Innovations and Limitations Involved in Treating Deploying Membrane Structures as Unfolding Tree Leaves

Marie-Josée Potvin
*Structural Dynamics
Engineer, Ph.D.
Space Technologies
Canadian Space Agency
e-mail: Marie-
Josee.Potvin@space.gc.ca*

Bruno Sylvestre
*Graduate Student
École de technologie
supérieure
e-mail:
bruno.sylvestre@polymtl.ca*

Johanne C. Heald
*Post-Doctoral Fellow, Ph.D.
Space Technologies
Canadian Space Agency
e-mail:
Johanne.Heald@space.gc.ca*

Abstract

Many structures in space must be deployed to cover a large area. They must be lightweight and packaged as efficiently as possible to reduce their launch cost. Nature offers interesting ideas in the way it packages tree leaves and then deploys them in a flat structure. Several authors have looked at these concepts, but no research has been undertaken to take into account the effect of electrical circuits on a membrane. This paper looks at which ideas can be used for the two applications of interest to the Canadian Space Agency, namely, membrane solar panels and membrane SAR antennae.

1. Introduction

The cost of launching spacecraft into orbit is directly proportional to the size of the required launch vehicle. Spacecraft that are smaller are therefore less expensive to deliver to space. With deployable membranes, structures with a relatively large extent in space can be deployed from platforms an order of magnitude smaller. The low mass of the membranes and their small package volume in their stowed configuration can disguise a large space structure as a small launch structure. This smaller spacecraft platform makes launching the structure into space much cheaper.

There are several applications for the large, two-dimensional structures that could be formed by flat membranes in space. These include large flexible solar panels, solar sails to provide interplanetary propulsion, communications antennae, synthetic aperture radar (SAR) antennae for remote sensing, and large flat optics for astronomy. Currently, the Canadian Space Agency is developing membrane technology for on-

orbit antennae, and is considering developing flexible solar panel technology. The question of how such membranes must be stowed for launch and deployed on-orbit is an interesting one. This paper considers whether the strategies adopted by tree leaves, a naturally deploying structure, might be adopted for deploying membrane structures in space.

2. Requirements

Typically, a satellite is classified according to its mass. In order to be considered a "small" satellite, the satellite platform and payload must together have a mass of less than 500 kg, where typical "large" satellites for communications and remote sensing have a mass of thousands of kilograms. A small satellite that has a mass in the range of 1-10 kg is further classified as a nano-satellite. Spacecraft are classified in this way because an upper bound on mass sets other limitations as well. The spacecraft platform, or bus, consists of certain standard systems (power, propulsion, attitude control, etc...) and the generally accepted design of those systems scales with decreasing mass. Therefore, if the platform is less massive, this directly implies that the platform has a reduced volume. If the platform is smaller, there is less area for the body-mounted solar panels that collect solar energy, and this places a limitation on the power the spacecraft is able to generate. In addition, the smaller platform will not have the space to accommodate all the redundant systems usually built into spacecraft to guard against the failure of individual components. Since these redundant systems are lacking, the spacecraft is expected to reach the end of its useful life much sooner. Hence, the mass requirements generally dictate volume, power, and expected lifetime requirements of the satellite as well.

The use of deployable membrane structures on spacecraft is a way of meeting the mass requirement and the limitation on volume occupied inside the launch vehicle, while circumventing that volume limitation once the structure is in space. The spacecraft shown in Figure 1 demonstrates this for a nano-satellite platform with a deployable membrane. Figure 1a) is the nano-satellite in its stowed state for launch, while Figure 1b) shows the nano-satellite with the membrane deployed. Note that there are several layers of membrane, which is often the case for SAR antennae. The electrical components of the antennae could be placed on different layers interconnected through flexible electrical connections. Such a concept is described in [1].

The mass requirements for the nano-satellite pictured in Figure 1 are 7 kg for the spacecraft bus and 3 kg for the spacecraft payload, where the deployable membrane is included as part of the payload. In the stowed configuration, the spacecraft must fit within an envelope of dimensions of 21cm x 21 cm x 21 cm. There are no requirements on the deployed size of the membrane structure, but it must not block the field of view of other instruments on board the spacecraft, including any attitude control sensors and a camera payload that will provide on-orbit inspection capability.

