Concept Design and Numerical Simulations of Deployment Mechanism for Foldable Planar Antenna

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Abstract: Deployable structures have been integral and crucial elements of spacecraft missions ranging from large deployable booms to reflector antennas and even a robotic arm. This paper brings out one prospective design solution for the deployment mechanism for a deployable planar antenna within given design considerations and constraints. The paper also presents various factors influencing the design of deployment mechanisms, including precise latching and launch environmental conditions. This work aims to simulate the deployment mechanism in a 3-D CAD environment and simulate the unfolding process of the planar antenna. Modeling the unfolding process with sequencing and latching mechanisms is one of the challenges addressed here. The software tool used for 3-D CAD simulation is Autodesk Inventor, whereas, Ansys rigid body dynamics is used to perform the dynamics and kinematics simulation of the arrangement. Design sensitivity has been checked by varying design parameters such as COF and spring stiffness. Static analysis of loaded components is performed in the Ansys transient structure environment. The results are compared with the requirements and limitations for the space missions.

Keywords: Deployment mechanism, unfolding, planar antenna, latching mechanism, sequencing mechanism, dynamics simulation, kinematics simulation.

INTRODUCTION

The satellite market has shifted towards a constellation of small satellites, rather than having one cumbersome satellite, in the recent past. The motive behind this approach is modularity, low launch and development cost, and faster turnaround time while not compromising on targeted payload objectives. ISRO has also geared up for competitive market strategies and has been focusing on developing small, micro, and nanosatellites for various missions in the past. A perineal problem with smaller satellite volumes is the limitation in their capacity for power generation and transmission of RF signals to and from the Earth. The problem has a direct solution of compressing the required size of various spacecraft structures into a compact stowed volume and deploying them once in orbit.

Deployment mechanisms are essential components of space missions for several critical reasons. Firstly, these mechanisms allow for the efficient packaging and transportation of spacecraft and payloads during launch. Spacecraft and satellites often have components such as solar panels, antennas, and scientific instruments that need to be folded to fit within the confines of the heat-shielded chamber. Secondly, deployment mechanisms are necessary to ensure that these folded components can be safely and reliably deployed once the spacecraft reaches its intended orbit or destination. Deployment mechanisms allow for the controlled and precise release of these components, ensuring that they function as intended in the harsh environment of space. [1]

The use of planar antennas is common in Microwave Payload for Remote Sensing and wireless communication due to their low profile, lightweight, low cost, low volume, versatility in design to meet different requirements such as frequency, bandwidth, and radiation pattern, cost-effectiveness for mass production, and ease of fabrication. Deploying a large array of planar antenna is a present-day requirement for high-resolution microwave imaging at various microwave frequencies and end-use applications. [2]

As reported in prior art deployment mechanisms can be either active or passive types depending on the fact, whether it requires electrical power to actuate mechanical components, typically utilizing electric motors or they make use of strain energy stored in mechanical springs to supply the necessary energy for deployment. Such passive deployment mechanisms are only triggered once the satellite is in orbit. [3]

This work proposes a methodology to design mechanisms for planar antenna deployment, where the inter-panel gap is required to be precisely maintained and also straight planarity across all the panels is ensured within specified tolerances.

A comparison of prior arts for both active and passive methods of deployment has been complied with and shown in Table 1 and Table 2.

As is well known (and can be observed in Table 2), the primary disadvantage of active mechanisms is their need for power to function, therefore, a common passive solution for rotary motion is torsion springs. These springs offer several advantages, such as no power consumption, linear mechanical behavior compact volume, and low mass, among others (see Table 1). [4]

A passive spring-based deployment solution comes with an inherent disadvantage of no defined final position. Thus, a precision latch mechanism is essential at the end of deployment to complement the passive deployment methods.

This work addresses the design of hinges, incorporating latching elements to ensure the precisely deployed position, coordinated with sequencing components. The proper integration of these elements ensures a controlled and reliable deployment process, enhancing the overall stability and functionality of the deployed antenna.

