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Deployable Booms and Antennas Using Bi-stable Tape-springs

Thomas W. Murphey
Air Force Research Laboratory
3550 Aberdeen Ave. SE, Kirtland AFB, NM; (505)846-9969

Sungeun Jeon
CSA Engineering
1451 Innovation Pkwy SE, Suite 100, Albuquerque, NM; (505)853-5681
Sungeun.Jeon@kirtland.af.mil

Adam Biskner
LoadPath, LLC
5555 Zuni Road SE, Ste 20-3342, Albuquerque, NM; (505)853-1156
adam.biskner@kirtland.af.mil

Gregory Sanford
LoadPath, LLC
5555 Zuni Road SE, Ste 20-3342, Albuquerque, NM; (505)853-2422
Sungeun.Jeon@kirtland.af.mil

ABSTRACT

Utilizing the orthotropic properties of composite materials, tape-spring structural elements can be made that exhibit the unique behavior known as bi-stability. Tape-springs with this behavior display a controlled and deterministic deployment path of simply unrolling once initiated; they do not bloom. Deployable booms and multi-element antennas have been conceptualized based on these tape-springs and are reported on within. Both inventions occupy approximately ¼U of a CubeSat volume (50 x 50 x100 mm) when packaged and self-deploy to lengths of several meters. The boom concept employs four tape-springs arranged so that the boom tips separate linearly (without any rotations). It is intended to be used as a gravity gradient stabilization boom, camera boom or sensor boom. A damper element can be used to control deployment rate. The antenna concept uses multiple elements in a log periodic configuration and is deployed without rate control.

INTRODUCTION

Storable tubular extendible masts (STEM) have long been a workhorse of the deployable space structures community.[1-2] As shown in Figure 1, STEMs are slit-tubes that can be flattened and rolled for compact packaging. Though not required, they typically overlap to increase the shear stiffness of what would otherwise be a fully open section. When the overlap is avoided and a more open section is used, the resulting structure is known as a tape-spring. STEMs are fabricated with resilient isotropic metals and strains are minimized so that all deformations are elastic. Unlike certain tape-springs that achieve unique behaviors through pre-stressing[3-4], STEMs are essentially stress free in the deployed configuration. As a result, packaging these structures stores a significant amount of strain energy and deployment requires substantial mechanism to control the deployment rate and path. Without such a containment mechanism, STEMs will bloom in a highly dynamic, uncontrolled and difficult to predictable manner.

In contrast, the tape-springs employed here are bi-stable. Such tape-springs have two preferred cylindrical configurations: the fully rolled and fully unrolled configurations. These two configurations are stable equilibrium configurations and are thus local minimums of stored strain energy. However, the strain energy stored in each configuration is generally different (only in the special case of a neutrally stable tape-spring are they equal). Once a tape-spring in a stable higher energy configuration is deformed to initiate it toward the stable lower energy configuration, it will proceed powered by the release of strain energy. Because each configuration is independently stable, the transition is stable and follows a single kinematic path that manifests as rolling or unrolling of the tape-spring. In neutrally stable tape-springs, the two configurations have the same strain energy density and the tape-spring is in equilibrium at every position in transition. Each equilibrium position is neutrally stable and the tape-spring will have no preference to either roll or unroll. Stable rolled and unrolled configurations and a kinematically deterministic transition region are illustrated in the neutrally stable tape-spring of Figure 2.[3]

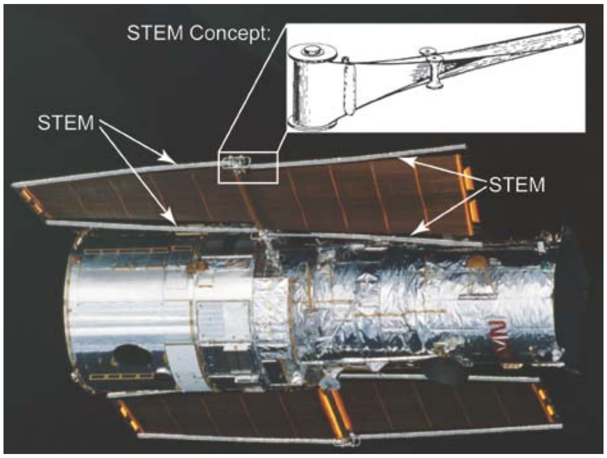


Figure 1: STEM structures used to deploy the original Hubble Space Telescope solar arrays.