Additional requirements on the membrane structure govern its deployment time and deployment dynamics. The dynamics induced by the deployment of the membrane must not coincide with the structure's designed first mode, assumed to be 30 Hz. This implies that the deployment be predictable and well characterized.

In the case of a SAR membrane antenna, once in the deployed state, any membrane layers (such as thermal protection layers, electrical ground planes, and radiation planes) must be held parallel to each other. The membrane layers must be flat and free of wrinkles, and the maximum possible out-of-plane displacement error in this respect is held to a certain limit. Generally, the flatness is achieved by placing the membrane in tension using a supporting frame of some kind, where the tension is uniformly distributed through the membrane [2,3].

There are limitations on the way in which the deployed structure can be folded for packaging in the stowed state. The membrane must not be folded in such a way that permanent deformation occurs along the fold lines that the tension in the membrane cannot overcome to

Figure 1 – Small satellite platform with membrane solar panel in a) stowed and b) deployed configurations

achieve the required flatness. Further, the individual modules on the membrane, or cells, cannot be cut through by the fold lines. For a flexible solar panel, this means that the fold lines must follow the seams between the solar cells, although the cells themselves can be oriented in whatever direction is desired.

For a SAR membrane antenna, these requirements are more stringent. While the size of the antenna is dictated by the minimum radiated power necessary for the signal, the overall membrane shape is fixed. The antenna must be rectangular to cover the along-track and cross-track signals correctly, with the individual cells regularly spaced and oriented parallel to each other [1], as shown in Figure 2. This orientation restricts the placement of the fold lines for the stowed configuration of the antenna. In addition, the flatness requirements for the membrane will be more stringent than for the solar panel application. In [4], Huang notes that the electrical design of a membrane antenna requires a flatness between $1/20^{\text{th}}$ and $1/40^{\text{th}}$ of the free-space wavelength. For an L-band antenna, this translates into a flatness requirement of ± 1 cm; for higher-frequency antennae, the flatness required reduces to millimetres.

3. Literature survey

Leaves are membranes with functional elements that require efficient packaging and deployment. Nature

can present us with interesting approaches to engineering problems.

In the early 1980s, Miura presented a new concept of packaging and deployment of large membranes in space based on the deployment of leaves [5]. Miura found the developable double corrugation (DDC) surface by solving the von Kármán's equations of a plate where an infinite plate is uniformly contracted in two orthogonal directions in its plane. The deformations in the plate are shown by the mean contour maps, which revealed the DDC surface. This way of folding a membrane is now known as "Miura-Ori." The most interesting property of this pattern is that it facilitates simultaneous extension or contraction in two directions perpendicular to each other. Several other designs using that method of folding were developed by the same author. A 2-D array experiment [6] was designed in 1985 and the authors evoked possible applications such as large solar arrays (a preliminary blanket design was described), solar sails, space radars and space VLBI's. A conceptual study of a solar sail racer [7] was performed in 1988. More pragmatically, Horner and Elliott [8] and Wright et al. [9] proposed a practical manner of fabricating an enormous solar sail based on the Miura-Ori pattern.

Figure 2 – Direct radiating membrane antenna

More recently, Kobayashi et al. [10] studied the geometry of unfolding tree leaves of hornbeam and beech using vector analysis. They found that those leaves have a relatively simple and regular corrugated folding pattern that is in fact a simple form of a Miura-Ori surface. Among their conclusions, the authors observed that a leaf with large ($75-85^\circ$) vein angle (i.e. angle between the central vein and the secondary vein) can be folded more compactly than one with a small vein angle ($30-45^\circ$). However, a leaf with a relatively small vein angle can attain a large deployed area at an early stage and requires less kinetic energy while deploying.