Table 1: advantage and disadvantages of passive deployment [5]

Element	Advantages	disadvantages
Shape memory alloy	Can be used for retracting	Risk of forgetfulness when stowed for a long time
Coil spring	Usable in axial and radial directions	Do not lock the panel in the end position
Flexible joints (bent strap)	Locks panel in final position	Difficult to damp at the end position
Torsion springs	Can be easily incorporated with Damping mechanisms	Small force remaining at end of Deployment
Spiral spring	Decelerates close to the final position	Small torques possible

Table 2: advantages and disadvantages of active deployment [5]

Element	Advantages	Disadvantages
Electric motor	High precision	Additional energy required
Hydraulic actuator	Retractable	The system required a large space
Pneumatic actuator	Retractable	Leak problem
Deployable boom	Suitable for large solar arrays	Additional power is required for Deployment.
Inflatable booms	small number of mechanical parts	suitable for thin-film solar arrays only
Rotating deployment	Low volume requirements in stowed position	Complex deployment process
Telescopic cylinder	Retractable	Too large volume requirements in the axial direction
Mechanical guidance	Good precise guidance; includes damping at the end of the deployment process.	Many components are required, suitable for one panel only.
Tether	Volume and mass-efficient solution	Inaccurate guidance

Deployment scheme

Figure 1 presents one of the numerous stowing and deployment methods for deploying Antenna panels onboard small satellites. The approximate size of antenna panels considered for the concept design is 0.7mX0.7m. The arrangement makes use of three deployable panels on either side of one fixed panel forming a deployed size of 4.9m X0.7m planar antenna aperture.

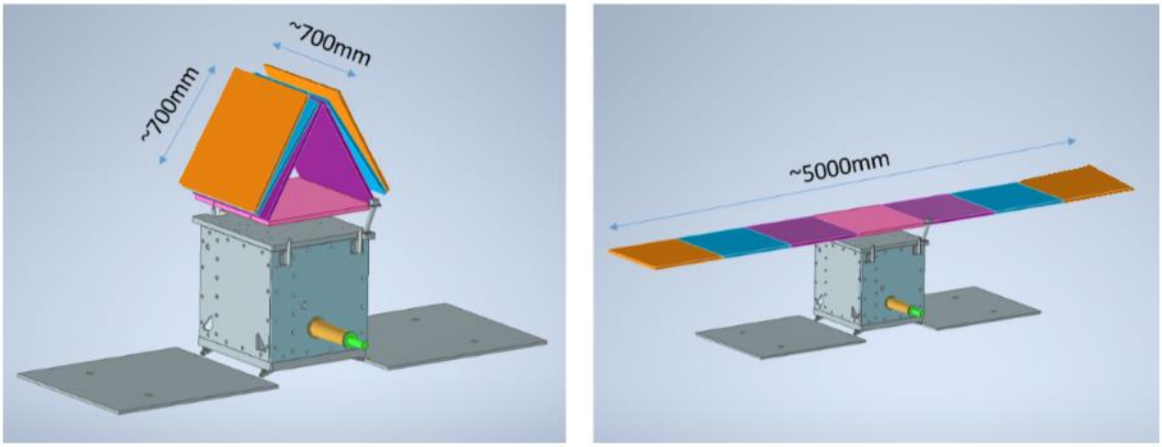

Figure 1: stowed and deployed condition of panels

The design of the deployment hinge is performed considering a maximum of 180-degree deployment angle for each panel.

Driving and Locking mechanism

The design of a hinge itself accommodates the driving torsional spring, which uncoils and provides driving torque as and when the panels are released for deployment. The design considers all panels to be symmetrically stowed and connected using hinges. The design of the hinge and assembly of the driving mechanism for a top-to-top folding condition is represented here. Figures 2 and 3 show the graphical representation of the assembly of the driving hinges from different views. As presented in Tables 1 and 2, there were several design options envisaged for achieving the required deployment and based on merit the preset solution is considered for its advantage over other options in terms of repeatability, manufacturability, modularity, and low cost.

The design of the latch serves as a locking mechanism at the deployed position. Latching involves two key components: a plunger that restricts the motion of the pin, and a latching pin that is designed to be latched. A spring-loaded plunger is used to latch onto the next panel from the side wall, ensuring secure attachment. [6] This latch is seamlessly integrated with the part of the sequence mechanism to minimize weight. The shaft of the pulley serves as a pin to be latched. To accommodate a compression spring, a gap is provided between the cap and plunger. Additionally, threads on the cap enable the adjustment of spring force by varying the gap. Here figure 4 represents the CAD model of the latching assembly and Figure 5 shows the cross-section of the latch component.

