TAPE DEPLOYMENT MECHANISM FOR SPACECRAFT DEORBITING

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ABSTRACT

Space debris is a major concern for exploitation of space in LEO. In that context, the H2020 FET OPEN Project E.T.PACK focuses on the development and construction of a system for deorbiting spacecrafts at their end of life. The Deorbit Kit system is based on electrodynamic tether technology using a long conductor tape which provides high specific impulse compared to other technologies. The tape deployment mechanism plays a key role in the Deorbit Kit allowing the tape storage in a reduced volume and a safe tape deployment.

SENER is developing the deployment mechanism with the associated electronics as well as the avionics of the whole Deorbit Kit. This new technology will be flight tested in a Demonstration Mission described in [1].

The paper will provide the details of the Design and Test performed for the deployment mechanism with emphasis in the most critical aspects. Besides, difficulties and lessons learnt found for the mechanism will be presented as well as the upgrade design after the test performed.

1 MISSION BACKGROUND

The objective of E.T.PACK project is to develop a deorbit Kit (DK) with TRL4 based on electrodynamic tether (EDT), i.e, a long metallic tape. This device will be attached to a Host SpaceCraft (S/C) and it will be activated after S/C life for deorbiting. Studies performed during the project indicate that an EDT of 3Km tape will deorbit a 700Kg-S/C from a 800Km altitude sun-synchronous orbit in less than 1.5 years. To prove this technology, a similar but scaled stand-alone Deorbit Kit Demonstrator will be flown by the end of 2025 at an In Orbit Demonstration Mission. This Deorbit Kit is composed of two modules that will separate in orbit extending a 500-m long tape-like tether. Current design is a 500m tether tape of 40 microns and 2,5cm width focussed to deorbit satellites of mass from 200Kg up to 1000Kg in a polar orbit at 1200Km and 800Km respectively. The deployed bare-Aluminium tether will capture electrons from the ambient plasma passively and the circuit will be closed with the ionospheric plasma by using an active electron emitter.

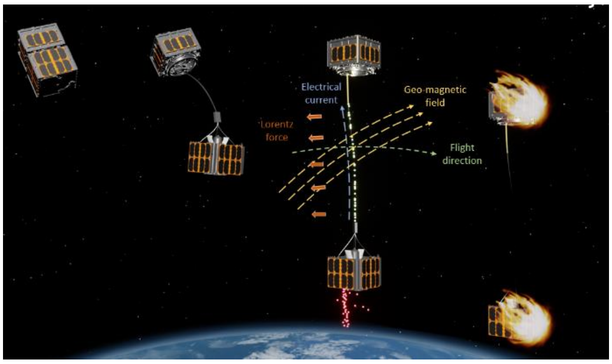

Figure 1.- Deorbiting scheme for E.T.Pack project

The Deorbit Kit (DK) is composed of two modules, one attached to the host S/C and the other one to be deployed that contains the electron emitter. Upon DK activation, a Hold Down Release Mechanism will separate both modules and the deployment mechanism will deploy the tape. Figure 1 shows a schematic view of the concept.

The Deorbit Kit demonstrator is compatible with a 12U Cubesat (240x240x360mm) and a total mass less than 22Kg including structure, deployment mechanism, avionics, and cold gas system.

The main components of the Deorbit Kits are:

- Tether: the tape shape device is the responsible of generating the drag and Lorenz force that will deorbit the Host S/C. Depending on the focussed S/C mass and orbit altitude the dimensions will be tuned to deorbit it in the required time.
- Electron Emitter: a Hollow Cathode (HC) and its associated Cold gas system is the technology selected to close the electrical loop emitting electrons to the space. The HC novel technology characterisation and details can be found in [2]. The cold gas system is activated in the first stages of deployment to help the separation of the modules when the gravity gradient is not working with enough force, details can be found [3].
- Hold Down Release Mechanism (HDRM): based on a Non explosive device, it will release both modules once the DK is activated.
- Avionics: an On Board Computer, batteries and several antennas and sensors are responsible of the telecommand and telemetry of both stand-alone modules for the demonstration mission.
- Deployment mechanism: responsible of the tether deployment and storage during launch.

Detail definition of the whole Deorbit Kit for the In Orbit Demonstration Mission can be found in [1]. This paper will focus on the deployment mechanism and its verification activities performed till the date.

