A Controllable Hinge Mechanism for the Deployment of a SAR Satellite Antenna

Véronique Tokateloff*, George Akhras,
Royal Military College of Canada (RMC)
and
Steeve Montminy, Yu Shen, Marie-Josée Potvin
Canadian Space Agency (CSA)

Abstract

An ongoing challenge in the aerospace industry is to implement novel ways in reducing the overall weight of a system so that significant cost savings ensue. For space-bound projects such as satellites, deployable structures must combine low mass and low volume, thus allowing the use of a smaller and less expensive launcher. The design of lightweight robust controllable hinges for these deployable structures is consequently very desirable.

In this project, a deployment mechanism for a high packaging efficiency satellite SAR (synthetic aperture radar) membrane antenna is developed. The device, a hinge, should be compact, space qualified, lightweight and able to actuate the lateral deployment of a large antenna wing from its initial stowed state of 1.2 m x 1.4 m to its final functional shape of 5.5 m x 4 m. Moreover, the controlled deployment to the final latching into place has to be achieved with low energy consumption and minimum dynamic disturbance.

Based on an earlier concept of the Tape Spring Rolamite Hinge (TSR), a new controllable hinge has been designed to deploy and lock the antenna frame into a final stiff and straight configuration with minimal disturbance on the attitude control of the spacecraft. The new modified hinge is composed of two tape-springs, two motion guide wheels, a motion control mechanism and a Shape Memory Alloy (SMA) actuator. The deployment control mechanism was inspired by a traditional clock escapement mechanism, such that the one degree of freedom hinge deploys as the hands of a clock would unwind. Moreover, instead of using a more traditional rotary motor approach to actuate this control motion, SMAs are used to control the unwinding speed of the mechanism. The use of SMAs greatly reduces the complexity of the setup and the number of parts, thus increasing the hinge's robustness for similar power requirements.

This paper presents the new hinge design. The hinge's motion and functionality are discussed. Previous work regarding the moment-rotation relationship of the tape-springs is compared with the current design’s experimental results.

* Primary author contact information: veronique.tokateloff@rmc.ca, veronique.tokateloff@space.gc.ca
1. Introduction

One of the main goals in improving deployable structures is to find novel ways, materials and mechanisms to increase its packaging efficiency (deployed volume/stowed volume) without sacrificing the structure’s capability, weight, precision or robustness. In this paper, the design of a lightweight robust controllable hinge capable of actuating the antenna’s deployment is presented. First, the SAR membrane antenna technology is outlined followed by the antenna structure’s design. Then, the focus is shifted to the decision processes that lead to the current design of a hinge responsible for the lateral deployment of the antenna’s frame. The hinge design and some experimental results describing its deployment behaviour are presented.

2. Synthetic Aperture Radar (SAR) and Membrane Antenna Technologies

A Synthetic Aperture Radar (SAR) satellite’s main tasks can include mapping, environmental monitoring and military observation. The SAR antenna emits electromagnetic waves to the Earth, which are backscattered to the SAR receivers. The waves are analysed using complex signal processing techniques that translate the received information into high resolution images.

As opposed to the more traditional solid surface paraboloid or mesh antenna structures [Tibert 2002], the Canadian Space Agency is researching membrane antenna technology which optimizes the packaging efficiency, since the sheet-like membranes can be rolled or folded into a much smaller volume. Another characteristic of this type of antenna is that its overall shape is planar and not parabolic.

Membrane array antennas are composed of sheet-like layers, one of which contains an array of small Transmit Receive (T\R) modules. These membrane sheets are tensioned by a catenary system, which is defined as tensioned cables that run along the periphery of the membrane and are attached to a solid frame. An example of the simplified structure’s appearance is shown in Figure 1.

