PRATHAM

IIT BOMBAY STUDENT SATELLITE

Preliminary Design Report

Mechanisms Subsystem

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1. Introduction

Whenever any particular task cannot be done solely with the help of electric circuitry and when some mechanical relative movement is required to realize an objective Mechanisms Subsystem comes into picture. Generally it's a case when electric circuits control the working of mechanical parts but sometimes vice-versa may be true! Since ours is a microsat there are many restrictions over designing a mechanism viz. low mass, compactness, space grade parts, no floating parts, friction and so on. Often its not feasible to use a highly complex multi-component mechanism since violent vibrations and vacuum conditions can endanger the proposed working of a mechanism. And there are always machining problems that can be minimized but not neglected.

The satellite structure has two symmetric monopoles separated by a distance> 15cm. if these monopoles are kept in the deployed state during launch following problem occurs:

Root Stress of Monopole

Aim: To find the root stress/deformation of the monopole under the loads that it will undergo in deployed position during launch. The 2 Monopole must maintain parallelism after the launch.

Physical Characteristics of the Monopole: Diameter 2.3mm, Length 18cm, Material Al6061

Solution:

1. Find the resonant frequency of cantilever beam (independent of damping)

$$f_n = \frac{1.875^2}{2\pi}\sqrt{\frac{EI}{\rho A L^4}}$$

From Al6061 properties matweb.com: E=68.9 GPa, ρ=2.70 g/cc

$$m = \rho * \pi * \left(\frac{0.23}{2}\right)^2 * 18 = 2.02 gms$$

$$A = \pi * \left(\frac{0.23}{2}\right)^2 = 0.0415\ cm^2$$

$$I = \frac{\pi * D^4}{64} = 1.374 * 10^{-12}$$

$$f_n = \frac{1.875^2}{2\pi}\sqrt{\frac{68.9 * 10^9 * 1.374 * 10^{-12}}{2700 * 0.0415 * 10^{-4} * 0.18^4}} = 50.2 Hz$$

$$\omega_n = 2\pi f_n = 315.4 Hz$$

Assuming damping ζ=1%,

Hence find the variables for the simplified spring mass system.

$$k_{eq,veritcal} = \frac{3EI}{L^3} = \frac{3 * 68.9 * 10^9 * 1.374 * 10^{-12}}{0.18^3} = 48.70\frac{kg}{s^2}$$

$$\omega_n = \sqrt{\frac{k}{m}}, \qquad m = \frac{k}{\omega_n^2} = 4.9 * 10^{-4} kg$$

The harmonic vibratory base excitations on the spring mass system coming from the Launch Vehicle are shown below.

Quasi-static Loads

- Longitudinal - ±11g
- Lateral - ±6g

Sine test levels

	FREQ. RANGE (Hz)	QUALIFICATION LEVEL	ACCEPTANCE LEVEL
LONGITUDINAL AXIS	5 - 10 10 - 100	10 mm (0 to peak) 3.75 g	8 mm (0 to peak) 2.5 g
LATERAL AXIS	5 – 8 8 – 100	10 mm (0 to peak) 2.25 g	8 mm (0 to peak) 1.5 g
SWEEP RATE		2 Oct/min	4 Oct/min

Figure 4: Data of quasi-static loads

If x is the displacement of the mass and y is the displacement of the base.

$$\ddot{y} = a_0 \sin(\omega_n t), \qquad a_0 = 3.75g$$

$$m\ddot{x} + c\dot{x} + kx = c\dot{y} + ky$$

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = -\frac{2\zeta\omega_n a_0}{\omega_n}\cos(\omega_n t) - \frac{\omega_n^2 a_0}{\omega_n^2}\sin(\omega_n t)$$

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = -a_0 \sin(\omega_n t - \varphi)$$

$$x_0 = \frac{\frac{a_0}{\omega_n^2}}{\left[\left(1 - \left(\frac{\omega_n}{\omega_n}\right)^2\right)^2 + \left(\frac{2\zeta\,\omega_n}{\omega_n}\right)^2\right]^{\frac{1}{2}}} = 0.0185m = 18.5mm$$

Hence we have **18.5mm tip deflection** due to sine vibrations near its natural frequency.

The harmonic vibratory base excitations on the spring mass system coming from the Launch Vehicle are shown below.

Random vibration test levels

	QUALIFICATION	ACCEPTANCE
Frequency (Hz)	PSD (g2 / Hz)	PSD (g2 / Hz)
20	0.002	0.001
110	0.002	0.001
250	0.034	0.015
1,000	0.034	0.015
2,000	0.009	0.004
g RMS	6.7	4.47
Duration	2 min/axis	1 min/axis

Figure 5: Data of random vibration level test

Hence the monopole excitation is shown below, and the 5Hz bandwidth that is chosen.