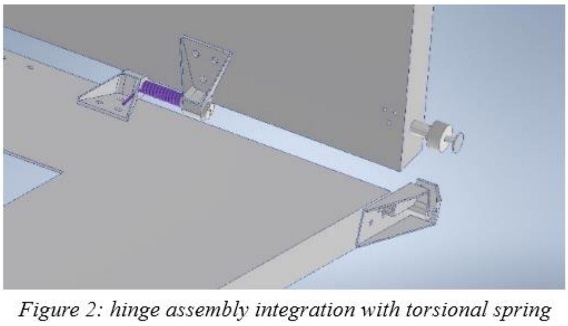

Figure 2: hinge assembly integration with torsional spring

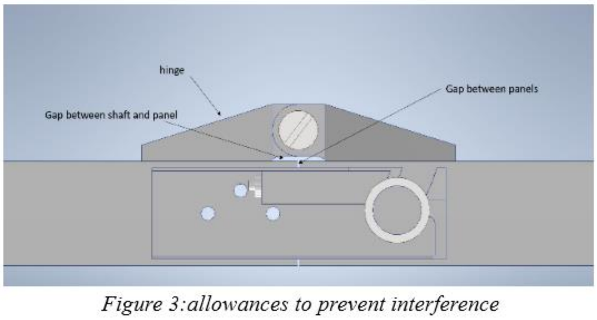

Figure 3:allowances to prevent interference

The axis of the spring-loaded plunger can be oriented either in the direction of the hinge axis or perpendicular to it. However, when the latch direction is perpendicular to the hinge axis, it offers a more rigid and fail-safe locking mechanism for the system. By maintaining offset of latching position to the revolute joint axis which provides greater accuracy for locking. This configuration enhances the stability and reliability of the locking mechanism, ensuring secure attachment and minimizing the risk of unintended movement or detachment of deployed components.

Figure 6 shows the position of the latch point as well as the locus of the pin during deployment. Figure 7 shows the final position of the pin at deployed condition.

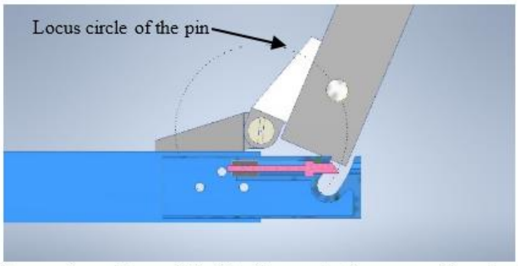

Figure 4: position of the latching point (cross-section view)

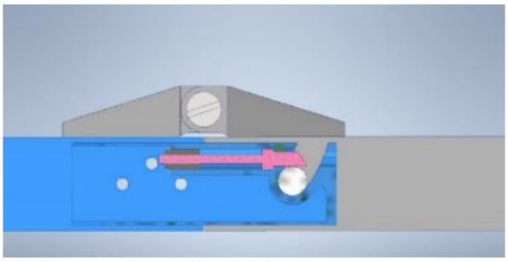

Figure 5: deployed condition (cross-section view)

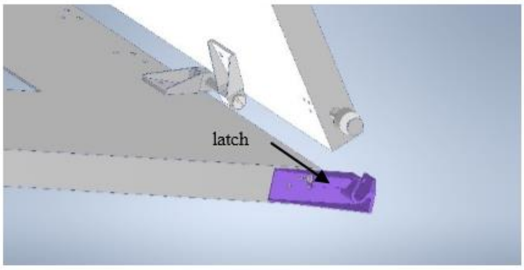

Figure 6: latch assembly

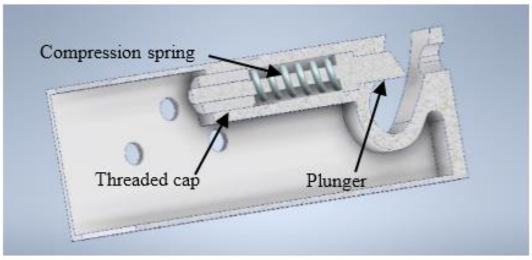

Figure 7: working of plunger [9]

Sequencing mechanism

To ensure controlled deployment in the space environment, integrating a sequencing mechanism is essential. This mechanism allows for the deployment process to occur in pre-planned phases, ensuring that each component deploys in a specific order. By utilizing the principles of conservation of momentum, the sequencing mechanism helps prevent panels from colliding with each other or with other payload components. This orderly deployment is crucial for maintaining the attitude stability of the satellite.