There are a variety of options and limitations in the pursuit of bi-stable and neutrally stable tape-springs. Cases involving either material orthotropy, pre-stress or a combination of these are well understood.[3-5] Due to the challenges associated with fabricating pre-stressed tape-springs, the material orthotropy approach is employed here. Using this approach, a straight forward fabrication method is to use one or more plies of a woven continuous fiber reinforced plastic material with the warp and fill fiber directions at a 45 degree angle to the axis of the deployed tape-spring cylinder. The tape-springs are cured (and are essentially stress free) in the straight (deployed) configuration so that rolling the tape-spring stores strain energy that is used to power the deployment. Due to the symmetry of this laminate, thermal stresses can be neglected.

This class of bi-stable tape spring exhibits same sense bi-stable configurations, as shown in Figure 3b. A material orthotropy (no pre-stress) based bi-stable tape spring will unroll such that the unrolled tape-spring opens towards the same direction as the rolled tape-spring. Pre-stressed tape-springs can be designed to have same-sense or opposite-sense curvatures (Figure 3a). Figures 1 and 2 show opposite-sense tape-springs while subsequent figures of the concept prototypes will show same-sense tape-springs.

a)
b)
c)
d)

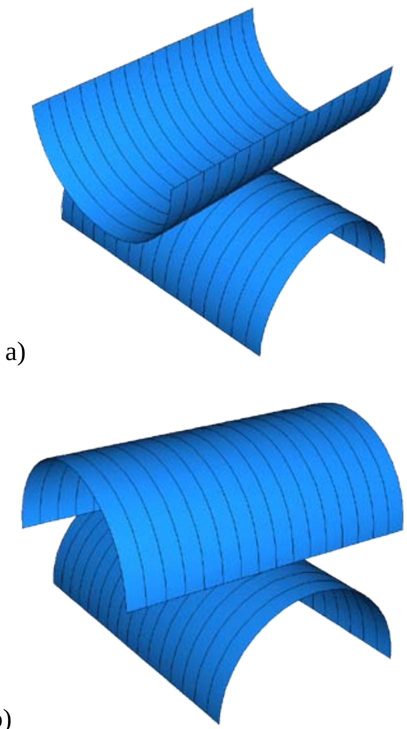
Figure 2: Reconfiguration sequence for an unconstrained neutrally stable tape-spring. The tape-spring is also stable in the fully rolled and unrolled configurations.

TAPE-SPRING STRAIN ENERGY DENSITY ANALYSIS

A strain energy density analysis based on classical laminate theory is used to better understand the design of deployable structures using bi-stable tape-springs. The analysis allows the curvature and associated strains of the rolled tapes-spring to be calculated and to evaluate margins against failure and creep. It also reveals a necessary condition for bi-stability and that a maximum roll radius exists. In rolls larger than this limit, the previously well defined kinematic unrolling path becomes unstable. If deployment kinematics are not controlled with a canister like mechanism, this can place a maximum length limit on the concepts as outer roll diameters increase with longer tape-springs.