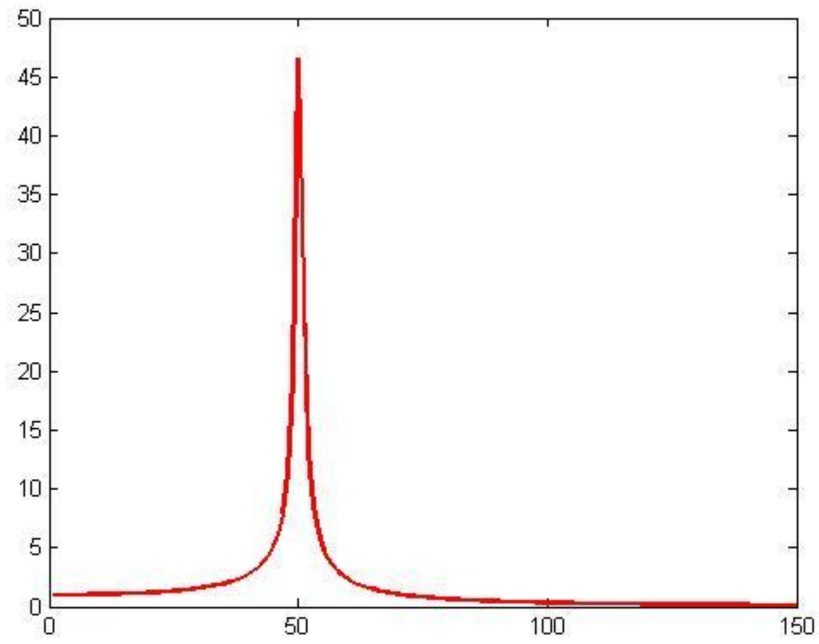

Figure 6: loading values for random vibration in PSD

The loading values for random vibrations in PSD are plotted below. Since we are doing a conservative estimate, we shall take the minimum value that falls closest to our central frequency.

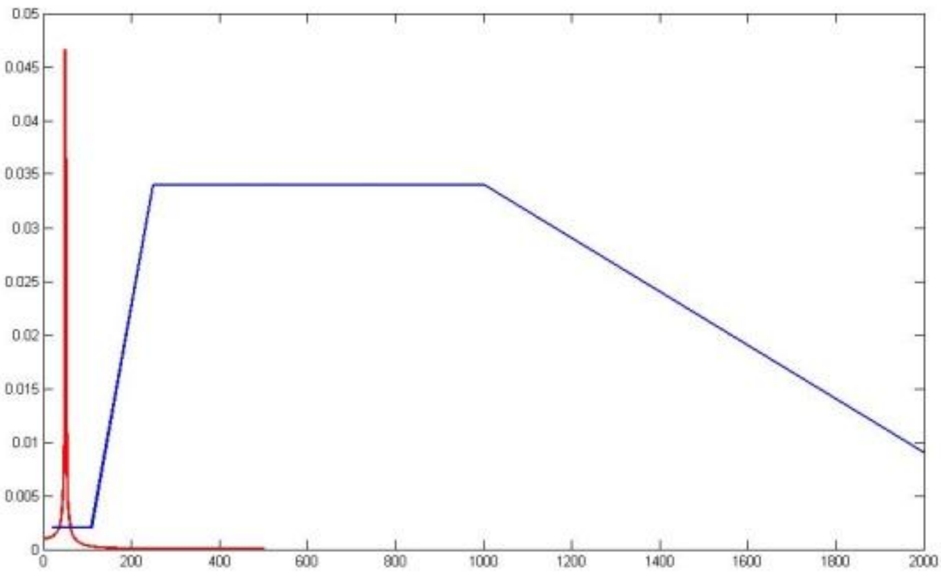

Figure 7: rms value of 'g'

Hence, we shall find the g_{rms} in the bandwidth around the central frequency.

$$a_0 = \sqrt{0.002 * 5} = 0.1g\,\frac{m}{s^2}$$

Substituting in the same equation as above.

$$X = \frac{\frac{a_0}{\omega_n^2}}{\left[\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(\frac{2\zeta\omega}{\omega_n}\right)^2\right]^{\frac{1}{2}}} = 0.0005\;m = 0.5mm$$

Hence the most conservative value of tip deflection is 18.5mm.

Assuming a tip loaded cantilever.[1]

$$\delta = \frac{Pl^3}{3EI}, \qquad s_{root} = \frac{Plr}{I}$$

$$P = \frac{3EI\delta}{l^3} = 0.9N, \qquad s_{root} = 135MPa$$

The ultimate tensile strength of Al6061-T4 is 241MPa.[2]

Since this is the simplified conservative estimate, with just the first mode taken into consideration. Many succeeding modes of the cantilever lie in the random frequency spectrum hence we expect the tip deflection and the root stress to increase.

Finally it is a mission requirement to design with 50% margin, which is already not satisfied.

Hence the antenna cannot be in deployed state during launch. Hence the Deployment Mechanism is necessary!

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1 http://www.engineersedge.com/beam_bending/beam_bending9.htm

2 http://www.matweb.com/search/DataSheet.aspx?MatGUID=d5ea75577b1b49e8ad03caf007db5ba8

2. Subsystem requirements

- Mechanisms Sub-System shall use the Launch Vehicle Interface to be provided by VSSC and attach it to the main frame of the Satellite.
- They shall detect the Satellite jettison into space by the launch vehicle using the Deployment Switch (SNAP circuit) which will switch on the Power circuit.
- The SNAP circuit should draw very low current (~10microA)
- The SNAP circuit should not trigger on due to the launch vibrations

Requirements on the Mechanism Sub-System from other Sub-Systems

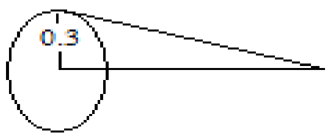
Requirements from Communication and Ground Station Sub-System to Mechanism Sub-System

Mechanisms Sub-System shall deploy the 2 monopoles such that they make 90 degrees angle with the side plane. The ± error is TBD.

They shall maintain the distance between the 2 monopoles greater than 15cm.

Requirements from Payload Sub-System to Mechanism Sub-System

Mechanism Sub-System shall maintain the parallelism between the monopoles as stated below. When two tips of the two monopoles are overlapped, the other tip of the 2nd monopole must lie within the cone; with a base radius of 0.3cm and the 1st monopole as its central axis.