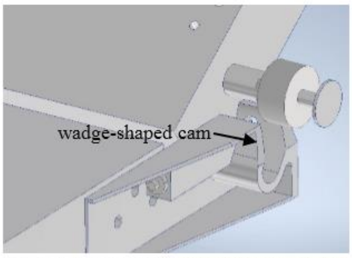

Figure 8: Element of sequencing mechanism

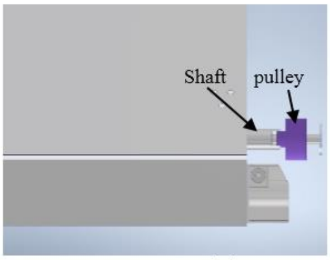

Figure 9: Engagement and disengagement of pulley

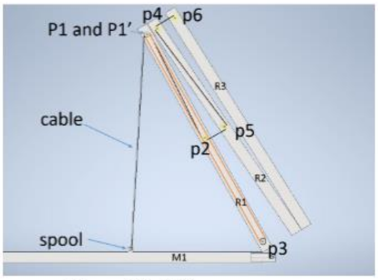

Figure 10: Pulley arrangement

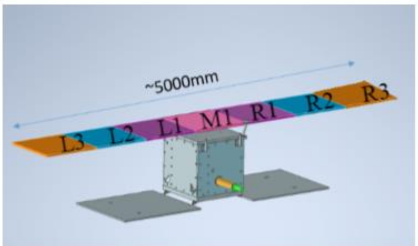

Figure 11: Panels nomenclature

The proposed sequence mechanism relies entirely on cables and the movement of pulleys. The graphical representation shows the arrangement on one side only, but a similar setup exists for the other three panels (not shown in the illustration). The pulleys are mounted on the sidewalls of the panels at specific locations, and their rotation can be locked or unlocked with a shaft. Initially, pulleys P3 and P4 are locked in place with shafts, preventing their rotation. Pulleys P1 and P1' are internally connected so that they rotate together (as illustrated in Figure 11). Pulleys P1, P1', and P3 are attached to panel R1, while P4 and P5 are on panel R2, and P6 is on panel R3.

At the start, a cable is threaded through the pulleys in a specific sequence, with the remainder wound onto a spool. One end of the cable is fixed at pulley P6, and it is routed through P4, P5, P2, and P1 in that order before being wound on the spool. An additional cable (shown in orange) connects pulleys P1' and P3 to ensure they rotate together; however, pulley P3 is initially locked, restricting the rotation of P1. The cable cannot pass through the locked pulleys due to the high friction between them.

At the beginning of the deployment process, the main cable cannot move through pulley P1, so the cable released from the spool remains between the spool and P1. As the cable is released, the angle between panels M1 and R1 increases, while the other panels remain folded. When panel R1 is fully deployed (marking the completion of stage 1, as shown in Figure 12(b)), pulley P3 is lifted by a wedge-shaped cam (shown in Figure 9), unlocking P3 for rotation (shown in Figure 10). Once P3 is unlocked, P1 is also free to rotate. The main cable (shown in black color) can now pass through P1, but it still cannot pass through P4, which remains locked.

When the cable is released between P2 and P5, stage 2 of deployment begins. Upon successful completion of stage 2, P4 is allowed to rotate (with a locking and unlocking mechanism similar to P3's). Until stage 2 is completed, panel R3 remains folded relative to R2 (as shown in Figure 12(c)). When P4 is free to rotate, the cable can pass through it, initiating the third stage of deployment.

Stage of deployment

Sequencing is essential for stabilizing the platform and controlling its attitude during the deployment of solar panels or scientific instruments. This sequencing mechanism divides the deployment of the planar antenna into distinct stages, preventing collisions and damage to the panels. Each stage deploys one panel at a time, symmetrically from both sides, while the remaining panels remain fixed relative to the deployed panel. The next stage initiates only after the previous panel reaches its required position, ensuring controlled, step-by-step deployment and maintaining the integrity and alignment of the structure. Figure 12 illustrates the various stages involved in the complete deployment of the panels.

