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Design and Prototyping of Novel Antenna Deployment System for CubeSats

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Abstract

This paper describes a design of the Antenna Deployment Mechanism made by the students of Team Anant, BITS Pilani for wire antennas of dipole configuration to be used on-board their 3U CubeSat. The antennas remain in a stowed configuration during launch and are deployed once the satellite reaches orbit. The deployment mechanism is designed to deploy the antenna in the required orientation and to minimize the potential failures. Material and stiffness for the antenna have been finalized considering several factors such as requirement, availability, and success rate of deployment. Principles used to decide the spring for deployment doors have been described in the paper. It has been ensured that the door remains locked in its position after deployment. Impact due to collision of the deployment doors with the satellite structure has also been minimized. Ample measures have been taken to prevent deployment failure due to cold welding in space. The antennas have also been electrically insulated from the rest of the structure of the satellite. The contour for support of stowed antennas has been designed to minimize the stress acting on the stowed antenna to prevent deformation of the antenna. Mass and space optimization considerations among other factors are described in detail in this paper. A burn-wire mechanism has been used for deploying the antennas at the appropriate time. A feedback mechanism has also been integrated into the circuit to signal the successful deployment of the antennas. The deployment process was also tested on 3D printed models of the designed antenna deployment system to check for possible errors and the reliability of the feedback mechanism.

Keywords: CubeSat, Antenna Deployment System, Wire Antenna, Testing

Acronyms/Abbreviations

ADS	Antenna deployment system
UHF	Ultra-High Frequency
CDS	CubeSat Design Specifications
P-POD	Poly-Picosatellite Orbital Deployer
OBC	On Board Computer
TT&C	Telemetry Tracking and Command
ROC	Radius of curvature
FEM	Finite Element Method
CNC	Computer numerical control
FDM	Fused Deposition Modeling
SLS	Selective Laser Sintering
PLA	Polyactic Acid
ABS	Acrylonitrile Butadiene Styrene

3. Introduction

The antenna is an essential component of a satellite, providing communication with the ground station. We intend to operate in the amateur UHF (435-440 MHz) frequency band for downlinking and S band for downlinking the data. The compact dimensions of a nanosatellite necessitate the need to develop an antenna deployment system for two reasons; Firstly, to house the antenna during launch to orbit; Secondly, to deploy it once in orbit. Over the years, several deployment mechanisms have been successfully designed and tested to achieve this goal. The unique requirements of our satellite led us to develop and test a unique deployment system, which can be categorized into Antenna Stowage and Antenna Deployment.

A CubeSat is a 10 cm cube-shaped satellite with a mass up to 1.33 kg. The CubeSat project was initiated by California Polytechnic State University and Stanford University to provide a standard of design for nanosatellites and to provide access to space for small payloads [1].

Team Anant is the student satellite team of BITS Pilani. The team was established under the Student Satellite Program by Indian Space Research Organisation with the aim of developing a 3U CubeSat with multi-spectral imager as the payload. The satellite will be used to image land surfaces which can help understand vegetation of the area and estimate crop yield.

Our proposed ADS design will be responsible for deploying a dipole antenna in stowed configuration within deployment module. For this purpose, a torsion spring will be used to deploy the door with required thrust and will also be responsible for locking the doors into the required configuration. The action of torsion of spring will be actuated by burning of nylon wire that would be wrapped around the deployment module to hold the antenna along with the door in stowed configuration by a separate burn-wire mechanism. A Feedback mechanism is also incorporated to provide a confirmation of the successful deployment of the antenna in form of an interrupt generated due to actuation of the feedback switch.

Many of these systems have been flight tested and much has been learned from their failures and successes. However, implementing already designed systems and structures into a satellite becomes difficult as satellite buses vary largely with payloads. For such missions, the concepts and learnings from such past research must be applied to design the most suitable and reliable mechanisms. This paper details such an approach to design a tape antenna deployment system for the 3U nanosatellite.

The specific mission requirements and structural constraints have been studied to find the parameters necessary to determine the optimal system. Different technologies for various components of the deployment mechanism have been compared based on these combinations. Selected combinations were then designed and manufactured using 3D printing for rapid prototyping. Final design choices have been made based on the results of testing and analysis.

Since the power requirement of our payload is high, a large portion of the outer surface area of the was dedicated for placement of solar panels amongst other components such as patch antenna as can be seen in Fig. 1. Hence, our goal was to design a configuration for the dipole antenna to minimize the surface area required for deployment.