As shown in Table 1, two plain weave material systems are considered. The boom will use a carbon fiber system while the antenna, which must be made from a non-conducting material, will use a less structurally efficient glass fiber system. Prospector:Composites, a web-based material property search engine produced by

Firehole Technologies and hosted by IDES, was used to search for the most complete data set for plain weave T300 or AS4 carbon fiber and epoxy matrix material system.[7] One entry was found with sufficient data.[8] A similar search was performed for a glass fiber and epoxy matrix plain weave and again only one entry was found with sufficient data.[9] Pertinent properties from the Firehole Prospector:Composites data sheets are listed in Table 1. Both data sheets provide independent properties in tension and compression as well as the weave warp and fill directions. The average of these four modulus numbers is used here. The sheets also report independent strength properties for the warp and fill directions. The fill direction strengths (converted to strain) are somewhat lower and are used here. The elastic properties are also listed with respect to the tape-spring *xy* coordinate system in Table 2.



a)

b)

Figure 3: Cylinders representing stable configurations of a) opposite sense and b) same sense curvatures.

As will be discussed, the shear modulus of the E-Glass material system is too large to exhibit a bi-stable behavior. A third column (Soft Matrix Antenna) has been added to represent a similar material system, however, with its shear modulus reduced by half. Such a material could be realized by selecting a reduced modulus matrix material.

These material systems are considered here because they represent the only consistent data sets that could be found in the literature; they are not the result of a material selection study. As described in Reference 6, the bending mechanics of thin composite flexures are not well understood and it is difficult to obtain accurate strength and stiffness properties for them. The properties listed in Table 1 and 2 suffice to capture the bi-stable characteristics of tape-springs and support an engineering estimate of the feasibility of the designs.

Table 1: Tape-spring geometry, material systems and associated mechanical properties (1 and 2 refer to the material principal coordinate system, i.e. the fiber directions).

Property	Boom	Antenna	Soft Matrix Antenna
Fiber	T300 Carbon Fiber	E-Glass	E-Glass
Form	Plain Weave	Plain Weave	Plain Weave
Matrix	E765 Epoxy (Park Electrochemical Corp.)	E765 Epoxy (Park Electrochemical Corp.)	Lower modulus material
Fiber Volume Fraction	44 to 54%	42 to 50%	42 to 50%
Thickness	0.127 mm	0.127 mm	0.127 mm
Inner Radius	6.35 mm	6.35 mm	6.35 mm
Section Angle	180 deg	180 deg	180 deg
E_1 and E_2	53.2 GPa	25.5 GPa	25.5 GPa
ε_1^T and ε_2^T	0.97%	1.49%	NA
ε_1^C and ε_2^C	1.19%	1.57%	NA
G_{12}	3.86 GPa	4.83 GPa	2.42 GPa
γ_{12}^F	3.37%	2.71%	NA
ν_{12}	0.059	0.157	0.157
ρ	1,450 to 1,500 kg/m^3	1,760 to 1,870 kg/m^3	NA

Table 2: Tape-spring material system elastic constants with respect to the tape-spring coordinate system (*x* and *y* refer to the tape-spring long and transverse axes).

Property	Boom	Antenna	Soft Matrix Antenna
Fiber	T300 Carbon Fiber	E-Glass	E-Glass
E_x and E_y	13.6 GPa	14.6 GPa	8.33 GPa
G_{xy}	25.1 GPa	11.0 GPa	11.0 GPa
ν_{xy}	0.760	0.516	0.725

Thin shells of the type considered here start as and deform into surfaces with zero Gaussian curvature, that is, cylinders. Such surfaces are also called singly curved (as opposed to doubly curved surfaces such as a bowl or saddle). It requires both bending and stretching strains to form a non-zero Gaussian curvature surface from a zero Gaussian curvature surface and these therefore store much more strain energy. Zero Gaussian curvature surfaces are simply lower strain energy states. Neglecting edge effects, the tape-spring stress state and curvatures are uniform throughout and the global shape is also uniform. This restricts tape-spring deformations to be in the shape of a cylinder. The transition region between two stable cylindrical shapes will not have zero Gaussian curvature, as shown in Figure 2.