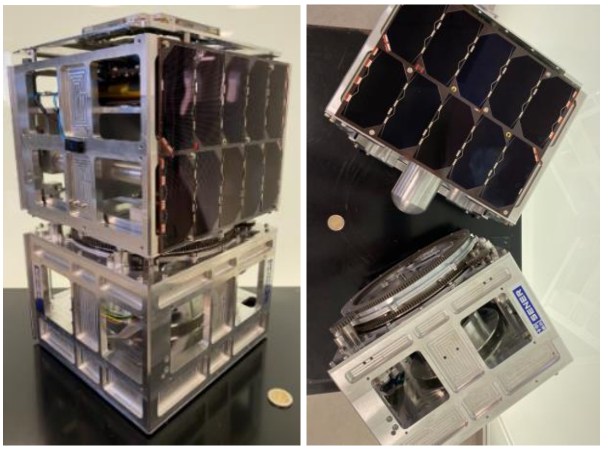

Figure 2.-E.T.Pack on stack configuration (Left) & Sectional view of the E.T.Pack with main components (Right)

2 MECHANISM DESCRIPTION

The tape deployment mechanism is one of the most critical parts of the Deorbit kit, as a failure in the deployment will imply a failure of the mission. It allows the tape storage in a reduced volume and a safely deployment of a tape shape tether.

The main requirements of the tape deployment mechanism can be summarized as follows:

- It should be as compact as possible minimising mass and volume. Target mass is less than 3Kg without tether tape
- It should be compatible with different tether dimensions: length, thickness, and width.
- It should follow the tether deployment profile
- It should withstand launch loads defined by the launcher.

The deployment mechanism is a two degrees of freedom orbiting structure with motorized pulleys. The uncentered rotation of the pulleys assembly unroll the stacked tape and the pulleys extract the tape outside the module. Both, motorized pulleys and orbiting structure, are moved by means of two brushless motors fixed on the module. The following figure shows a schematic concept of the mechanism.

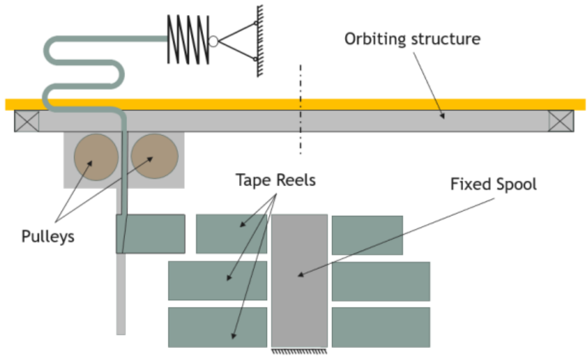

Figure 3.-Tape deployment mechanism for deorbiting schematic concept

The volume of the actual deployment mechanism is a 200 mm diameter cylinder and 140mm in height. One of the main advantages of this mechanism concept is that it is totally scalable for any tape length and material.

The main part of the mechanism consists of two coupled planetary gear train that transfer the power from the fixed motors to the orbiter and pulleys. Besides, other important components are the tape guidance element, the spool, and the HDRM required to maintain the mechanism locked during launch.

Mainly, the mechanism consists of several pinions, satellites and planets gears. There are two main paths of power transmission, each of them actuates different components. One motor has the main duty of moving the orbiter to unwrap the tape from the central spool. The other motor actuates the upper satellite gear, which transmits through 4 plane pinions and 2 conical gears the power to the pulleys. The pulleys are used to extract the tape from the inner compartment once the orbiter has unwrapped it from the central spool.

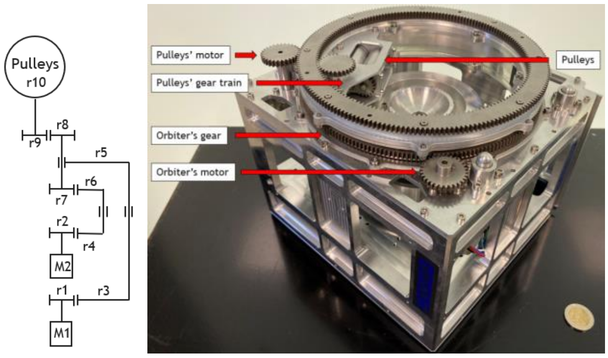

Figure 4.- Schematic gear train diagram and manufactured tape Deployment Mechanism BreadBoard

As previously mentioned, electrical motors are used to transfer power to the pulleys and orbiter. On a first trade off design phase, one fixed motor was used to rotate the orbiter and a second motor was placed on the orbiter for transmitting direct power to the pulleys. This design had the advantage of been simple in terms of mechanical design and interfaces, but the main drawback of motor electrical connection was required while the orbiter is continuously rotating. Therefore, the final design includes another kinematic gear chain with the main objective of transmitting power to the pulleys that are rotating with the orbiter from a motor statically attached to structure.

