The method approximates the material properties of a plain weave fabric composite to an equivalent classical cross-ply laminate plate by a thickness scalar, which is computed by modeling the micro-mechanics of a one-quarter, symmetric, uniformly distributed weave unit cell. The undulation curvatures of the warp and fill yarns are modeled by a sinusoidal shape function, and the yarn cross-sections are assumed to have a quasi-elliptical shape. Fabric gaps and weave height are also included as parameters in the model. Naik successfully shows that his plain weave model is in good experimental agreement with various types of single-ply plain weave composites.[15] Table 1 display the bi-stable tape spring laminate properties computed by the Naik analytical method in terms of the bi-stable tape spring model coordinate frame.

**Table 1. Bi-stable tape spring laminate properties**

| Naik Plain Weave Equivalent Laminate Properties | |
|---|---|
| $E_x$ | 10.53 GPa |
| $E_y$ | 10.53 GPa |
| $\nu_{xy}$ | 0.87 |
| $G_{xy}$ | 38.2 GPa |
| Equivalent Layup | [-45 45 -45 45] |
| Equivalent Thickness Scalar | 0.64 |

Figure 5 illustrates the contour plots of the strain energy per unit length of the CFRP bi-stable tape springs in the SIMPLE boom. The two elongated and deep strain energy wells along each curvature axis and a high energy saddle point relative to the energy wells indicate two prominent, stable configurations at the boom radius of $6.4mm$ and roll radius of $7.3mm$, as computed by Eq.7. This implies a bi-stable tape spring design that is strongly prefers to be in either the elongated boom or the rolled configurations.

The secondary stable rolled configuration has a minimum strain energy per unit length of $0.63Nm/m$, as computed by Eq.8. From this state, given the opportunity, the bi-stable tape spring will move toward the elongated boom state with zero strain energy along the path of minimum strain energy, as shown in Figure 5, assuming the interaction of internal forces along the transitioning length of the tape spring are neglected.

The presented SIMPLE boom design has an estimated ideal deployment torque output of 17.2 m$Nm$ total, with 4.3 m$Nm$ torque contribution from each of the four tape springs, computed by Eq.11 at $k_{xs}$. This deployment torque translates to a consistent $2.7N$ separation force of the spacecraft end masses, sufficient to ensure the deployment of the boom and to minimize inertial loads at the end of deployment. By the more complete model and accounting for increasing roll radius with length, Figure 6 shows the total predicted separation force over the deployment of the SIMPLE boom. The separation force is at a peak at the beginning of deployment with a maximum force of $3.46N$ and steadily decreases to $2.7N$ at the end of deployment, when $k_x = k_{xs}$.

The bi-stable tape spring roll of the SIMPLE boom begins to depart the $k_x$ axes at a curvature of