Cylindrical deformations can be described with only two parameters: the orientation of the cylinder θ and the curvature of the cylinder κ. A contour plot of tape-spring strain energy density with respect to all possible deformations (combinations of κ and θ) reveals the behavior of the tape-spring. The bottom of an energy well on this contour plot represents a stable equilibrium point and unstable points are peaks and saddles. Plots are shown in Figure 4 for each material system. In each plot, the strain energy density is zero in the fabricated configuration (curvature equal to 1/(6.35 mm) = 157.5 m^{-1} and orientation equal to 0 deg). Any deviation from this configuration stores strain energy in the tape-spring.

The boom material system plot shows a second stable equilibrium point (energy well) at an orientation 90 deg to the original axis and with a curvature of 119.6 m^{-1} (radius of 8.36 mm). This is the rolled configuration. It can be shown that the ratio of the as rolled curvature to the fabricated curvature is simply the laminate Poison's ratio with respect the boom axes. 119.6/157.5 = 0.759, which is the value reported in Table 2.

$$\nu_{xy} = \frac{\kappa_{rolled}}{\kappa_{fabricated}} \tag{1}$$

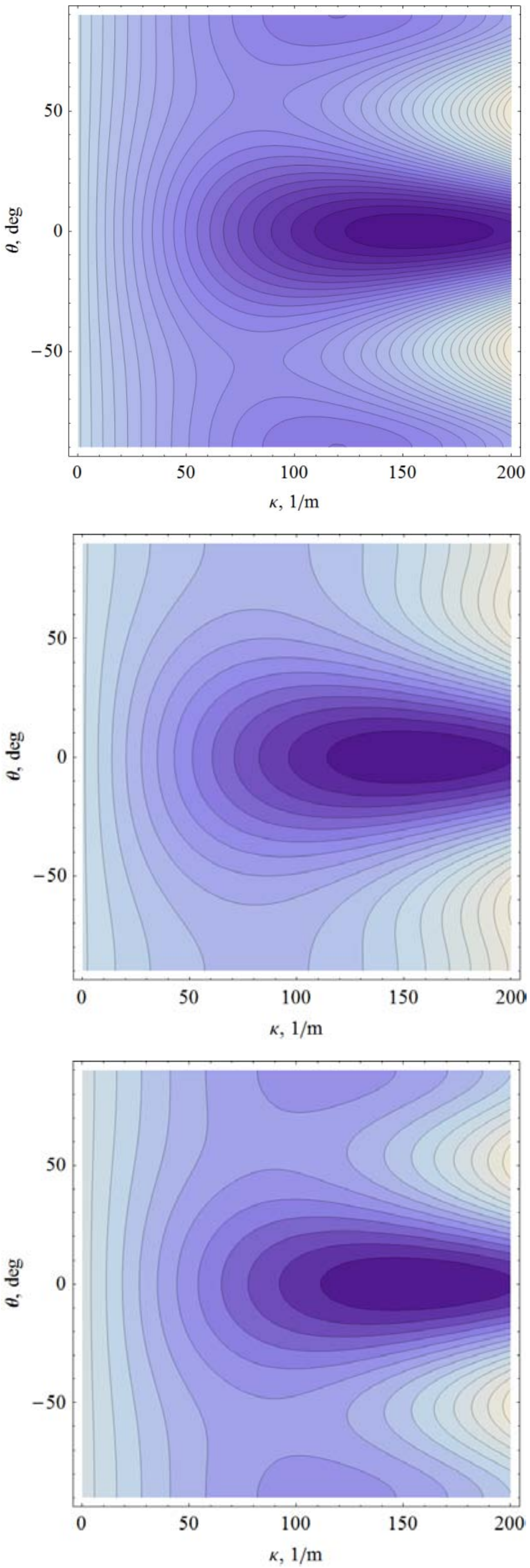
Figure 4b shows that the antenna material system is not bi-stable because no energy wells exist. Symbolically carrying out the strain energy density analysis, as in Reference 3, it can be shown that the pertinent necessary (though not sufficient) condition for bi-stability in the laminate considered here is

$$\frac{E_1}{G_{12}} > 2\left(3+\nu_{12}\right). \tag{2}$$

ν_{12} is generally small in plain weave composites so that E_1 must be about 6.4 times greater than G_{12}. Isotropic materials are not bi-stable without pre-stress because this ratio is typically closer to 2.7 (assuming $\nu = 0.33$). Inspecting Table 1, the boom material system has a ratio of 13.8 while the antenna material system has a ratio of only 5.3, significantly less than the required 6.4.