For this project, the antenna’s frame is used to deploy the membrane into its final 11 m by 4m surface configuration. The membrane antenna’s frame design has been guided by the following criteria:

1) Best possible first natural frequency
2) Low mass (entire antenna mass< 400kg)
3) Reliability (reduced number of components and ease of deployment)
4) Flatness (less than 1/20\textsuperscript{th} antenna's wave length)
5) Packaging efficiency (approx. 1.4 m by 1.2 m stowed to 4m by 11m deployed)
6) Mechanical stability
7) Compatible materials with launch and Low Earth Orbit (LEO) space environment
8) Low energy consumption
9) Space heritage

As studied by Shen et al. (2007), the frame design’s first natural frequency had to be higher than 4 Hz to minimize the membrane vibration caused by satellite attitude control. As well, the structure’s natural frequencies must avoid the entire spacecraft’s resonant frequency (25 to 60 Hz), to protect it from damaging the bus’ electronic components. These demands were met with the structural model shown in Figure 1, which presents a first natural frequency of 7.09 Hz.
The frame’s actual deployment sequence is shown in Figure 2. For clarity, the layers of Kapton membranes, the complementary support structure, and its electronic components are not shown. The figure shows the deployment sequence first in the longitudinal, then in the lateral directions.

![Figure 2: Antenna deployment sequence](image)

The surface accuracy will depend on the supporting frame’s geometric accuracy and on its membrane tensioning system. This entails that the frame’s hinges must deploy the frame into a final stiff and straight position to support the membrane’s in-plane tension.

The project’s current phase involves the design, manufacture and testing of a scaled down 2:1 mechanical antenna prototype for which two deployment activation methods will be used: a motorized six-bar linkage used for the longitudinal deployment and a tape-spring controllable hinge used for the lateral deployment. This paper will concentrate on the latter case.

3. Decision Process of the Hinge Design

As Gantes explains in “Deployable Structures: Analysis and Design” (2001), deployment actuation can generally be achieved by one of two means: the release of internally stored elastic energy, or by mechanical means that require a power/energy source. Kota et al. (1997) explain the tradeoffs between open and closed kinematic chains and between mechanisms and motors, and relates them to the design’s flexibility requirements.

The main candidates, motors and springs alike, are weighted with respect to qualitative selection criteria. This debate is summarized in Table 1 and partly discussed below. Some criteria that were not included are maximum speed, stroke, and torque since all cases can be catered to fulfill the hinge’s angular displacement (180 degrees), relatively light torque load (0.15 Nm), and low speed (up to 45 minutes to deploy) deployment requirements. As well, cost is not considered at this early stage of the development.

In the table below, the most desirable cases are shown in bold. Note that the evaluation is general, since it is difficult to encompass all commercially available cases. The “Support structure complexity and mass” category being the most important of all, we can easily prioritize the research and development of the tape-spring option. The tape-spring design must improve the deployment’s controllability, which is achieved in the herein design.
Table 1: Comparison of deployment actuation mechanisms

<table>
<thead>
<tr>
<th></th>
<th>Support structure complexity and mass</th>
<th>Electronic complexity</th>
<th>Smoothness and controllability</th>
<th>Space heritage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stepper Motor</td>
<td>HIGH</td>
<td>LOW</td>
<td>LOW-MEDIUM</td>
<td>HIGH</td>
</tr>
<tr>
<td>Brush Motor</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>MEDIUM</td>
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<tr>
<td>Brushless Motor</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
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<tr>
<td>Solenoid</td>
<td>HIGH</td>
<td>LOW</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
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<tr>
<td>Torsion spring</td>
<td>MEDIUM</td>
<td>LOW</td>
<td>LOW</td>
<td>HIGH</td>
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<tr>
<td>Tape-spring</td>
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Tape-springs are longitudinally bent metallic strips as shown in Figure 3. Two tapes can be used in the following configuration to create a hinge. This design was modified by [Watt et al. 2002] to include motion guide wheels as shown in Figure 4.

![Figure 3: Tape-springs](image_url)

![Figure 4: Tape-spring Hinge](image_url)

The design criteria of the controllable hinge are discussed as follows [Lin Engineering, (2006)], [Sclater, Chironis, (2001)], [Sarafin, (2002)]:

i) Support structure complexity and mass
The motors and solenoids have to be attached to the frame structure and the motion transmission devices need to be inserted to ensure that the motor’s power is properly coupled to the frame for an aligned deployment. This presents an increase in weight, part number and overall mechanical complexity and a decrease in packaging efficiency.