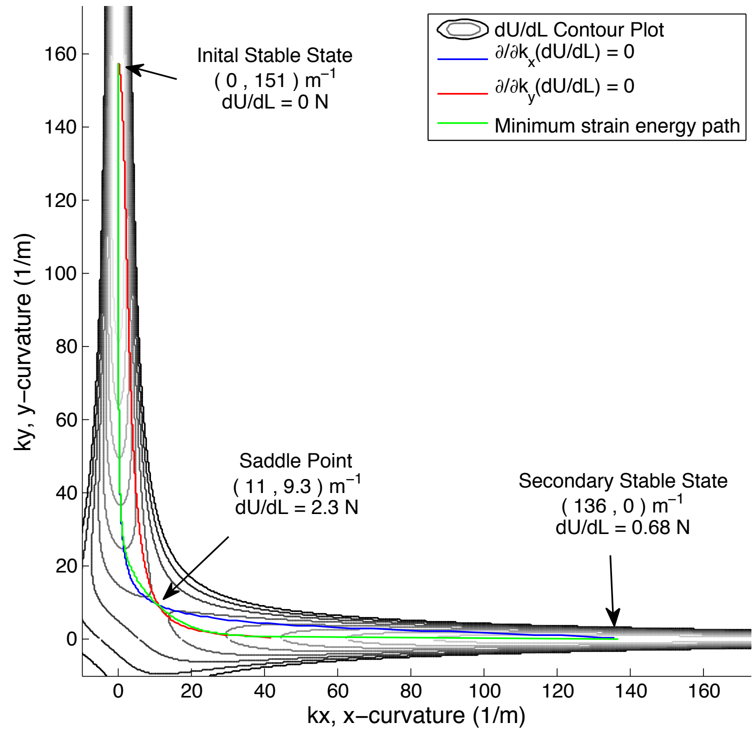



**Figure 5. Strain energy per unit length of a single SIMPLE boom bi-stable tape spring.**

approximately $40m^{-1}$, which translates to a maximum roll diameter of $2in$. Figure 4 shows the roll instability of the SIMPLE boom bi-stable tape spring. At a $1.5in$ roll diameter, or $52.5m^{-1}$ $k_x$-curvature, the onset of roll instability begins to manifest, particularly if the roll is relatively loosely wrapped and the imperfections in the tape spring cause a small degree of roll warping. At $2in$ roll diameter, the roll instability is fully realized and disallows the use of this particular bi-stable tape spring design from being implemented into the SIMPLE beyond this roll diameter.

Hence, from Eq.13, the presented SIMPLE boom tape spring has a conservative maximum roll radius of roughly $2.0cm$ and a maximum feasible boom length of $4.6m$. To reach the maximum feasible boom length, two dimensions of the stowed boom packaging would approximately double to accommodate the larger rolls, and the deployed axial rotation of the ends would increase due to the increase in change of stowed and deployed roll radii. As demonstrated, the SIMPLE boom can feasibly reach lengths well over a meter. With thinner laminates and different layups, longer booms may be designed, but at the potential cost of reduced deployed structural stiffness and deployment energy.

## V. SIMPLE Boom Experiments

Figure 7 illustrates a simple experiment to validate the bi-stable tape moment and laminate models. A bi-stable tape spring is folded to become parallel with itself, where a clamped weight is attached to the free end. The location of the bend is moved relative to the weight until the bending moment at the bend freely supports the weight. The distance from the bend to the weight is then measured. To mitigate errors, several measurements along the length of the tape springs with varying end masses from $50gm$ to $200gm$ were taken.

At the imaginary cut of the bend, the internal beam forces must be related to the supported weight by static equilibrium. Internal shear forces become zero, the internal axial force must be equal to the supported weight, and the bending moment is related by the moment arm of the supported weight. Since the internal shear force in the bend is approximately zero or small, the influence of in-plane bending stiffness of the flattened bend will not significantly affect the experiment. By symmetry, the internal forces of the lower tape spring also should not significantly influence the experiment either. Therefore, the measured moment is approximately equal to the release of strain energy of the bi-stable tape spring transitional length between

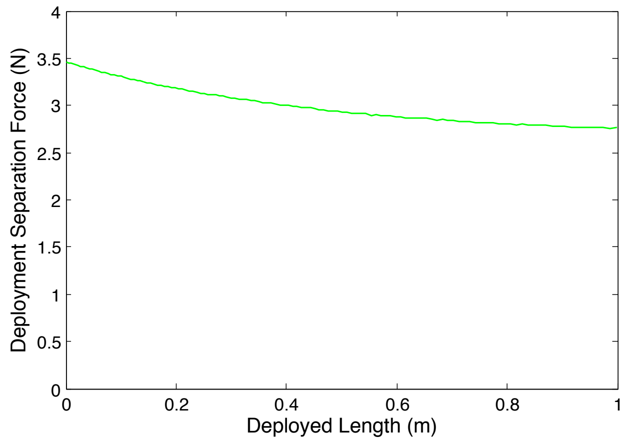



**Figure 6. Predicted total ideal separation force over SIMPLE boom deployment.**

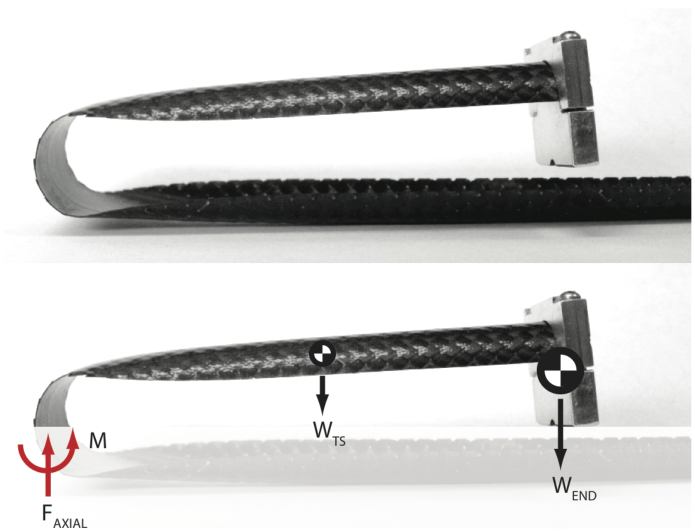



**Figure 7. Bi-stable tape spring moment experiment.**



stable states, or the approximate deployment moment.