Requirements from Quality Sub-System to Mechanism Sub-System

The reliability probability of the monopole deployment mechanism and the SNAP circuit should be ~1. Hence the hardware needs to be tested a large number of times (~500 times).

3. Description of mechanisms

3.1. Overview of monopole deployment mechanism

Table 1: Deployment Mechanism Parts

Leaf 1	One leaf of hinge.
Leaf 2	Other leaf of the hinge, having a semicircular rail perpendicular to it.
Hinge axle	A cylindrical rod holding the two leaves of the hinge.
Hinge spring	It is a torsion spring placed concentric with the Hinge Axle.
Locking cover	Outer Cover for the locking assembly.
Locking pin	Circular plate with a cylindrical protrusion.
Locking spring	Compression spring, to push out the Locking Pin from the cover.
Back plate	Plate to close the Locking Cover.
Dyneema string	Polymeric wire to hold Antenna.
Heating resistors	Value 5 to 10 ohms

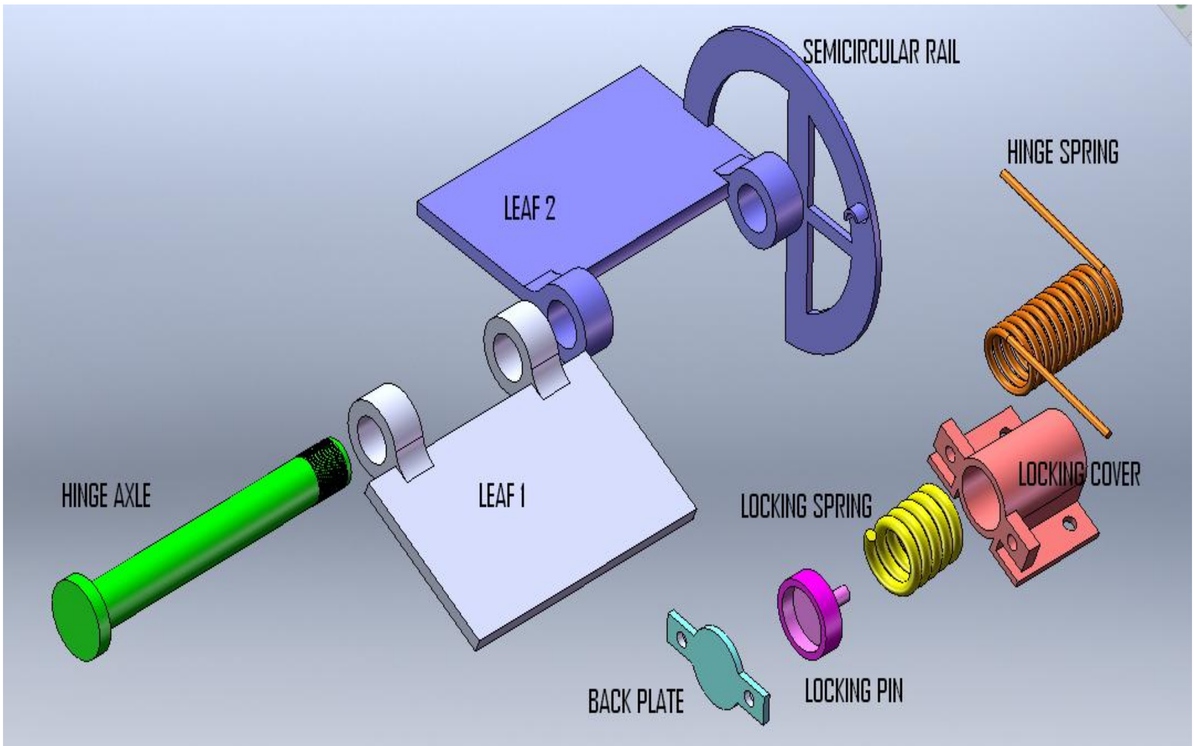


Figure 5: Exploded view of hinge

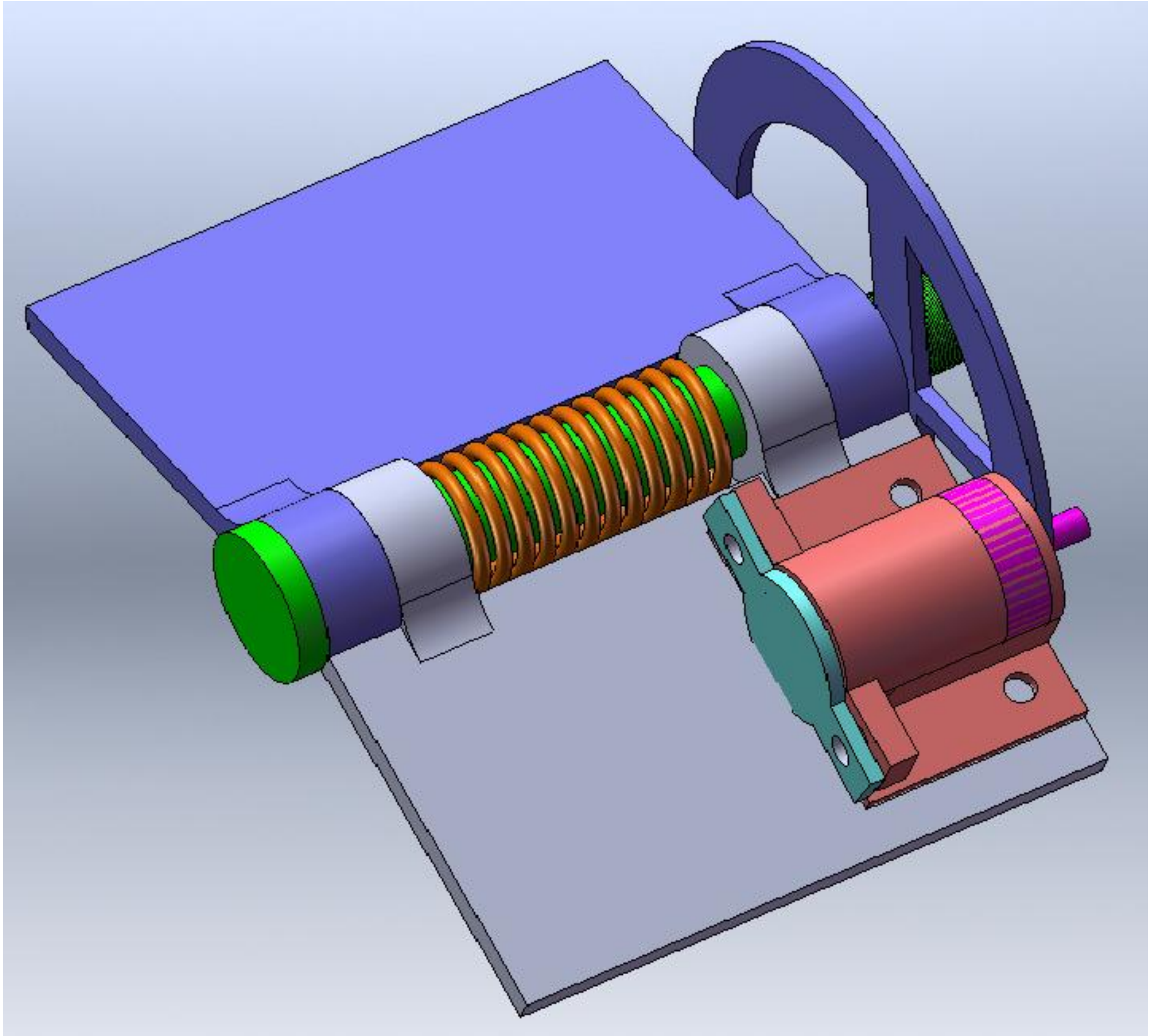


Figure 6: Integrated view of hinge

3.2. Stowing mechanism

In the stowed state the angle between the leaf 1 and leaf 2 is 90 degrees. The Hinge Spring is in stressed position. This position is maintained by tying a thread to the antenna which is connected to LEAF1. Resistors are attached to the vertical side. The thread passes over these resistors.

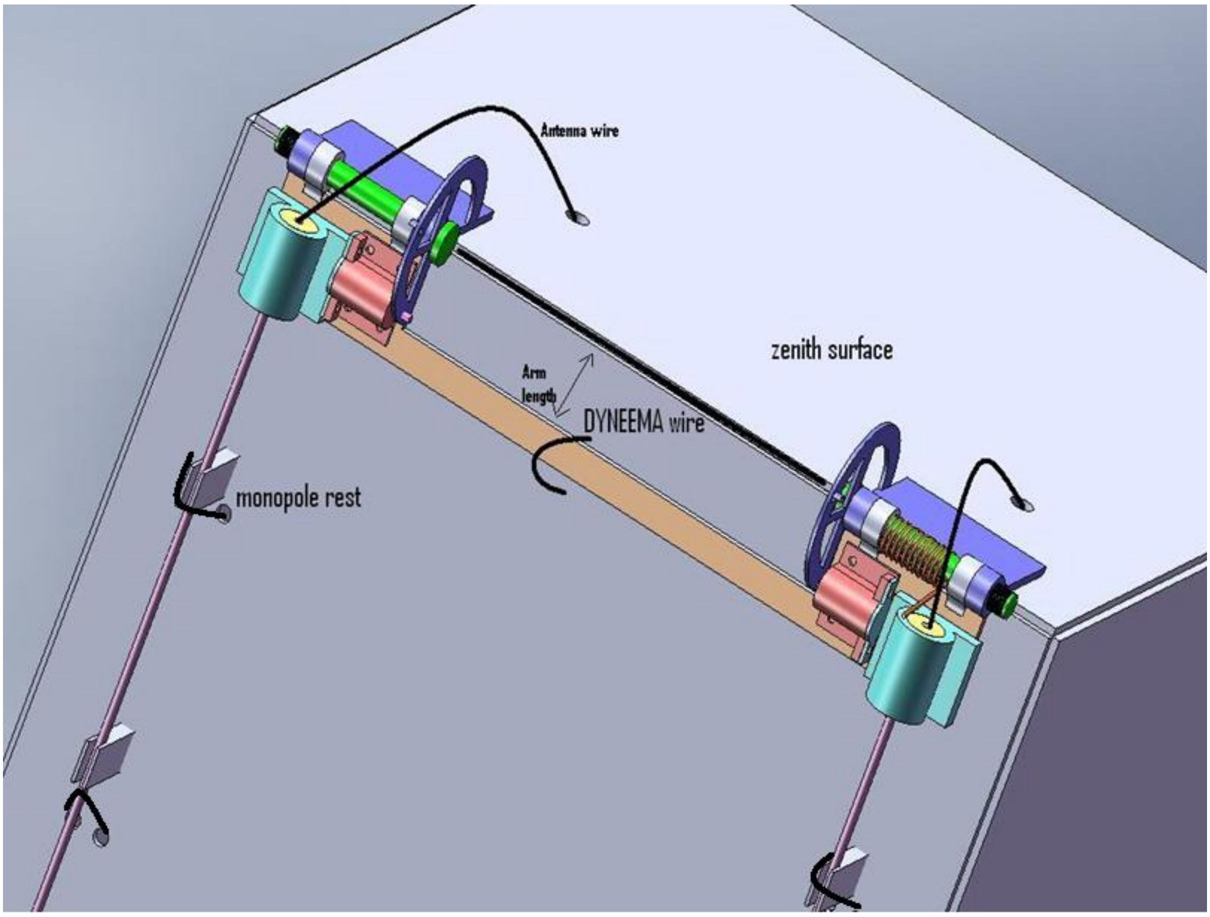


Figure 7: Monopole in stowed state

Before launch:

The Leaf 1 will be tied parallel to the vertical surface using the Dyneema string. The spring is in under tension and the tension in the Dyneema string prevents it from going into natural state.