The advantage of both spring options is their low weight and small size which allows them to be integrated more compactly into the frame itself. Both spring cases require a deployment alignment mechanism. However, the tape-spring hinge presents an inherent advantage over the torsion spring which alleviates the alignment mechanism’s weight: it is a self-locking device that remains stiff and geometrically precise once deployed.

This eliminates the need to add a hefty backbone to the spring, as is required for the torsion spring option. The tape-spring hinge’s disadvantage is that its unfolding moment-rotation relationship is quite nonlinear, so a damping mechanism must be devised to allow it to work well under these conditions. To conclude, the use of motors can easily become overly complex and heavy, so the alternative spring options would be preferable, particularly the tape-spring hinge.

ii) Electronic complexity
Stepper motors and escapement-controlled hinges require current pulses to function (ON/OFF), whereas brush and brushless motors use motion controllers that require a more complex signal and electronics, which in turn increases the system’s weight. Brush and brushless motors require some forms of feedback, whereas stepper motors can operate in a simpler open-loop system. However, the disadvantage of the absence of...
feedback is that it gives us no knowledge of whether the motor is actually working. At this point in time, the mission requirements do not specify a preference for an open or closed-loop system.

iii) Smoothness and controllability
Generally speaking, motors provide a smooth and controllable motion. The spring options require a mechanism to control the release rate of internally stored elastic energy. Otherwise, large displacements could impart high inertia to the frame, and this can be very difficult for the spacecraft’s attitude control compensation.

iv) Space heritage
Space heritage is an indicator of the history and frequency of use of these mechanisms in the space environment.

To conclude this section, choosing the tape-spring option can offer weight savings, but presents the design challenge of finding an acceptable mechanism that could control the release of strain energy to minimize the inertial effects during deployment. For this reason, the project’s hinge design will first be based on Pellegrino and Watt’s “Tape-spring Rolamite Hinge” shown in Figure 4 and subsequently modified to include a deployment breaking mechanism.

4. Proposed Tape-spring Hinge Design
The earlier Tape-spring Rolamite Hinge (TSR) [Pellegrino, 2002] combines the tape-spring configuration shown previously with motion guide wheels that ensure the deployment’s position repeatability in one degree of freedom. Once deployed, the hinge becomes locked due to the tape-spring’s snapping into a final stiff straight configuration. This design’s motion is not controllable and produces a violent snap-through shock when the tape-spring locks into its final configuration.

This initial design was modified to break the deployment motion in order to reduce its output inertia. The new hinge design shown in Figure 5 respects the frame and hinge design constraints without sacrificing the hinge’s light weight, robustness and electronic simplicity. The many changes that were made from Pellegrino’s initial design include the use of spring steel tape-springs, a planetary gear system with pins, a motion control mechanism, and a Shape Memory Alloy (SMA) actuator.

Figure 5: Modified Tape-Spring Hinge Design

When studying tape-springs, Pellegrino has worked with many materials such as composites, copper-beryllium and off-the-shelf plastic-coated carpenter tapes. Due to availability and ease of manufacturing, spring steel strips were used as they could readily be cold formed at the Canadian Space Agency’s machine shop to acquire their longitudinal curvature. This enabled the manufacture and testing of different tape thicknesses, and that experimental work is detailed in the following sections.

Pellegrino’s design used tensioned cables that ran along the periphery of the Rolamite wheels to keep the contact between both wheels at all rotation angles. This tensioning scheme required overly complex fastenings that needed to be equally tensioned on either side of the hinge. We also found that this design made the hinge susceptible to slipping and lower positional precision, so we opted for gear-surfaced guide wheels and pins placed on either side of the hinge to ensure repeatable and aligned motion.
The deployment control mechanism was inspired by a traditional clock escapement mechanism, such that the one degree of freedom hinge deploys as the hands of a clock would unwind. The escapement mechanism shown in Figures 5 and 6 is meant to break the hinge’s deployment by allowing the tape-spring’s stored elastic power to be released intermittently. A Graham or dead-beat type was chosen and designed following clock-maker’s handbooks and guidelines [Britten, 1978] [Headrick, 2002]. The escapement’s pallet is activated by an SMA wire.