The fiber direction modulus of a composite material is primarily determined by the fiber modulus while the shear modulus is determined by the matrix modulus. Thus, a composite material can be tailored to have a relatively low shear modulus while maintaining high fiber direction modulus by lowering the matrix modulus. A hypothetical material system in given in Tables 1 and 2, Soft Matrix Antenna, where it is identical to the antenna material system other than G_{12} is reduced by a factor of two. The ratio of extensional modulus to shear modulus is now 10.5 indicating the tape-spring should be bi-stable. The strain energy density plot for this material is shown in Figure 4c and energy wells can be observed showing it is bi-stable. Again, the rolled tape-spring curvature can be calculated from (1) and is 114 m^{-1}.

The contour plots in Figure 4a and 4c show additional unstable saddle equilibrium points. These points are important because they indicate the maximum strain energy that can be added to a rolled tape-spring before it will spontaneously reconfigure to the unrolled configuration. For example, as long tape-springs are rolled the curvature of the outer wraps decreases as the roll diameter increases. This increases the strain energy stored by the tape-spring. The saddle point in Figure 4a has a strain energy density of 37.8 J/m^2. As roll diameter increases, the store strain energy will reach this value at a radius of 16.1 mm, 1.92 times the nominal roll radius. The soft matrix antenna material system reaches this value at 1.54 times the nominal roll radius.



a)

b)

c)

Figure 4: Strain energy density plot for the a) boom, b) antenna and c) soft matrix antenna tape-spring described in Table 1.

CONCEPTS

Deployable Boom

The boom concept is shown in Figure 5. It consists of two pairs of bi-stable tape-springs rolled around two cylinders connect by a shaft with bearings. The tape-springs self deploy due to their stored strain energy and cause the spools to counter rotate. Once fully deployed, the tape-springs lock out to form a structure. Deployment rate can be controlled by placing a damper or motor between the two counter rotating spools.

The shroud controls the direction of deployment as the system is able to freely pivot about the shaft without it. Once the tape-springs are fully deployed, the shroud does not touch the tape-springs or otherwise add stiffness to the boom.

The strain energy density analysis of the previous section can be used to estimate the energy release. Each tape-spring releases $u = 0.57$ J/m as it deploys. Equating this to the work done by a force resisting the motion gives,

$$F = \frac{U}{d} = u \tag{3}$$

The energy release per length actually is the deployment push force. It has units of J/m, which is reduce to N. The boom push force of is the sum of two tape springs, 1.14 N.

This push force can be reduced by matrix creep as the stored boom highly loads the laminate in shear. The maximum fiber direction strains in a stored boom are,

$$\begin{aligned} \varepsilon_1^T &= \varepsilon_2^T = 0.12\% \\ \varepsilon_1^C &= \varepsilon_2^C = -0.12\% \\ \gamma_{12} &= 1.76\% \end{aligned} \tag{4}$$

While these strains are well below the failure limits listed in Table 1, the matrix is highly loaded and is subject to creep.