As per the requirements of the mechanism the spring is designed in such a way that it can easily overcome the friction cum gravity without even lubrication of parts, on earth(the additional force of gravitation will not be required to be overcome in the orbiting satellite but for the testing purpose on earth as well as extra redundancy such a design).

Table 2: Data related to string

Parameter	value	unit	status
max stress in string	1.40E+09	N/m^2	var
dia of string	0.002	m	var
dist. of face from axel	0.02	m	var
tension in string	4396	N	
max torque based upon string	175.84	Nm	
safety factor	1000		var
max torque	0.17584	Nm	
max spring const. k	0.09254737	Nm/rad	

Table 3: Data related to Torsion Spring

Parameter	symbol	value	unit	status
Mean diameter	D	0.015	m	var
wire diameter	D	0.0015	m	var
no of visible coils	Nv	15		var
free arm length	Lf	0.04	m	var
youngs modulus	E	2E+11	N/m^2	var
yielding stress		1.00E+09	N/m^2	using table
spring index	C=D/d	10		
no. of active coils	Na	16.6985138		using Nv&Lf
total length of wire	L	0.7865	m	using D&Na
angle in natural state		1.9	rad	
I	I=pi*d^4/64	2.4838E-13	m^4	
Ki= K(assumed)	Ki=(4c^2 -c -1)/(4c (c -1))	1.08055556		
Ko	Ko=(4c^2 +c -1)/(4c (c +1))	0.92954545		
k aquired	k=Ed^4/(64DNa)	0.06316056	Nm/rad	
k aquired (john)	k=0.0100365*Ed^4/(DNa)	0.0405703	Nm/rad	
max torque aquired	Mb=k*theta	0.12000507	Nm	
max. bending stress	st=(Ki)(Mb)d/2(I)	3.92E+08	N/m^2	

3.3. Monopole Deployment mechanism and circuit

After receiving the deployment signal from the OBC, the power microcontroller starts the deployment process by providing a constant voltage of 5 volts across each resistor .Heat generated in the resistors melts the wire, unfolding the spring hinge which causes the deployment of antenna.

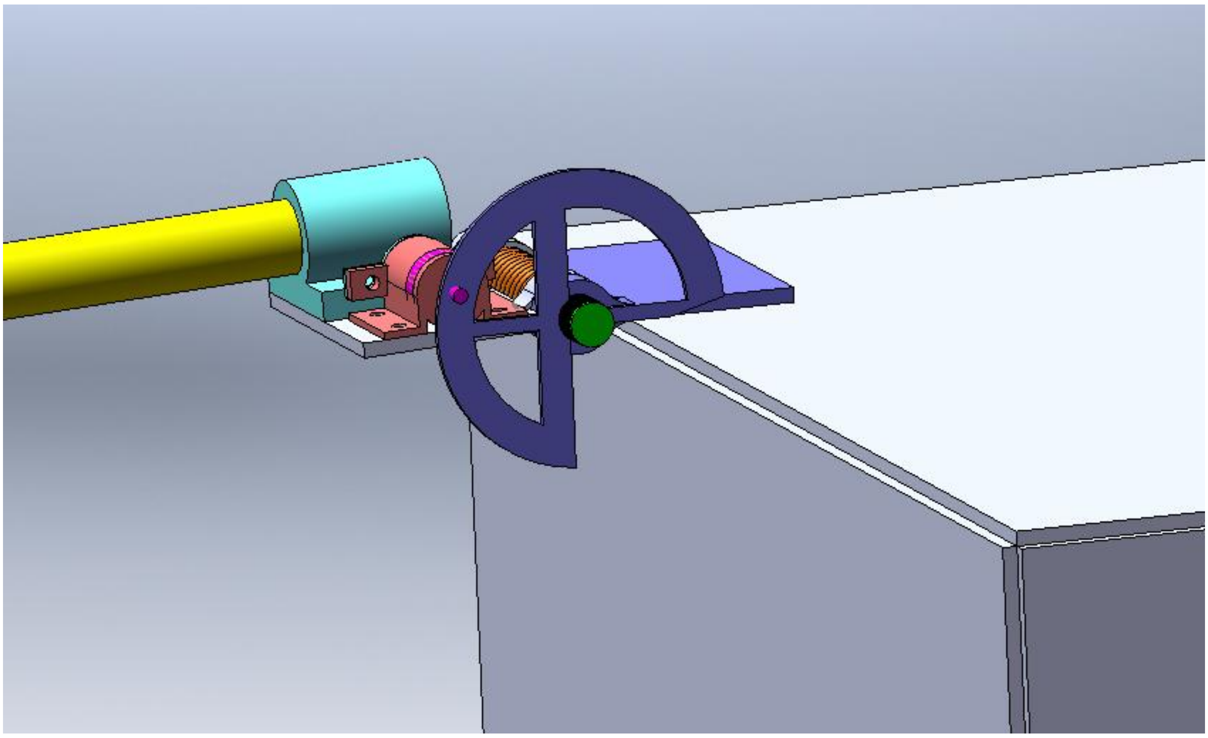


Figure 8: Final deployed state

3.4. Locking mechanism

During the deployment the locking spring is in compressed state and the locking pin moves on the semi-circular rail of the leaf 2. the leaf1 stops after rotating through an angle because of the protrusion in the rail, at the same place the pin encounters the hole and goes into it thus preventing the further motion(in both direction) of the leaf 1.