Clock mechanisms were chosen over watch mechanisms, because it is preferable for the pallet to exhibit a minimal loss of mechanical contact with the wheel as to ensure maximum controllability of its movement at all times. The Graham escapement is regarded as the 'ideal' escapement in terms of motion predictability, low friction, and efficiency.

This mechanism’s pallet swivels back and forth around its pivot point to allow the step-by-step rotation of the wheel, i.e. an angular rotation of half a tooth at a time. To minimize the inertia that would result from each beat, the number of teeth chosen was 45. Thus, the hinge deploys in 8 degree shots, which was determined to be a safe arc length for the end of the masts to travel without endangering the loosely-attached membrane. The membrane’s in-plane tension is only applied once the deployment sequence is complete.

As seen in Figures 5 and 6, an SMA wire is used to control the clock escapement’s pallet. The “shape memory” characteristic is manifested when an apparently deformed martensitic (or cold) SMA specimen recovers its previously undeformed shape upon heating to its parent (or austenitic) phase. During this reversible crystal lattice transformation, a wire specimen’s shape change can be observed macroscopically by a contraction or shortening of the wire. This simple movement creates a relatively large output force that can be exploited mechanically to produce work [Kohl, 2004].

For this case, the SMA is to be used as a pulsing actuator, i.e. it must repeatedly contract and relax to allow the gradual release of the tape-spring wheels. The escapement pallet's necessary displacement (within millimeters) and pull-force required for releasing the wheel is of the same order of magnitude as what can be achieved with an SMA wire length of 5 to 10 cm and diameter of 0.381 mm (0.015”).

The SMA’s transition temperature must be chosen to be higher than what the mechanism would see in orbit, which is considered to range around +/- 60 degrees Celsius for an insulated mechanism at LEO (Low Earth Orbit). Once the SMA is experimentally optimized for transition temperature, length and current input, its fixed extremity can simply be fastened to the antenna frame. In summary, the use of SMA wire actuation instead of motor actuation greatly reduces the redundancy and complexity of the setup.
5. Experimental Setup and Results

The tape-springs hinge’s experimental setup needs to best reflect the lower gravity environment. The hinge’s testing should cover the overall functionality of the mechanism and the choice of the tape-spring parameters.

5.1. Experimental Setup

To keep the gravity vector constant and minimize its effect throughout the hinge’s deployment, it was set to deploy horizontally. An antenna frame member was sized and attached to the free extremity of the hinge to mimic the prototype’s inertial load. However, since this member proved to be quite heavy, it increased the friction in the hinge and impeded its motion. Consequently, an air bearing was added to support the frame’s weight and minimize friction within the hinge. At 689.5 kPa (100 psi), the bearing’s air cushion let the tape-spring hinge deploy with minimal gravity-induced friction. The hinge’s opposite extremity is fastened to an elevated table. The table was machined to permit the installation of a load cell in a variety of fixed angular positions with respect to the hinge. This permits the measurement of the tape-spring’s force output with respect to the hinge’s position as it deploys. The experimental setup is shown in Figure 7.

5.2. Deployment Control Functionality

The next step is testing the effectiveness of the deployment control mechanism: the clock escapement. These components were machined from high carbon steel by EDM (electro-discharge machining) to achieve high geometric accuracy. As shown previously in Figure 6, one extremity of the pallet was fastened to the SMA, which in turn was connected to a power source. By sending a pulse of current through the SMA, it would heat up and contract, thus swivelling the pallet and thereby releasing a tooth of the wheel. As the wheel is allowed to rotate since its motion is powered by the force of the tape-spring, the opposite side of the pallet catches into a wheel tooth and blocks the mechanism. When the SMA cools, it gradually returns to its initial position, thanks to a bias torsion spring within the mechanism.