On the same note, by vector analysis, folding and unfolding of maple leaves were studied [11] and a fan-type bellows pattern was elaborated. An important conclusion drawn by the study of the folding/unfolding of this pattern is the fact that most of the energy needed to unfold it is required at the beginning of the unfolding. In the last stage of unfolding, only a small amount of energy, less than 10% of the maximum, is required. Another interesting conclusion is that when the V-cuts on the contour of the leaf are smaller and the edges are less sharp (as in the case of a fan, which is almost circular with respect to a Maple leaf with deep cuts), it requires less energy for full-unfolding than a leaf with large V-cuts. Vincent [12] stated that this type of folding is shown to be a class of Miura-Ori with the primary folds radially arranged rather than arranged in parallel.

De Focatiis and Guest [13] investigated different ways of folding several corrugated leaf patterns in order to produce deployable surfaces (flat and curved). In addition to also looking at the geometry of Miura-Ori (to which they gave the name "one-leaf unit" for the folding pattern used by hornbeam and beech leaves), they also concluded that leaves can be arranged in two basic ways: leaf-in (pointed units pointing towards the centre of the polygon) or leaf-out (pointed units directed away from the centre of the polygon). They further studied the folding incompatibility of the leaf-in pattern to discover that it requires a small amount of distortion in order to accommodate its folding/unfolding. They discovered a variation of this pattern, the skew leaf-in pattern, which shows less distortion during the unfolding process but has a disadvantage in that it cannot be fully folded.

Figure 3 – Classic Miura-Ori Prototype Deployment

The literature on the folding patterns of tree leaves provides interesting examples of how to fold a membrane. However, the materials and elements used in space bring their own constraints and limitations to these concepts.

4. Concepts from Nature that are Applicable to Space

Currently, two membrane applications are considered in the Canadian Space Agency research program, membrane solar panels and membrane SAR antennae. Three different leaf folding concepts that could be useful are being studied: Miura-Ori (classic), Miura-Ori (radial) and central-type of folding.

Miura-Ori (classic)

The basic Miura-Ori folding pattern is made of several rows of parallelograms. A simple form of this corrugated pattern type is found in hornbeam and beech leaves, which only have two rows of parallelograms (see Figure 3). This type of folding can be applied to membrane solar panels. The solar cells can be arranged to fit the shape of the membrane as long as it collects solar radiation. The total area of the deployed membrane is an issue for this application, but not the shape of the membrane itself. Indeed, different membrane shapes could be built by arranging the parallelograms differently. The solar cells should not be located on the fold lines, and this restriction results in some loss of effective area.

This type of folding can be applied also to the membrane SAR antennae. The concept requires a rectangular membrane, which can be implemented by long rows of parallelograms. However, here we have two sources of loss in the effective area. First, there are the positioning requirements of the electrical patches,

which should be placed in a rectangular configuration at regular inter-element distances. The bottom and the top of the membrane have an arrow shape where it would not be possible to put the patches. Because the parallelograms are placed side by side along diagonals, whereas the electrical patches must be placed along perpendicular lines as demonstrated in Figure 2, the angle at which the parallelograms are deployed will have an impact on the number of elements that can be placed on the membrane. Second, there is the placement of fold lines. Electrical elements must not be on the path of a fold line. Accommodating an orthogonal pattern of electrical elements on a folding pattern with diagonals involves increasing the spacing between elements to avoid possible damage to the electrical patches. Even the most efficient packaging would result in a significantly larger membrane to accommodate the same number of elements.

The current material of choice for space membrane applications is Kapton, a polyamide-based polymer. Figure 3 shows the Miura-Ori folding pattern using a Kapton prototype. In order to work with the material and create the pattern, it was necessary to crease permanently the Kapton. The deployed structure was not perfectly flat afterwards since the creases created irregularities. For a solar panel, the flatness requirements are not very stringent and these creases are not a problem. However, for a SAR antenna, requirements can be of the order of ± 1 mm. A large tension applied at the boundaries of the membrane would be required to overcome the out-of-plane deflection caused by the creases. This would be a serious drawback since a sturdier frame would be needed to apply a larger tension, potentially offsetting the mass gain made by using a membrane antenna instead of a conventional antenna panel.