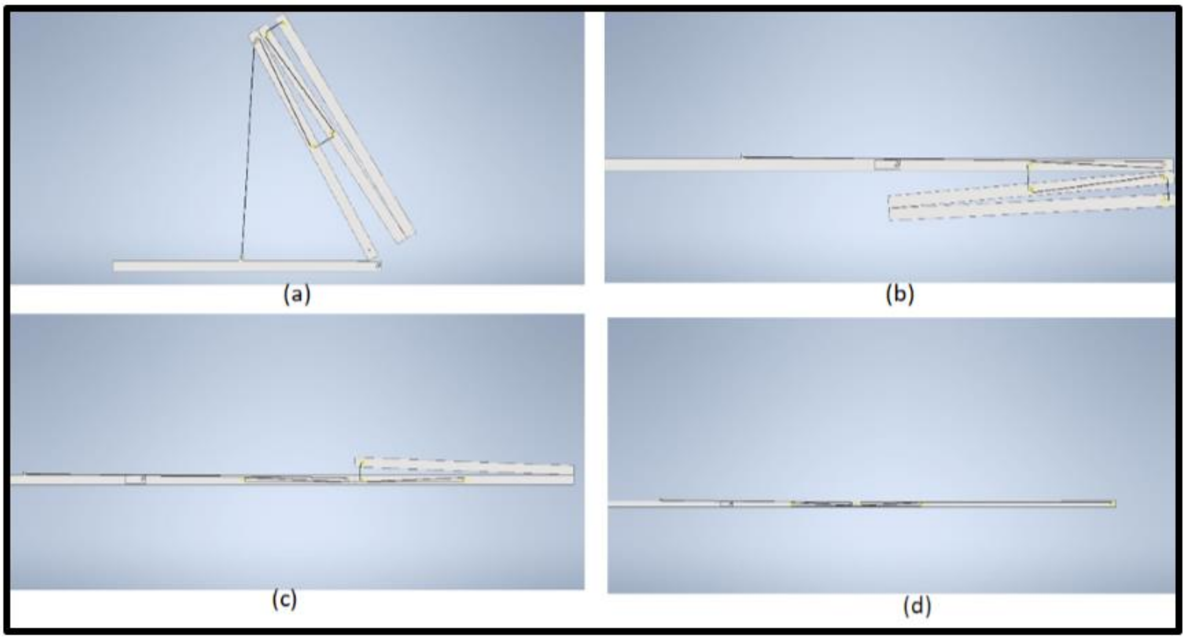

Figure 2: (a) stowed configuration (b) stage 1 (c) stage 2 (d) final configuration

Rigid Dynamics simulations of the mechanism

Here, dynamic simulation was conducted for the deployment of up to two panels, analyzing results under all relevant space environments and conditions. The hinge elements are considered to be made of Aluminum alloy.

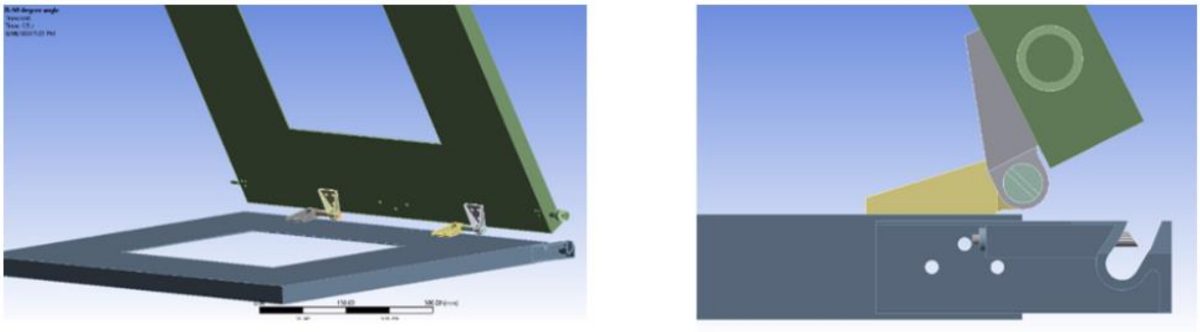

Figure 3: FEM design validation

The mass of each panel is considered as 3 kg, to simulate actual antenna mass and measures 700 x 700 x 30 mm. For dynamic simulation, a coefficient of friction (COF) of 0.43, for dry aluminum surfaces, was applied to all connecting surfaces. In the first iteration, the stiffness of the torsional and compression springs was set to 3 N*mm/deg [7] (calculation is shown below) and 1 N*mm/deg. Respectively for successful latching. These values are calculated from the standard formula for torsional spring, with a damping factor of 0.5% [8]. The torsional springs were pre-loaded to 210 degrees.