Some concepts which are helpful to understand the work discussed in this paper are detailed in Section 2. Section 3 details the constraints and requirements imposed by the CubeSat standards and other subsystems. The various components of the designed antenna deployment system are described in Section 4. The 3D-printed prototype of the deployment system was also tested to check for deployment success rate and the results of the same are mentioned in Section 5. A thorough analysis of the design is done in Section 6, while Section 7 provides the conclusion of the work done by the team.

2. Theory

2.1 Torsion Spring design

Torsion spring are helical shaped springs which when twisted by a specific angle exert a torque in opposite sense of rotation and could also be seen as rotational energy storing device. Knowledge of Torsion spring design parameters was widely utilised to meet our requirements and perform post deployment simulations.

Some basic formulations are summarised below.

2.1.1 Spring rate

Spring rate (k) can be approximated by a popularly used empirical formula for a torsion spring having Young's Modulus (Y), wire diameter (d), mean diameter (D), number of active coils (N) as

$$k = \frac{Ed^4}{3667nD}$$

Where,

$D = outside\ diameter - d$

$N = N_c + \frac{First\ arm\ + Second\ arm}{3\pi D}$

2.1.2 Elastic potential energy

Elastic potential energy (*E*) stored inside a torsional spring of spring rate (*k*), when twisted by angle (θ), is given by

$$E = \frac{1}{2}k\theta^2$$

3. Constraints and Requirements

While designing the antenna deployment system, a number of constraints were kept in mind to ensure that the structure was compatible with the CDS [2] (The CubeSat Program, Cal Poly SLO, 2015), standards and our mission requirements.

3.1 CubeSat Design Specification (CDS) Requirements

The objective of the CDS standards is to provide specifications for the design of CubeSats and ensure that the satellite is compatible with the launch vehicle. Some of the specifications of interest for deployable are mentioned below.

(a) Clause 2.1.1: All parts shall remain attached to the CubeSats during launch, ejection and operation.

(b) Clause 2.2.4: Deployable shall be constrained by the CubeSat, not the dispenser.

(c)Clause 2.4.4: All deployables such as booms, antennas, and solar panels shall wait to deploy a minimum of 30 minutes after the CubeSat's deployment switches are activated during dispenser ejection.

(b) Clause 2.4.5: CubeSats shall not generate or transmit a signal earlier than 45 minutes after on-orbit deployment from P-POD.

3.2 Mission Requirements

The deployment module is required to meet the mission specific requirements of all the involved subsystems.

3.2.1 Structural and Thermal System Requirements

(a) As the deployment module is to be accommodated within the satellite, hence the structure of the must be compliant with the mechanical requirements of CDS

(b) The positioning of components and the deployed state of the antenna should be carried out such that it does not interfere with the field of view of the payload

(c) The antenna generates magnetic field of its own and is thus required adequate magnetic shielding from onboard electrical and magnetic components
(d) A 3U CubeSat restricts the size of module within 96.4 x 96.4 x 30 mm
(e) The deployment module should cover the least area possible on the outer faces to ensure maximization of solar panel area
(f) If two surfaces of similar metals are in contact in vacuum for a long period of time, they could fuse together due to cold welding. The surface of the antenna would have to be coated with suitable material to avoid cold welding. This would be done using anodization or suitable paints.

3.2.2 Telemetry Tracking and Telecommand requirements
(a) The chosen antenna must satisfy the frequency requirements of the onboard and ground station communication architecture (details)
(b) The antenna is also required to satisfy the gain requirements for optimal rate of data transfer
Based on these requirements following design specifications were finalised,

- Downlinking of data would be achieved using a dipole antenna of length 17 cm operating on UHF band (455 MHz)
- Uplinking would be performed by a patch antenna operating in S band (2.4 GHz)
- For maximization of antenna gain the deployed dipole antenna must be 180 degrees apart

3.2.3 Electrical Power Subsystem
The antenna deployment should have a maximum power usage of 7.5W

3.2.4 On board computer requirements
The OBC is required to assess the current state of deployment of antenna to execute the flight plan accordingly. If the deployment of one or both antenna fails, the OBC is responsible for restarting the deployment sequence. If a deployable element is not deployed even after set repeated attempts OBC will direct the TT&C and execute the most suitable flight plan.

4. Mechanism Elements of the Deployment System
This section will describe the involved elements in the deployment of antenna and also the reason for their specific design. The complete assembly can be subdivided into four sub-assemblies namely, Main base and curvature, gating assembly, Electrical circuit assembly, locking assembly

4.1 Main base and curvature
It represents the base of antenna deployment module on which other assemblies will be installed. It is dimensioned 96.4 x 96.4 x 30 mm. The first important design parameter for this component is its structural strength against the various loadings during the launch. Al-606-T-6 was chosen as the material for this part which is popularly used and largely tested for space applications for a long time [3].