Three bi-stable tape spring designs with identical geometry but differing material and layups were studied: the presented SIMPLE boom tape spring, a bi-stable tape spring with 0° bias S2-glass unidirectional tape with 45° bias Astroquartz plain-weave fabric upper and lower layers, and a bi-stable tape spring with two 45° bias S2-glass plain-weave fabrics and a nano-silica loaded epoxy resin. All pre-preg materials were supplied by Patz Materials & Technology with a $350°F$ toughened epoxy.

Table 2 shows the results of the bi-stable tape spring moment experiment. The results have good agreement with the measured and calculated moment of both plain-weave specimens by the Naik laminate approximation model. For the S2-glass unitape laminate, the results showed classical laminate theory had better agreement. The Naik plain-weave laminate model does not account for multiple laminate layers. However, these results suggest overall that the Naik model provides a lower bound on calculated deployment moment, while classical laminate theory provides an upper bound.

Another simple experiment has been performed to determine the extensional force during deployment of the SIMPLE boom. The SIMPLE boom ends were affixed the base and crosshead of an Instron tensile testing machine with a load cell in-line with the crosshead. The crosshead was jogged to initiate vertical deployment with gravity, and the force exerted on the crosshead was measured. By force balance and the mechanics of the boom, the measured crosshead force must be equal to the deployment separation force

**Table 2. Bi-stable tape spring moment experiment results**

| Tape Spring Design | Number of Measurements | Moment ($mNm$) Measured | Naik | Laminate Theory |
|---|---|---|---|---|
| Simple Boom CFRP Tape Spring | 12 | $4.8 \pm 0.55$ | 4.3 | 16 |
| Astroquartz Plain-Weave and S2 Unitape | 12 | $18 \pm 1.1$ | 7.5 | 15 |
| S2 Plain-Weave with Nano-silica Loaded Epoxy | 14 | $15 \pm 1.2$ | 11 | 41 |

minus the supported weight of the boom, $0.61N$ for end plate and central spool assemblies. In Figure 8, the experimental results shows a steady and consistent extensional force over the limited range of the experiment with a force of $-0.11 \pm 0.085N$. Therefore, the estimated separation force of the SIMPLE boom is $0.5N$.

The measured separation force is one fifth of the ideal force calculated earlier. The experimental results suggests that internal friction losses from the deployment mechanism is substantial compared to the released strain energy of the tape springs. However, since the strain energy primarily held in shear, rather than along the fibers of the composite laminate, qualitative observations of the bi-stable tape springs also suggest material hysteresis and creep of the composite resins may significantly contribute to the deployment mechanism losses. Although the experiment is rudimentary, the data is consistent through the recorded ranges of all three experimental runs and indicates that the presented SIMPLE boom design will deploy.

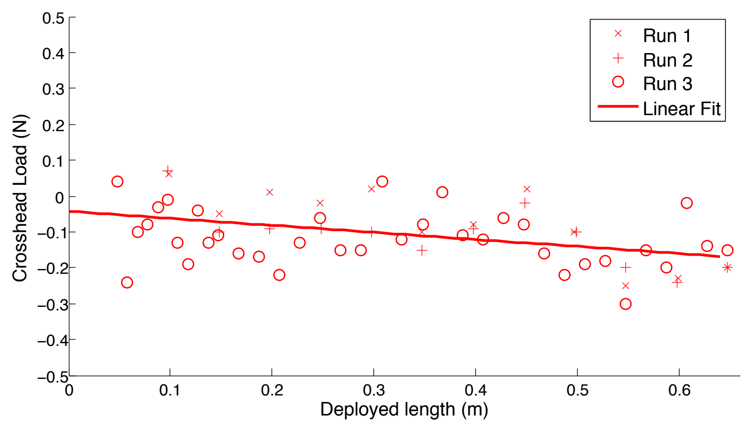



**Figure 8. Experimental data of SIMPLE boom extensional force vs. deployed length.**

# VI. Conclusion

This research presents a new deployable structure architecture based on the unique characteristics of bi-stable tape springs, where a substantial containment and deployment mechanism is not required to constrain the stored strain energy and concurrently removes the deployment degree of freedom at the end of deployment by design. The compact packaging of the deployable boom allows it to be used in nano-satellites, enabling immediate capabilities as a gravity gradient boom of the spacecraft or a camera boom on a larger spacecraft. The scalability of the device is primarily constrained by the design feasibility of the bi-stable tape springs and have been showed to be on the order of several meters.