Torque produces by torsional spring:

$$d\tau = k\, d\theta$$

$$d(I\ \alpha) = k\, d\theta$$

$$I \int_0^1 d\alpha = k \int_{90}^{210} d\theta$$

$$\left[\frac{ml^2}{12} + \frac{ml^2}{4}\right] \int_0^1 d\alpha = k \int_{90}^{210} d\theta$$

$$\frac{(3)(0.7)^2}{12} + \frac{(3)(0.7)^2}{4} = k\ (120)$$

k = 4.08 N mm/deg

here, the coefficient of friction is 0.43 for the dry aluminum surface so the required spring stiffness will be:

k = 4.08/0.57 = 7.15 N mm/deg

Here, 2 similar springs are provided to apply torque.

The maximum stiffness of each spring will be:

k = 3.57 N mm/deg

The minimum stiffness required to overcome friction will be:

k’ = 3.57 (0.43) =1.5 N mm/deg

Required spring stiffness: $1.5 \leq K \leq 3.57$

Initially, the torsion spring is preloaded to impart torque to the system. As the deployment angle increases, the torque provided by the spring decreases accordingly. This design ensures that the spring exerts sufficient force to overcome friction and initiate the desired motion, which is critical in the space environment where gravity does not influence the dynamics.

In the gravity-less environment of space, the primary purpose of torque is to counter inertial and frictional forces and set the object in motion. Therefore, the focus is on achieving the precise amount of torque necessary for the task rather than generating large amounts. The preload of the spring is carefully calibrated to achieve this balance, ensuring smooth and controlled motion of the object. Additionally, it must be capable of countering the reaction force applied by compression springs.

Moreover, the remaining torque generated by the preloaded spring can be utilized to secure the panels in the deployed position, thus minimizing potential vibrations. In the microgravity environment of space, even slight vibrations can have significant consequences, affecting the stability and performance of sensitive equipment. By utilizing the inherent torque of the preloaded spring to stabilize the panels, we can enhance the reliability and precision of the deployment process.

SIMULATION RESULTS AND DISCUSSIONS

(1) angular acceleration

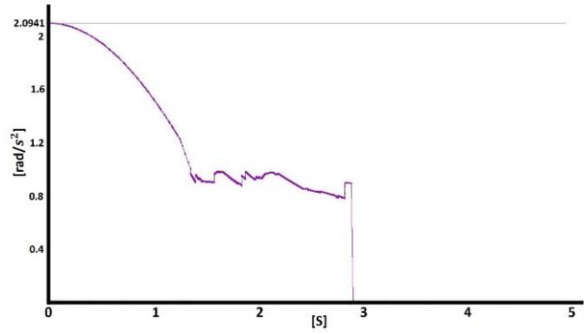

Figure 4: angular acceleration

The graph (Figure 14) depicting angular acceleration illustrates the behavior of the torsion springs. Initially, when the preloaded torsion spring provides ample torque, it results in a significant acceleration, which gradually decreases from 2.09 to 0.9 m/s^2 as the spring unwinds. At around 1.3 seconds, the shaft of the pin begins to engage with the latching mechanism and encounters the latching plunger. During this contact, friction opposes the motion, leading to fluctuating acceleration values in the bounded range from 0.9 to 1 m/s^2 until approximately 2.9 seconds. Subsequently, as the shaft releases from the plunger, the graph returns to its initial characteristics. At 2.9 seconds, when the panel locks into the latching position, the acceleration becomes zero.

(2) Angular velocity

The angular velocity graph (Figure 15) serves as a visual timeline of significant events throughout the simulation. Initially, there is a sharp ascent in velocity until 1.3 seconds, reaching 2.4872 m/s, showing the free motion of the panels which is followed by a sudden drop to 0.1 m/s. Subsequently, a period of sustained low velocity persists, due to the occurrence of the latching event, until around 2.3 seconds. Following this phase, there is a gradual increase in velocity again after the max displacement of the plunger. At the crucial moment of 2.9 seconds, the mechanism latches, at the desired position, and velocity becomes zero.