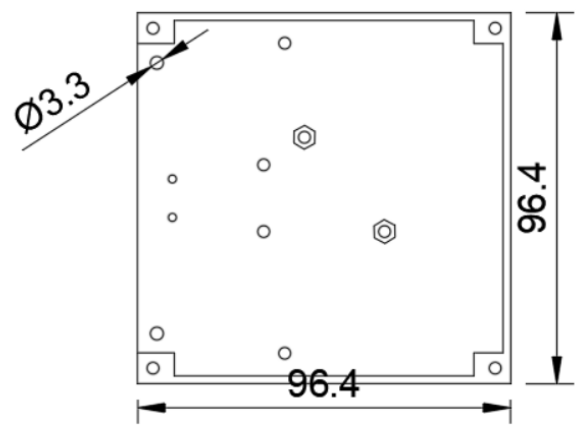

Fig 1. Main base

The two holes of 3.3 mm diameter at left end represent the assembly point of gating mechanism and main base. 0.3mm clearence is given for avoid overfitting and also take in account the accuracy of 3D printing. The two holes in between shaft holes are required for wrapping the nylon thread. All the remaining holes are there for accommodating modular design and thus would not be present in flight model. Main base also includes the curvature which holds the stowed antenna in its place with its shape being an important deployment consideration directly related to the probability of success of deployment.. The two proposed designs for this curvature based on difference in radius of curvature and shape are depicted below,

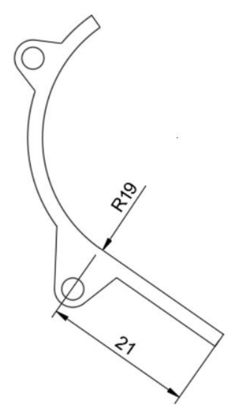

Fig. 2. Small curvature

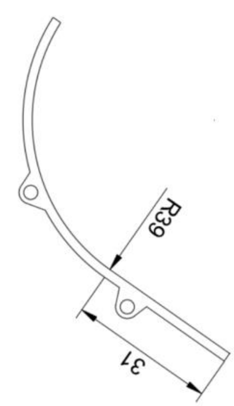

Fig. 3. Large curvature

In order to analyse the change in probability of successful deployment with curvatures, two values of curvatures were chosen with smaller curvature having 19 mm ROC while the larger one having 39 ROC. A linear length is added at the end of the curvature which facilitates the opening of coiled antenna. The curvatures contains screw holes due to the modular 3D printed prototype that is to be tested. But in the flight model the finalised curvature (after testing) and main base will be manufactured together using CNC with no holes other than ones required for wrapping nylon wire.

4.2 Gating Assembly

Gating assembly consists of the door, torsion spring , antenna and cam.

4.2.1 Doors

Doors are the element on which the antenna will be directly mounted and thus it need to be an insulator.

After approximating the impact load on door after opening through post deployment simulation, polyoxymethylene (POM) was chosen as its material.

4.2.2 Torsion spring

Torsion spring design was critical for successful and reliable deployment of the antenna. The most essential design parameters for the selection were the maximum allowable deflection, rest angle between the arms of the torsion spring and the wire diameter. After finalizing the deployment mechanism and door design, requirements for the torsion spring were clearly specified. The finalized specifications on the basis of mechanism and geometry only are summarised as followed.

Parameter	Specification
Material	Stainless steel
Height	3-5 mm
Outside diameter	4-5 mm
Wire diameter	0.4-0.5 mm
Maximum deformation	>180°
Rest angle between arms	0°
Wind	Left or right both

Table 1. Torsion spring specifications

Stainless steel springs are common option for space grade springs and thus stainless steel was chosen as the material of the spring. Height and outside dimeter ranges were given to incorporate the clearance required between the spring and the shaft. Since the required deformation was quite large, lower wire diameter was preferred which would exert lesser force on the door for the same deflection(k is proportional to 4^{th} power of wire diameter). Rest angle of 0° was a ADS design requirement. Left or right wind springs can be accommodated on the diagonally opposite shafts in the design.

4.2.3 Cam

A cam like shape is to be attached at the end of the shaft with the help of a pin (due to its small dimension) which would be responsible for actuating the microswitch when the antenna along with the door would be fully deployed.