Figure 4 – Radial Miura-Ori Prototype Deployment

Miura-Ori (radial)

The radial Miura-Ori folding pattern is based on the study of the maple leaf, which has a fan shape. A maple leaf with distinct pointed sections would not be suitable for a membrane antenna. It could accommodate the requirements of a solar panel. However, distinct pointed sections do not offer a large surface area in comparison to the size of the frame that would be required. A better option is as shown in Figure 4, where the shape is almost circular. The membrane opens like a fan, deploying on both sides at the same time.

The folding lines all initiate from a central point at base of the leaf pattern. In the small model displayed here, the fold lines created a stress concentration at the central point and cracks in the material started propagating from that point. A stress relief strategy or reinforcements would have to be employed to make this a feasible folding concept for membranes used in space.

Because the folding lines all converge at one point, the area around that point does not offer much surface area for electrical components. However, further away

from that point, the folding lines diverge and would offer more space for either elements of SAR antenna or flexible solar cells.

An important advantage of this pattern is that it can be packaged without creasing permanently the Kapton, the different sections being simply pushed one against another. This would reduce the required tension of the membrane to attain a certain flatness requirement.

Central

De Focatiis and Guest [13] studied two main types of folding patterns that unfold from a central point, which are referred to as leaf-out and leaf-in. The interesting property of these folding patterns is that the central point of the membrane can be attached to the spacecraft, offering a membrane which deploys centrally from the bus, as shown in Figure 1

Figures 5 and 6 show the deployment sequence of the leaf-in and leaf-out folding patterns respectively. This time, the leaf deploys from the centre of the square membrane. When unfolding, each point tends to increase its distance with relation to the centre point.

Figure 5 – Central Leaf-In Prototype Deployment

Figure 6 – Central Leaf-Out Prototype Deployment

For both cases, there are only four diagonal folding lines. The area further away from the centre of the membrane, the more area is divided into squares or rectangles, with diagonal folding lines found only at the corners. The large square areas would accommodate the positioning of SAR elements away from the diagonals. In the case of solar panels, flexible solar cells could be placed anywhere and in any orientation between folding lines.

Although the patterns on both the prototypes made of Kapton have been implemented by creasing permanently the membrane, the leaf-out pattern could probably be packaged without permanent creases. The lack of permanent creases would ease the ensuing tensioning after deployment to reach the required flatness. Both packaging methods could produce a rather long shape if the membrane was large, but they could be rolled after the initial folding to obtain even tighter packaging.

In this section, we have presented three different concepts taken from nature that can be applicable to space. Up to now, only very preliminary studies have been done in order to judge the viability of the concepts shown by unfolding tree leaves. Further studies should be performed in order to evaluate which concepts will best suit our applications. In addition to identifying the concepts, a proper tensioning system should be developed in order to accommodate the deployment and the resulting flatness of the membrane.

5. Conclusions

Several authors have explored the mechanisms developed by nature to package and then unfold tree leaves. This paper explored the possibility of using these methods for membranes used on spacecraft. The

classical Miura-Ori pattern would be suitable for a solar panel, but would be difficult to implement for a SAR membrane antenna, given that the elements of the SAR antenna must all be aligned and evenly spaced.

The radial Miura-Ori pattern offers the advantage of not requiring permanent creases on the membrane for packaging. This translates in a greater ease in reaching the required flatness after deployment. Flatness is an important factor in the efficiency of a SAR antenna. However, the area around the converging point of the fold lines could be a weak point where cracks could develop. This area also contains so many fold lines that even flexible solar cells would be difficult to place. Further away from that point, sufficiently large areas could be used for solar cells or for the pattern of a SAR antenna.

The leaf-in and leaf-out patterns are the most promising for a SAR antenna since, at a certain distance from the centre, they offer large areas where the folding lines are all orthogonal and where the elements of a SAR antenna could be easily positioned.

All these patterns offer interesting packaging efficiencies. They are easily applicable to membrane solar panels. Some of these patterns offer possibilities for a SAR antenna. It is important to note, however, that this paper has only considered the constraints imposed by a single layer of elements for a SAR antenna. Electrical concepts will require more than one layer and further thought must be given to the configuration of a multiple layer antenna packaged in a similar fashion to what nature suggests.

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