The possible designs are not limited to the presented two-beam SIMPLE boom. Figure 9 show alternative three-beam and four-beam SIMPLE boom designs with increased structural stiffness and deployment force, but without compromising the linear, self-contained design properties. Unlike the two-beam SIMPLE boom, the three and four beam boom configurations have a complete balance of deployment forces due to their fully symmetric design, where the two-beam boom deploys with a small axial end rotation. In addition, the three-beam and four-beam SIMPLE boom designs may be stacked and deployed in sequence to create a truss-like beam several meters in length and easily capable of reaching tens of meters in length.

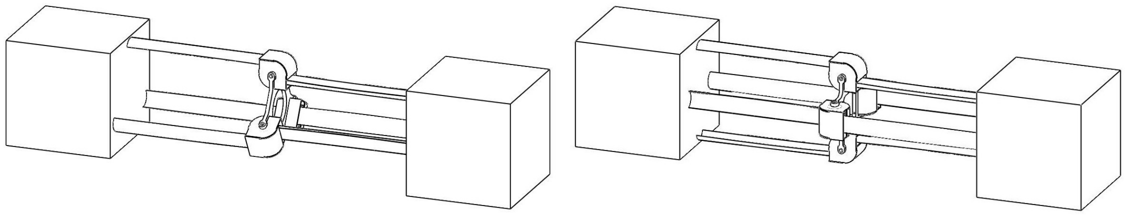


**Figure 9. Three-beam and four-beam alternative SIMPLE boom configurations.**

# VII. Acknowledgment

This research is funded by AFRL contract IDATS #FA9453-03-C-0231. The author thanks Jeremy Banik, Greg Stanford, and Nick and Gary Patz for their insight and assistance.

# References

[1] Silver, M., Dobson, B., and Warren, P., 2009 CubeSat Developer's Workshop Presentation, Cal Poly San Luis Obispo, CA, April 2009.

[2] Walker, S., "An application of tape springs in small satellite area deployment devices," *5th Cranfield DCSSS Conference*, July 2002.

[3] Sim, A. and Santer, M., "Analysis of a segmented compliant deployable boom for cubesat magnetometer missions," *51th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, April 2010.

[4] Annon, "Tubular Spacecraft Booms (Extendible, Reel Stored)," Tech. Rep. SP-8065, NASA, Feb 1971.

[5] Kebadze, E., Guest, S. D., and Pellegrino, S., "Bistable prestressed shell structures," *International Journal of Solids and Structures*, Vol. 41, 2004, pp. 2801–2820.

[6] Murphey, T. W. and Pellegrino, S., "A Novel Actuated Composite Tape-Spring for Deployable Structures," *45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, April 2004.

[7] Schultz, M. R., Hulse, M. J., Keller, P. N., and Turse, D., "Neutrally stable behavior in fiber-reinforced composite tape springs," *Journal of Composites*, Vol. A, No. 39, 2008, pp. 1012–1017.

[8] Galletly, D. and Guest, S., "Bistable composite slit tubes I: A beam model," *International Journal of Solids and Structures*, Feb 2004.

[9] Galletly, D. and Guest, S., "Bistable composite slit tubes II: A shell model," *International Journal of Solids and Structures*, Feb 2004.

[10] Guest, S. and Pellegrino, S., "Analytical models for bistable cylindrical shells," *Proceedings of the Royal Society A*, Vol. 462, 2006, pp. 839–854.

[11] Naik, N. K. and Ganesh, V. K., "An analytical method for plain weave fabric composites," *Journal of Composites*, Vol. 26, No. 4, 1995, pp. 281–289.

[12] Pellegrino, S., "Bi-Stable Structures," *Deployable Structures*, SpringerWien, New York, 2001, pp. 99–111.

[13] Hyer, M. W., *Stress Analysis of Fiber-Reinforced Composite Materials*, WCB/McGraw-Hill, 1998.

[14] Murphey, T. W., Jeon, S., Biskner, A., and Sanford, G., "Deployable Booms and Antennas Using Bi-stable Tape-springs," *24th Annuall AIAA/USU Conference on Small Satellites*, No. SSC10-X-6, 2010.

[15] Naik, N. K. and Ganesh, V. K., "Prediction of on-axes elastic properties of plain weave fabric composites," *Journal of Composites Science and Technology*, Vol. 45, 1992, pp. 135–152.