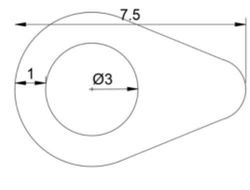

Fig.4 Cam

4.2.4 Antenna

The only restriction imposed on antenna design parameter by TT&C was its length, material and other properties was not constrained. The length of the antenna was finalised as 17 cm while its height was taken as 1cm to minimize the height of the ADS. The material was chosen as steel which can be anodized to prevent any chances of cold welding. Given the requirements steel strip of a measuring tape was decided to be used as antenna (After removing the coating to reduce the chances of antenna getting stuck by its wearing). The reasons for choosing it were mainly due to its availability. One added benefit is the curved cross-section shape of such antenna which allows long lengths of antenna to be completely straight during application.

The complete gating assembly is depicted as follows

The complete gating assembly is depicted as in the diagram below

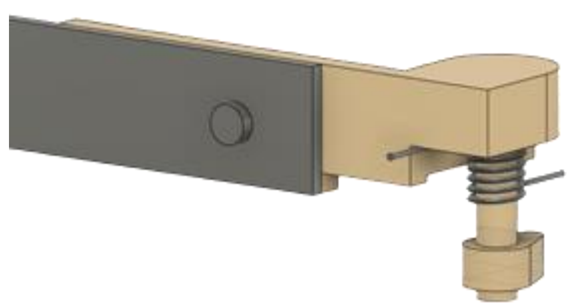

Fig.5 Gating assembly (CAD)

4.3 Electrical assembly

The electrical assembly consists of a MOSFET, TI MSP430 microcontroller, microswitch, resistances in a closed circuit and also a nylon wire which is external to the circuit, wrapped around the ADS in such a way that it prevents the deployment door from opening and is always in contact with the resistance. The circuit and its reliability were tested in an older ADS model by our team

seniors and its results were published in IAC 2019. All the details about the working of the circuit can be found in that research paper[4].
The circuit connections can be summarised by the circuit diagram below,

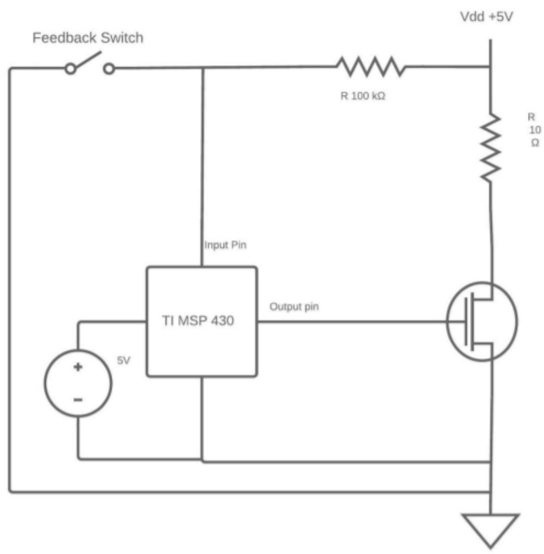

Fig.6 The deployment circuit

Only the method of actuation of the microswitch is enhanced in the current model, which only creates an interrupt only when the antenna is successfully deployed (no false positives), which was not the case in the previous model.

4.3 Locking assembly
Lock-key mechanism was initially proposed in the ADS designs, but after testing the potential of torsion spring in locking the antennas in required configuration, the need of additional locking mechanism was not worth the added complexity of the structure, and it was thus discarded. Nevertheless, for larger deployment systems it could prove useful for dampening the vibrations and reaching the steady deployed stage of antenna faster. Additional benefit of using this mechanism is that it is capable of locking the deploying antenna at any given angle, which is not possible with a torsion spring. Since in our case the antennas are 180 degrees apart it is not required, torsion spring alone was found sufficient for the task.
The mechanism simply comprises of a uniquely designed flat spring. And a requirement of slot on the shaft of the door. Simulation was done to find the most efficient load bearing design of the tape spring which is discussed in the next section. The shape finalised for this purpose is depicted below

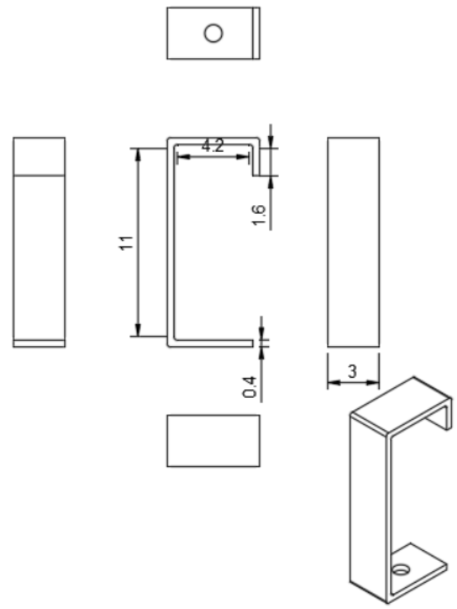

Fig.7 Tape spring design

4. Designs and working mechanism

We are proposing the following two types of ADS setups:

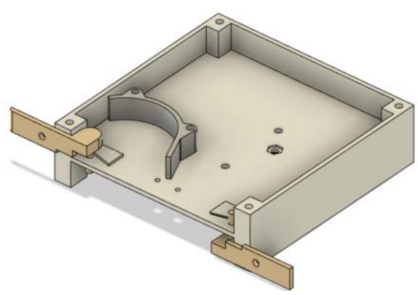

Fig. 8 Design 1 : Low curvature design

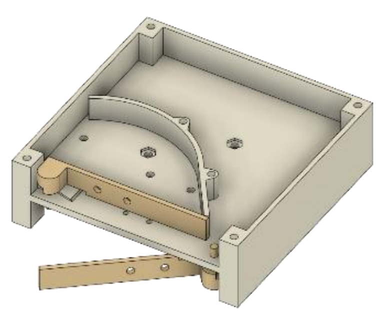

Fig. 9 Design 2: High curvature design

Below is the list of components that will be used.

5.1 Spring Position

The door will open by leveraging the potential energy stored in the twisted torsion spring.. The lower leg of the spring rests on the protrusion made on base. A cover was made on the upper side to hold the leg in place when facing launch vibration loads. The upper leg will apply torque on the inner side of the door as shown in the figure below.

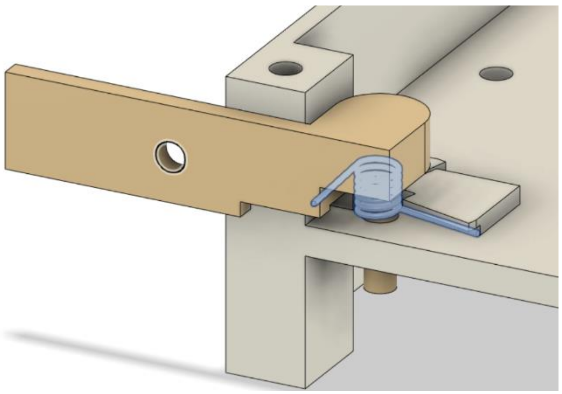

Fig.10 Torsion Spring Placement

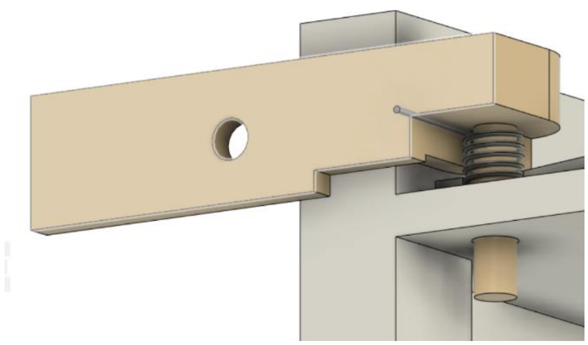

Fig.11 Torsion Spring Placement

There was lower supporting protrusion on base was slant with a buffer angle 15 degrees. This would help us test the designs even with a 90-degree torsion spring, which can twist by 195 degrees safely, without any permanent deformation.

5.2 Spring state

The torsion spring used in the model was a 0-degree torsion spring. In the free state, the legs are at a 0-degree angle. The torsion spring will be twisted by 90+15=105 degrees to fit in the door in the open state. This pre-stress keeps a constant force applied on the door. It will help us account for the following:

- Permanent deformations that can occur in the torsion spring before deployment
- The machining tolerances
- The angle made by spring due to the gap between the shaft and inside cut radius, due to the unavailability of required spring, in our case, the angle was about 7 degrees on each side, adding up to 14 degrees.

The spring will twist by a net total of 285 degrees when the door is closed. The spring used could twist safely up to 360 degrees without any permanent deformation.