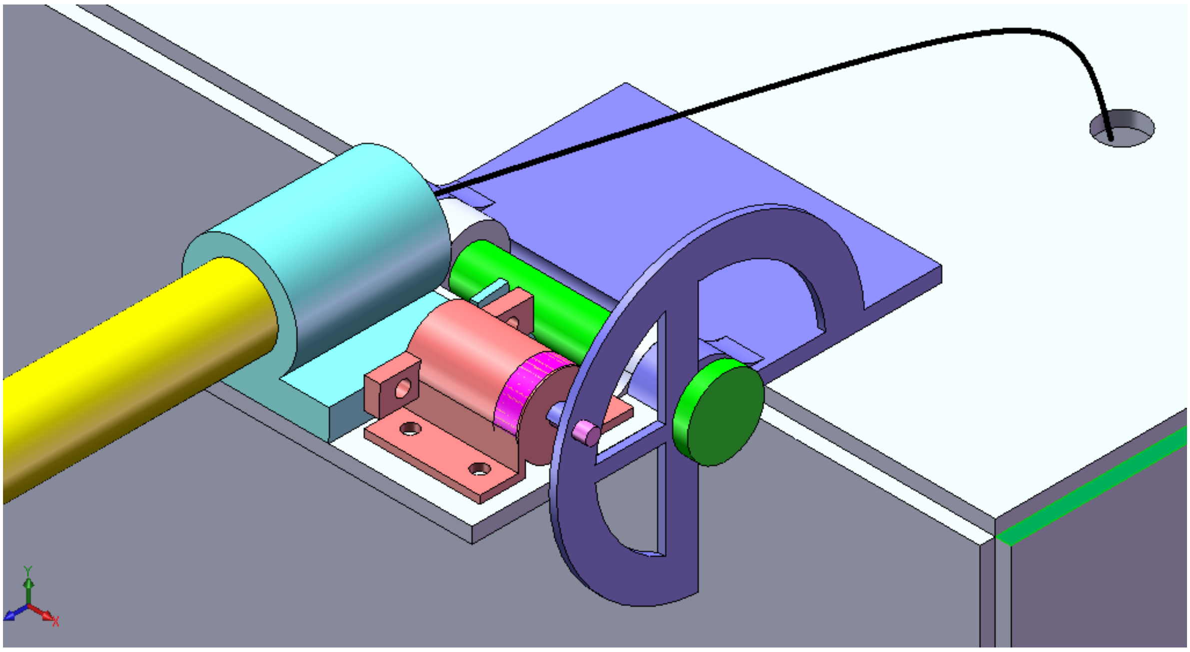


Figure 9: Locking mechanism

3.5. Feedback circuit

It consist of two metal pins attached to the vertical side(electrically insulated from the vertical side) such that both of them touch the leaf in the stowed state, since the electrical continuity is maintained in the two pins in the stowed state ,the pins are at same high potential(3.3 volts). After deployment the leaf moves, breaking the electrical contact, now the potential of one of the pins decreases, which shows the deployment of monopole.