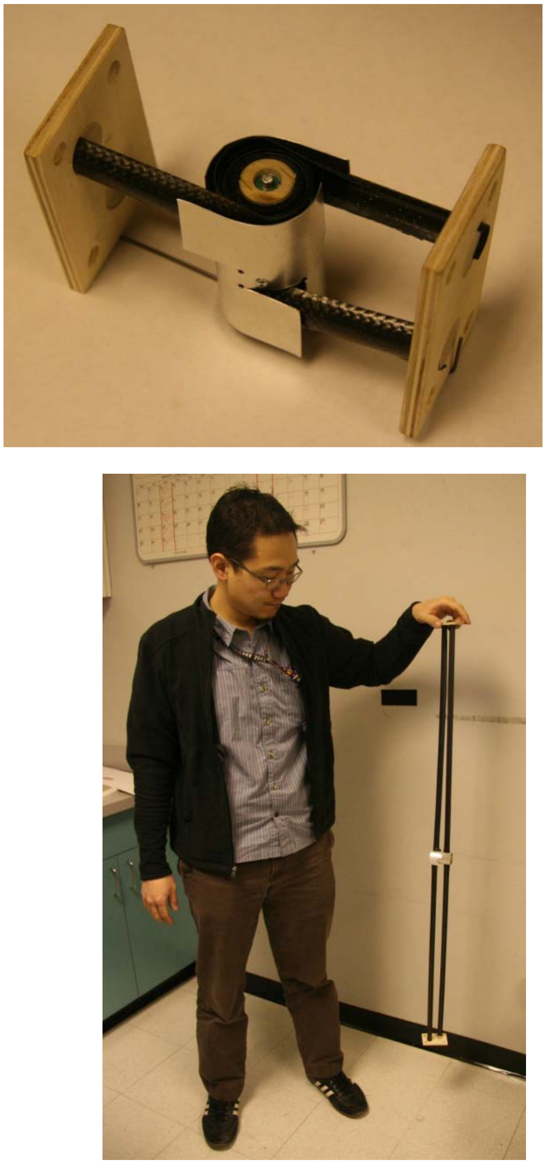
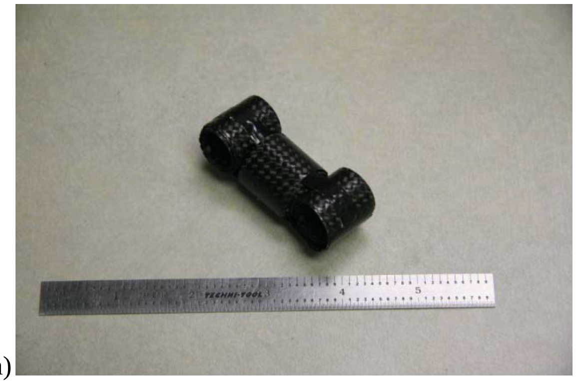


Figure 5: Boom concept in packaged and deployed configurations.

Deployable Antenna

The deployable antenna concept and its deployment sequence are shown in Figure 6. It is a log periodic antenna tuned to UHF frequencies. Due to the absence of any significant mass attached to the antenna, it is intended to freely deploy without rate control. The kinematics of the bi-stable tape-springs control the deployment path. While the deployment rate towards the end of deployment may be very fast, there is essential no mass associated with the motion as the roll diminishes to nothing during deployment. This results the deployment shock being much lower than would otherwise be expected.

a) 

b) 

c) 

d) 

e) 

f) 

Figure 6: Deployment sequence of antenna concept.

CONCLUSIONS

Bi-stable tape-springs were shown to enable very simple deployable booms and antennas. They also have the potential for packaging efficiencies compatible with the limited stowage volume of CubeSat missions. For example, the carbon fiber tape-spring studied here has a natural rolled diameter of 16.7 mm and can be rolled as large as 32 mm. The flattened width of a tape spring is 20 mm. These dimensions permit the design of deployable booms and antenna occupying 1/8 to 1/4 the volume of a 1U CubeSat (100 x 100 x 100 mm).

While conceptually simple, the mechanics and design of bi-stable tape-springs are less straight forward. The limited availability of thin plain weave materials, conditions for bi-stability, roll diameter restrictions and matrix creep all place significant confines on one's design freedom.

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