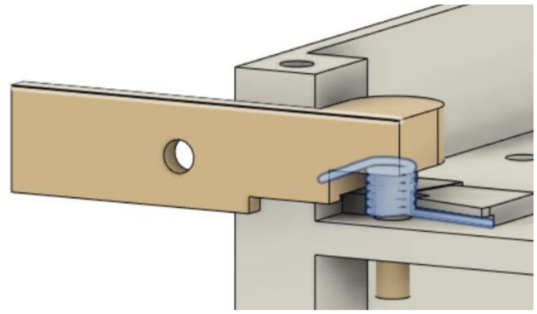

Fig.12 Torsion Spring in open door state

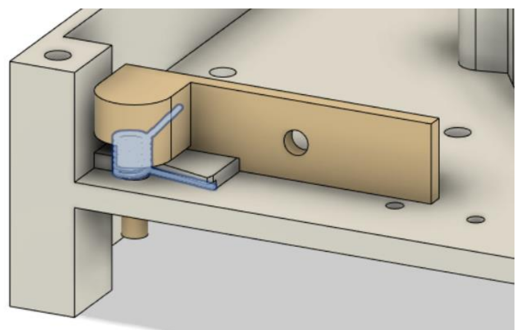

Fig.13 Torsion Spring in closed door state

5.3 CAM Mechanism

A CAM mechanism was used to report the antenna deployment. The CAM will be rigidly joined with the door shaft using a pin. A microswitch will be placed just behind the shaft. When the door will open, the inertia due to the antenna throwing open and the torsion spring torque will produce enough force for the CAM to press the switch.

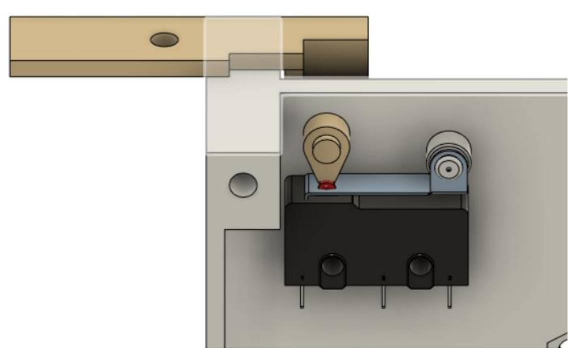

Fig.14 CAM Mechanism

5.4 Locking Mechanism

The flat spring locking mechanism discussed can be used to lock the antenna door without needing a torsion spring at any specific angle in some applications. It is widely used in complex antenna deployments. However, for our purpose, the pre-stress in the torsion spring was enough to hold the door. The flat spring can be mounted on the base plate, and the upper front face can be pulled up and placed on the upper face of the door, generating a contact force between the two surfaces. When the door opens, the flat spring will slip into the slit cut on the door shaft. This will then transfer the vibrations from the door to the flexible spring and dampen the vibrations faster. Once stable, the spring will hold the door at 180 degrees open state.

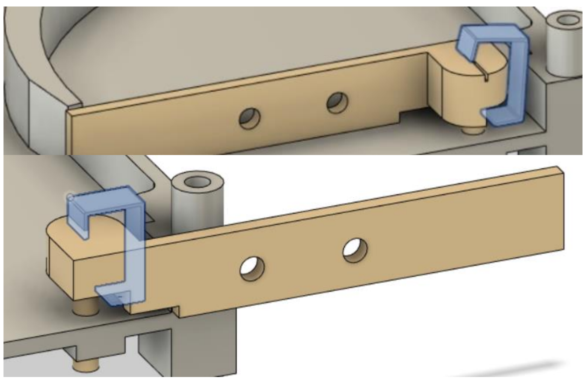

Fig.15 Flat spring locking mechanism

6. Pre-analysis

To find the probable design faults before functional prototyping of the proposed design pre-analysis using FEM based software was carried out. Probable sources of failure were analysed and then an attempt was made to accurately simulate them. Thorough analysis of results provided us the chance detect any source of failure beforehand. The two simulations results which effectively contributed to the final designs are explained below

6.1 Impact simulation

During the deployment sequence the door collides the mainframe of the CubeSat, which results in impulse loading of the door and generation of vibrations within the structure. Probable failures could be failure of door material (since it is plastic) and uncertainty of the order of vibrations might be detrimental for the structure if it is near the fundamental frequency of the structure. A model was setup to analyse the stress generated and frequencies generated due this collision in Explicit dynamics module of ANSYS. The model simulated the ADS just before the collision. The input for these simulations were mainly the spring rate of the torsion spring and velocity of door just before collision. The spring rate can be estimated using the formula proposed in the theory section or could be directly retrieved from the spring supplier. In our case we were able to obtain it from the supplier, for the given ranges of the torsion spring specifications, highest possible spring rate (k) possible was 38.791 N-m/degrees, which was used as an input to simulate the worst loading condition. To approximate the velocity just before the collision, simple energy balance between elastic potential energy and rotational energy of the door about its hinge was computed (assuming no frictional loss) to obtain the upper bound of the velocity of impact. Moment of inertia about the door axis was directly obtained from Fusion 360. The calculations yielded the

$$\omega_{max} \sim 30\ rad/s$$

Using these two values explicit dynamic simulation was performed and results are as followed.