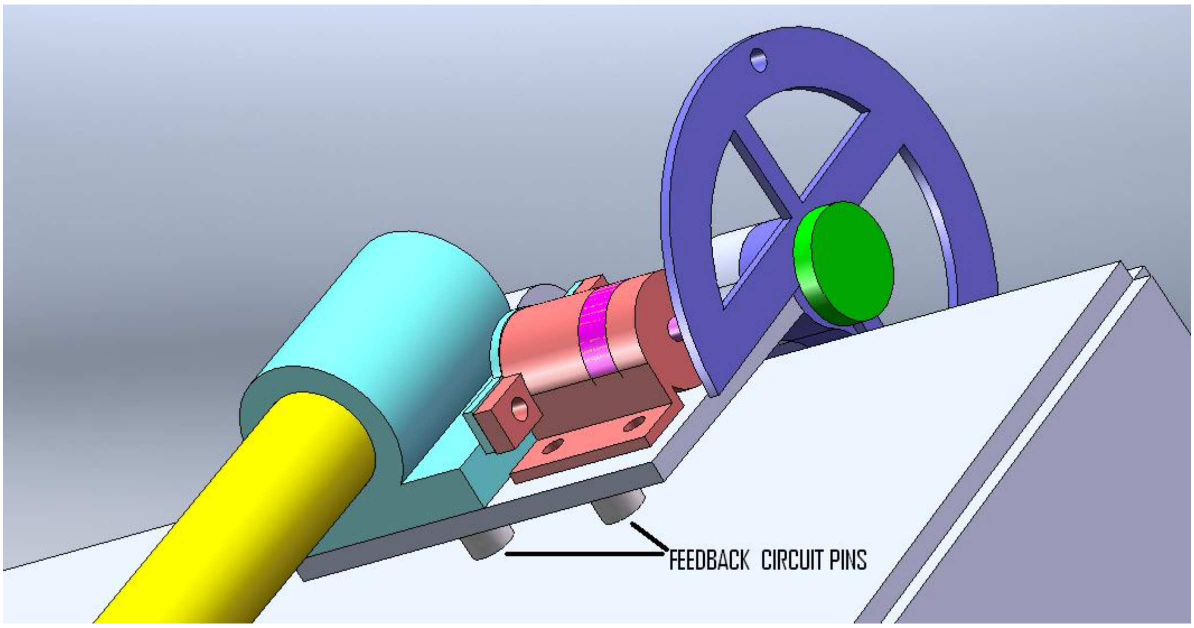


Figure 10: feedback pins shorted

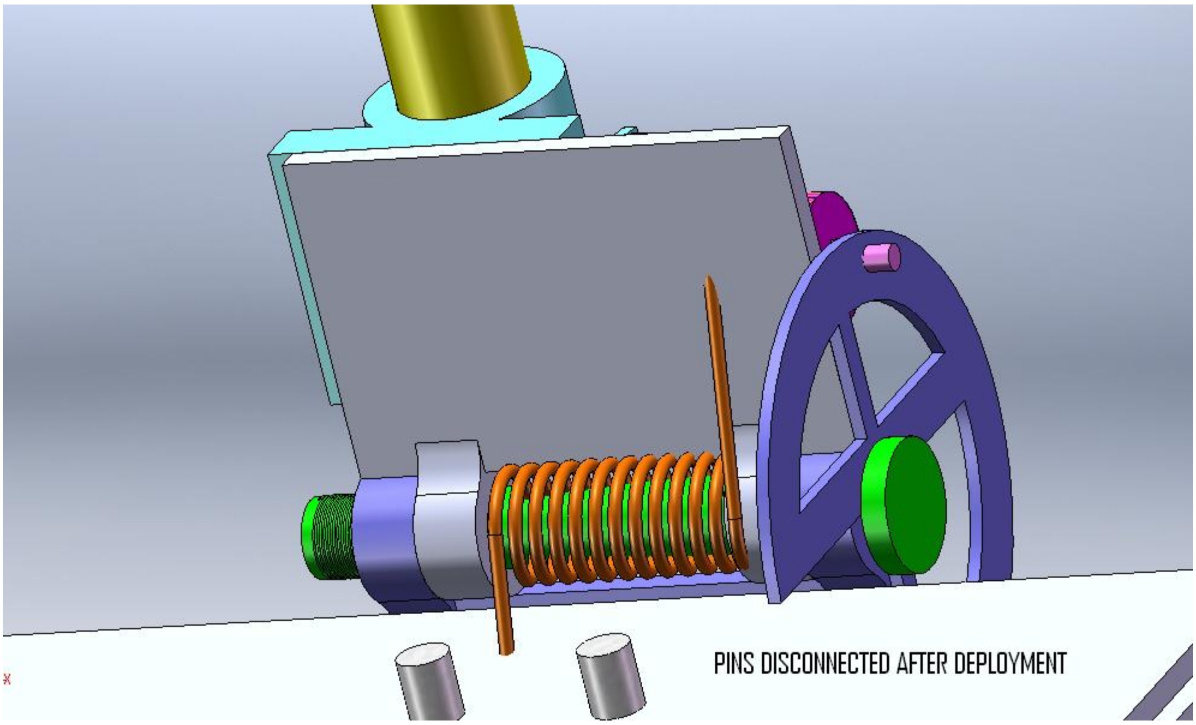


Figure 11: feedback pins open

The feedback pins are of compression forced contact type insulated by delrin.

3.6. Redundancy measures

The use of four resistors for melting the string makes this mechanism redundant.

Using single string for connecting both monopoles further increases the probability of successful deployment.

The feedback circuit can detect the movement of antenna so the deployment process can be restarted on failure of the preceding one.

3.7. Snap mechanism overview

The purpose of having a snap mechanism is to switch on the power circuit after the jettisoning of the satellite off the launch vehicle.

Snap Circuit Requirements:

1. It should not switch on during the launch.

2. It should not interfere with ejection system (IBL 230)

3. It should be light weight and small.

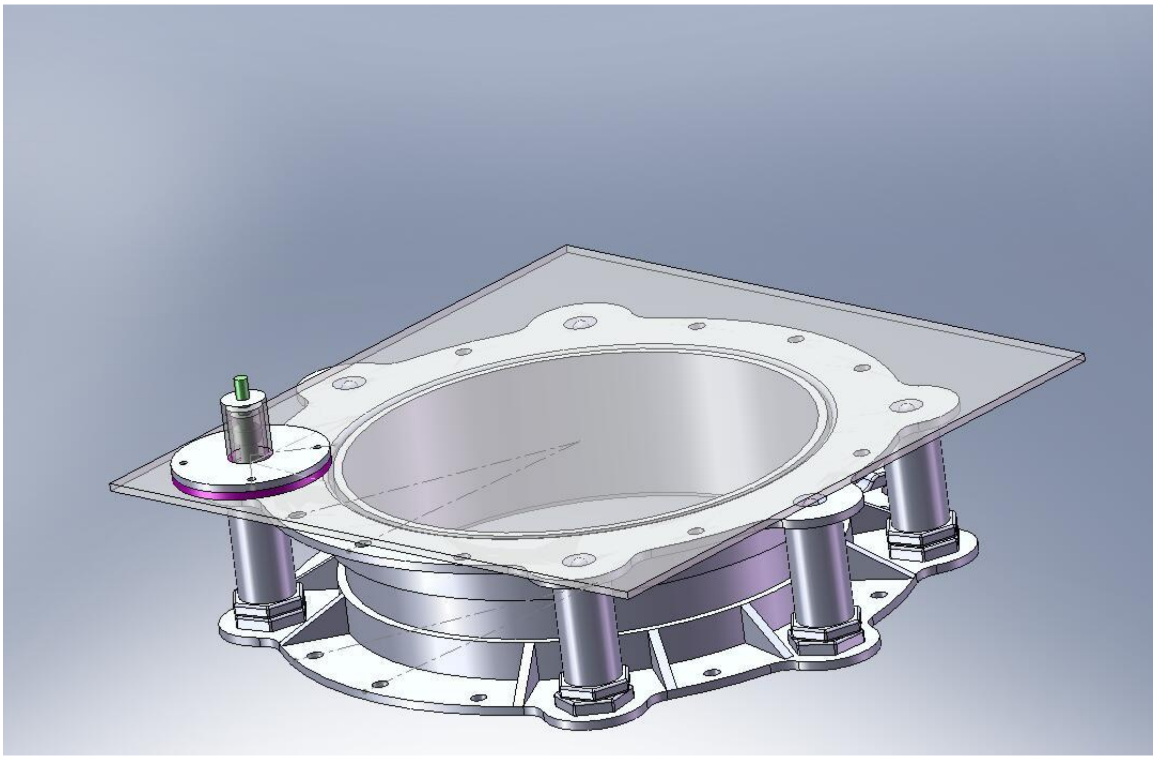


Figure12: position of snap switch

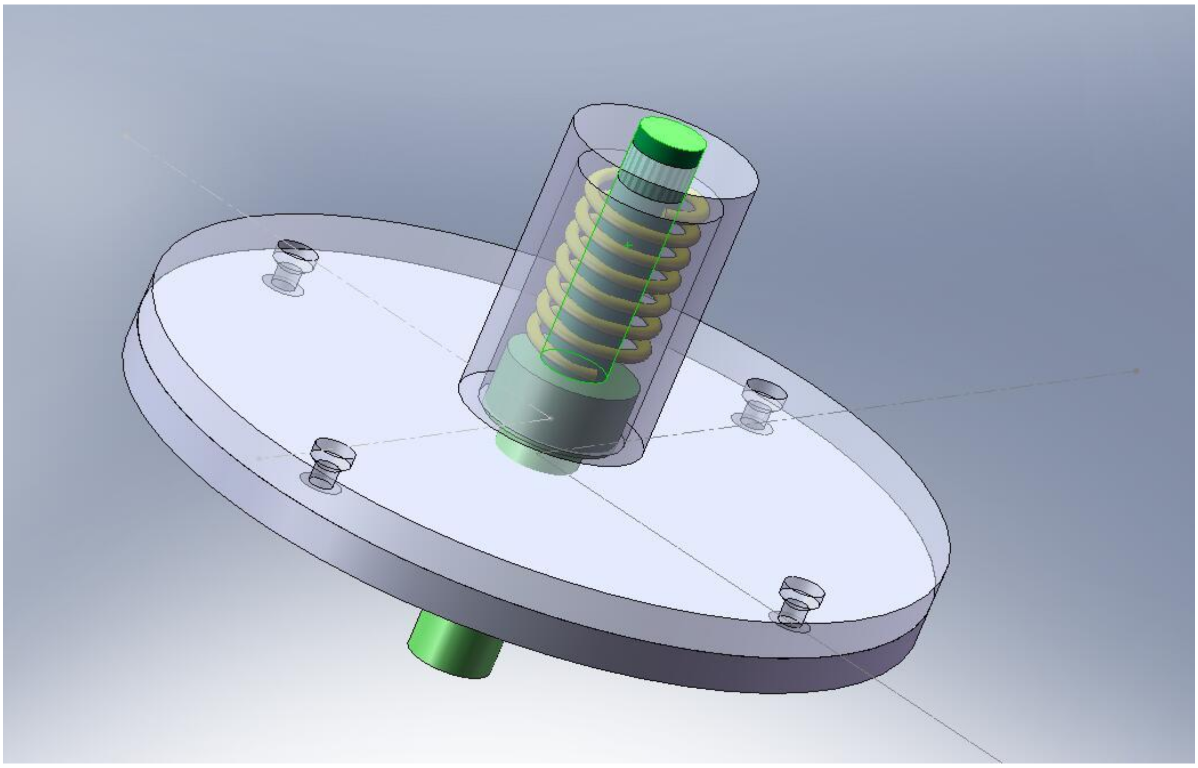


Figure 13: zoomed view of snap switch

4. Fabrication of mechanism

All parts except springs and string are to be made from SS 304 material. Springs to be made out of spring steel TS16949.

4.1 Tolerances, errors and validation.

To be determined.

4.2 Possible errors present in model.

Snap mechanism:

Load analysis of the snap mechanism has not been done yet.
Vibrations may cause erratic behaviour like loose contact leading to false trigger.
The mechanism may be prone to getting jammed.
The dlc films coats can be done to prevent jamming due to cold welding.

Deployment mechanism:

During deployment the monopole has to pull out the string this exerts a bending moment on the monopole which may destroy parallelism. We are reconsidering using truss for structural strength but bringing a dielectric material in may affect the communications subsystem.

5. Reliability

The reliability of locking mechanism and springs ~1. Dyneema string used for stowing has got a space heritage and has been used by Delfi-C3. It has high tensile strength (1400 - 3090 Mpa.) and a low melting point(140-150 degree C).

An experiment has been performed on nylon thread (cs diameter:1.5mm) to melt it with the range of electrical parameters specified by power subsystem and complete melting at a point was obtained in 50-60 seconds. Time required to burn Dyneema will be less than this time.

6. Conclusion

The stowing mechanism sets the monopole in third harmonic mode preventing the large deflection occurring if the monopoles were in pre deployed state. However the release mechanism needs to be improved upon.

Snap switch can detect the jettisoning of the satellite and has good reliability. Structural details need to be worked upon.