For the escapement to work, the friction between the escapement pallet and the wheel must be minimized, since the SMA’s force must make the pallet escape from the wheel. When the SMA contracts and the pallet momentarily escapes, the hinge unfolds under the elastic strain release of a sufficiently strong tape-spring pair. Once the
opposite side of the pallet locks into a wheel tooth, it stops the hinge’s motion. As the SMA cools down, the bias torsion spring overcomes the friction between the pallet and the wheel and forces the pallet out of the slot. At this point, the hinge continues to unfold until the opposite side of the pallet catches a tooth once again. The SMA is then heated, it contracts, and pulls the pallet out against both the bias spring and the friction between the pallet and the wheel. The pallet is then released and the cycle begins anew.

Many deployment experiments were conducted. Though some problems were encountered, it was possible for the hinge to deploy completely and independently.

The main challenges were due to the pallet’s incapacity to dislodge itself from the wheel teeth due to excessive friction. The mechanical play and friction in the mechanism can be reduced by using tighter tolerances between the motion guide wheels and by including bushings at the pin connections. The friction in the escapement can be reduced by polishing the pallet surface, by varying the materials, by minimizing the tape-spring thicknesses, and/or by including a bushing at the pallet’s pivot point. Another mishap that could impede the entire deployment would be the slipping out of the SMA wire from its fasteners. If the overall bias force on the SMA cannot be reduced, an improved wire crimping method should be explored.

5.3. Tape-Spring Experimental Results

The experimental setup described earlier was used to acquire the moment-rotation relationships for three different tape-spring thicknesses: 0.127mm, 0.152mm and 0.178mm (0.005”, 0.006” and 0.007” respectively). These thicknesses were chosen so that the antenna structure’s mechanical prototype has strong enough tape-springs for the hinge to deploy the frame laterally without any gravity-compensation structure such as the air-bearing. With the study of these three thicknesses, the possibility to extrapolate the behaviour to other spring tape thicknesses is evaluated. The tape-spring’s material and geometric parameters determine their elastic response, as discussed in Pellegrino (2002) and Shen et al. (2007). Other than the varying thicknesses, the tape-spring’s geometry was kept constant as detailed in Figure 8 and Table 2.

![Figure 8: Tape-spring Geometric Parameters](image)

| Table 2: Tape-spring Geometric Dimensions |
|-----------------|-----|
| L between fasteners (mm) | 85.4 |
| R (mm) | 17 +/- 2 |
| α (deg) | 35 +/- 10 |
| h (mm) | 16 |
| a/2 (mm) | 9 |
| B (mm) | 6 |
| Width of rectangular cross-section (mm) | 25.4 |

The hinge was gradually folded from the fully deployed (0 degrees) to the fully stowed (180 degrees) position and the force output measurements were taken at 2.5 degree intervals with an Omega load cell. For each thickness, three pairs of tape-springs were tested twice each. The force output readings were not affected whether
the hinge was folding or unfolding, and this conclusion was also confirmed in Pellegrino et al. (2002).

The moment-rotation curves for all three thicknesses are shown in Figure 9.

Figure 9: Experimental results of the moment-rotation behaviour during the deployment of the tape-spring hinge

The deployment’s pattern is very similar to that found in Pellegrino (2002). In all cases there is a kick-off moment at the hinge’s release (180 degrees), and as it deploys, the output moment gradually decreases and stabilizes as the tapes unfold and as they lose contact with each other. Just before attaining their final deployed state, the tapes unbuckle, providing a last jump in output moment as the hinge snaps through and self-latches into its final straight and stiff position. It is intuitive to observe that the output moments increase with the tape’s thickness.

6. Conclusions and Recommendations for Future Work

This paper presents a design for actuating the deployment of a satellite antenna frame. The modified tape-spring hinge design was presented and included a novel way to control the deployment motion intermittently by using a clock mechanism. Experiments were carried out using three thicknesses of spring steel tape-springs and were compared to previous work. The overall functionality of the hinge was discussed and solutions were proposed to relieve the challenges encountered during the testing phases.

The use of SMAs in space presents itself as an interesting low-weight option for actuation. However, many of its parameters (dimensions, input current) still need to be optimized. Finally, thermal analysis should be carried out to ensure the system’s performance in the rigorous space environment.

References