6.2 Tape spring loading simulation

To minimize the maximum stress and contact force between the spring and the shaft of the door several designs were considered and simulated under actual loading conditions. A static structural model was setup in ANSYS to analyse the same. The results of the simulation in form of equivalent von mises stress mapping and deformation are present in the Appendix (Results). The tape spring with the shortest distance between the two vertical faces before and after the deformation (the second flat spring from the left) was preferred over others because of the minimal bending stress generated in the spring element. The contact force is known to increase with the thickness of the spring and thus a value of 0.4 mm was found to be ideal [5].

5. Functional prototyping

Prototyping testing was carried out to ensure the reliability of the proposed design. For this purpose the diffrenent components were 3D printed to simulate the flight model components that would later be manufactured through CNC. The main base was printed using FDM with PLA white at 200 layer height and 50 infill. While the curvatures, door, cam were printed using SLA with Tough resin ABS at 100 layer height. Finally the bottom and top plate covering the ADS was printed using FDM with PLA white with 100 layer height. The printing was accurate upto dimensions of 0.8mm and thus features having dimensions less than 1 mm were removed from the design to be sent for 3D printing. Margins were given wherever assembly of parts was expected. To save the cost modular design of the ADS was adopted, which allowed testing of both the designes using single base. The curvatures have screw holes with base having complementary holes for attachment. Thus, one curvature on one face can be tested at a time.

The 3D printed parts are individually shown below.

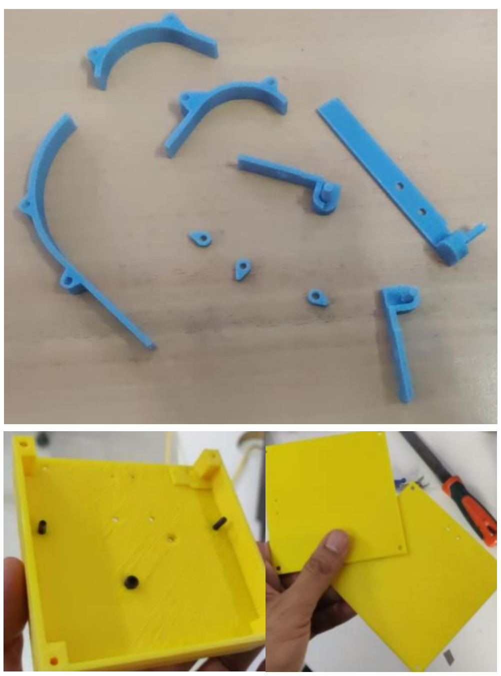

Fig . 16 3D printed parts

The 3D printed parts were then assembled into sub-assemblies and then final proposed design was generated by integrating these assemblies. The whole assembly is shown below.

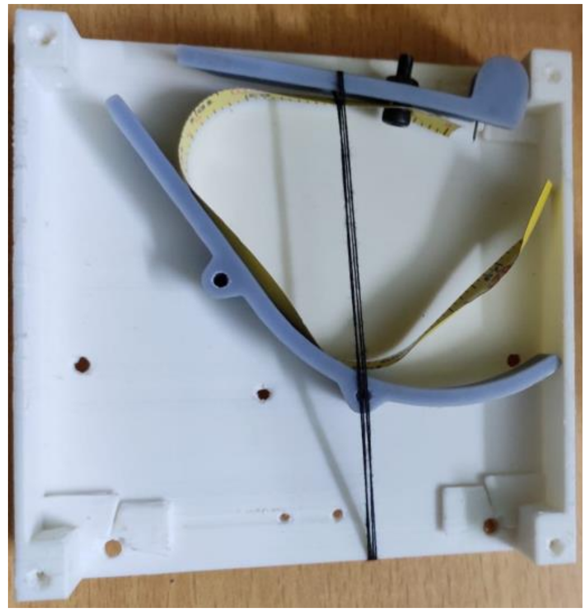

Fig. 17 Top view of Design 2 with large curvature

After assembly the deployment mechanism was tested 50 times for each of the designs to approximate its reliability. Since the deployment circuit was already tested, only deployment of antenna was tested under the constrained geometry, by cutting the wire externally. The testing results are provided in a tabular form in the Appendix (Results)

5. Discussion

After completing 50 trials for each design probable sources of failure of deployment were evident. For the first design with shorter curvature, the success of mechanism deployment was largely dependent on the type of coiling used for storing the antenna. After two failures due to incapable coiling a coil shape was found for which it was always deploying as shown in the figure below.