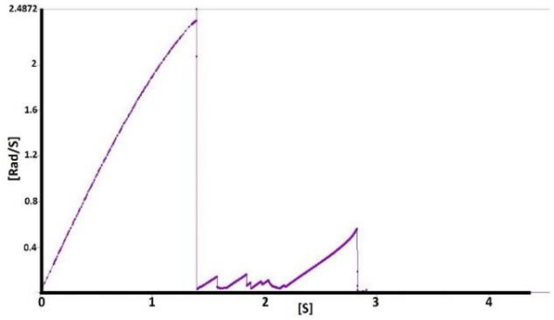

Figure 5: angular velocity

(3) Reaction force on the hinge shaft

A graph (Figure 16) shows the reaction force acting on the shaft which helps to determine the appropriate shaft design parameters to meet the specific requirements of the application. Upon analysis of the graph, it is observed that initially, the spring exerts reaction forces on the shaft in the negative y and z directions. However, as the angular velocity increases, the reaction force in the negative y direction escalates while the resultant force in the z direction diminishes due to centrifugal forces. Due to contact with the plunger, the angular velocity of the shaft instantaneously decreases, resulting in a reduction of the reaction force in the negative y direction. Subsequently, the pulley imposes reaction forces on the shaft in the z and negative x.

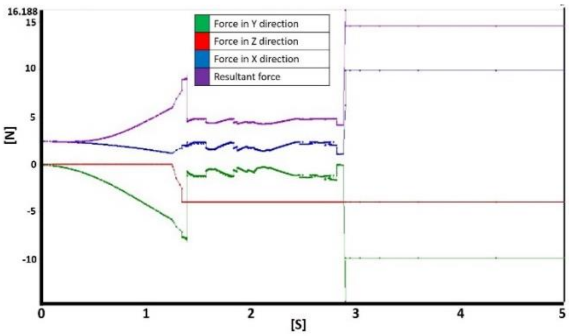

Figure 6: reaction force on the hinge shaft

Design sensitivity

The surface finish directly impacts the coefficient of friction. We aim to leverage it to dissipate excess kinetic energy at the deployed position. By reducing velocity, we can keep changes in the spacecraft's attitude within controllable limits also minimize the jerk. Design sensitivity is checked by varying the coefficient of friction in dynamic simulation and comparing the value of acceleration, velocity, reaction forces, and total energy. Dynamic simulation is performed by taking the coefficient of friction 0.2, 0.3, 0.43.

Here, after analyzing data (Table 3) we can conclude that as the coefficient of friction increases frictional loss increases in the range of 200 mJ which can be useful to reduce the velocity before the latching. Here, the change in max velocity is negligible, which that illustrates the frictional loss between the shaft and hinge is very low.

Table 3: Comparison of dynamics analysis data

	Coff. of friction =0.2	Coff. of friction =0.3	Coff. of friction =0.43
Max velocity(rad/s)	2.493	2.49	2.4872
Velocity range during latching(rad/s)	0.1	0.09	0.08
Max acceleration(rad/s^2)	2.0941	2.0941	2.0941
Acc. Range during	0.97	0.95	0.9

latching(rad/s^2)			
Reaction on shaft(N)	4.2	4.4	4.6
Kinetic energy(mJ)	1868.7	1864	1860
Frictional loss(mJ)	2771	2792	2927

CONCLUSION

This paper proposes an innovative concept design for latching and sequencing for the passive deployment mechanism of planar antennas. This deployment mechanism offers significant advantages over other solutions, employing a rope and pulley concept for stage-wise deployment. Stage-wise deployment helps in minimizing eddies, affecting satellite stability, towards the end of deployment.

An analytical, as well as, simulation-based approach is used to evaluate the spring rate required for deployment and precise latching of the mechanism after deployment.

The transient analysis has been conducted to understand the system's behavior during the deployment process. The role of revolute joint friction has also been assessed during the deployment and it's concluded that the change in friction coefficient of a revolute joint doesn't significantly affect the deployment kinematics and reaction forces.

This conceptual design for the hinge marks the initial step in developing a fully operational prototype suitable for space conditions. Future work will involve vibration validation and prototype testing on the designed components. Additionally, manufacturing constraints must be taken into account for all mechanical elements to ensure the feasibility and reliability of the final product.

In brief, the proposed design offers several advantages. It utilizes a passive deployment technique with motion guidance that operates without external energy, ensuring efficiency and simplicity. The locking mechanism provides rigidity at the final position, while the sequencing mechanism ensures stability and fail-safe deployment.

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