Fig. 18 Coiling shape

The coil shown was producing immense feedback force which made the deployment successful for each trial. The only issue encounterd using this coil was that after repeated testing the antenna started to yield which was not a good sign. Thus for better design a ROC slightly greater than this value will can be used. For the second design the deployment success was not dependent on the type of coiling, torsion spring was suspected to deploy the antenna irrespective of its coiling and it thus had higher success probability than the other design.

A source of failure (accounted ~40% of the total failures) which was common to both design was inefficient wrapping of nylon strings. If they were not wounded properly, not enough tension is generated tu which it hinders the opening of one or both doors. Thus, a special attention should be paid on the quality of winding of nylon wire for increasing deployment rate. Other critical design observations and their practical solutions that could be improved in future designs are as follow,

1) While mounting the antenna on door by tightening the M3 bolt, the C shaped curvature of antenna flattens, resulting in bending the antenna. To counter this, stapler pins can be used for mounting the antenna to door. Holes can be made inside the door and antenna, such that the minimum distance between the holes will be equal to the stapler pin width. The stapler can then be passed through the holes, at the center of the C curvature, along the length of the antenna and the ends can be bent to lock the antenna.
2) The door was bending too much due to the forces of the stowed antenna. Currently, the door thickness was 2 mm, which can be increased. The thread positioning can also be done nearer to the center of the door.

6. Conclusions

After thorough testing of the proposed mechanism the second design was found to be slightly more reliable than the first design. But it was also observed slight changes in the radius of curvature and carefully coiling the antenna and wrapping the nylon string can potentially make the first deployment highly reliable. Recently due to space restriction in the satellite, electrical components are required to be kept inside the ADS module and thus the shorter curvature design which is highly compact in nature with proposed modifications can prove to be a viable solution for the problem.

7. Acknowledgements

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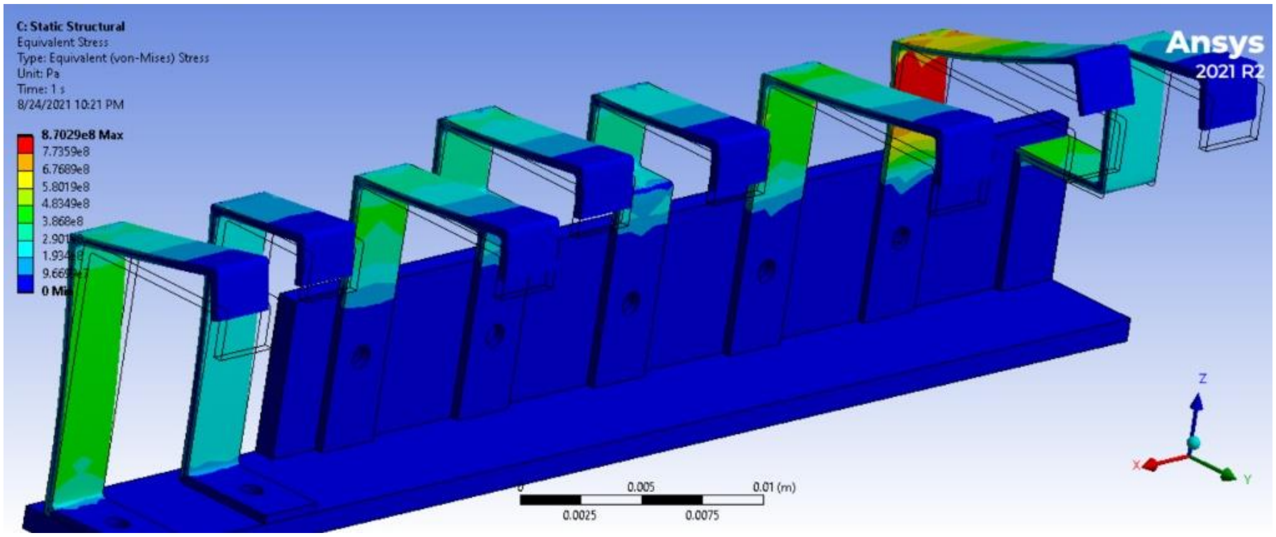
Appendix (Result)

Flat spring results



Von mises stress mapping with deformation of various flat springs

Testing results

Operation	First design (short curvature)	Second design (long curvature)
All gates opened successfully	47	48
Antenna deployed successfully	47	48
Probability of successful deployment	94%	96%