Regarding the motor selection, considering the tether velocity profile defined at mission level, brushless motors are the ones that fits better on the torque and speed requirements. Also, in terms of mass, brushless motors have a good performance to mass ratio. Maxon motors were selected due to its previous heritage and good price-quality ratio, at least for the Demo mission.

The pulleys are a key part of the mechanism as they are responsible of extracting the amount of tape that is unwound from the spool by the orbiter. To pull the tape, the gap between both pulleys needs to be smaller than the thickness of the tape. Besides, to standardise the mechanism, the pulley assembly needs to be compatible with different tape thickness. That is the reason why, a preloaded pulleys were designed, so the gap could be adjusted with a change in the thickness. Moreover, with this design, the pulleys can absorb any irregularity in the tape and in manufacturing process of the pulley assembly. Basically, the design consists of one pulley with a fixed axis and the other one compressed with a spring. With this concept, the pulleys can compress the tape with a predefined pressure, so the necessary friction is ensured during the tape unrolling.

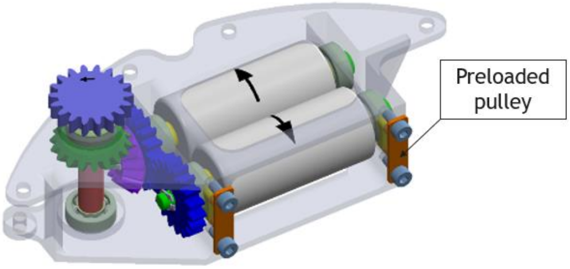

Figure 5.- deployment mechanism Pulley assembly

The DK will be launch stacked, and after activation, the two modules will separate with a HDRM. This release phase is important for the mission as any failure will have fatal impact to the mission. The HDRM is composed of a non-explosive release actuator, a spring located in the central spool and several contact points. The actuator selected for the mechanism is a SENER commercial product known with the name of NEReA (details in [4]). Nevertheless, the mechanism is compatible with any other type of actuator release. Similar to almost all the HDRM systems, once the release actuator is activated, the bolt will be ejected to the bolt catcher.

To ensure that the modules do not remain stuck together, a second spring is used to guarantee a first impulse once the bolt is released. The spring travel displacement could be tuned if the required energy to the system needs to be slightly modified.

Finally, to withstand the moments and torque generated during launch, some additional plain contact points have been included in each corner.

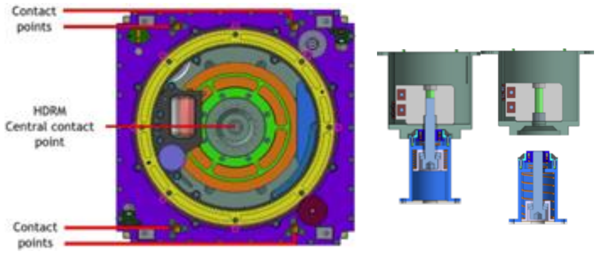

Figure 6.- HDRM functional scheme and contact points location

3 DEPLOYMENT SIMULATIONS

In case the DK is linked to a Host S/C, the potential instability of the deployment mechanism uncentered tape exit is compensated with the higher inertia and mass of the Host S/C. However, in the Demonstration Mission, as the kit will be launched alone with both modules deploying independently and self-deorbiting, the deployment simulations are required to ensure that the tape does not entangle.

Accordingly, a multibody simulation in ADAMS software has been performed. The following forces has been considered in the simulation:

- Cold gas force of 0.2N in the first 60 secs of the deployment
- Gravity Gradient
- Centrifugal and Coriolis forces for an Orbit at 550Km altitude

On the other hand, the model is composed of the following elements:

1. Electron emitter module (EEM)
2. Deployment mechanism module (DMM): Both the fixed structure and the orbiter has been included in the model
3. Tether tape and its stiffness

Masses, inertias, dimensions, and centre of gravity are taking from the mechanical design to consider a proper simulation model.

The tether velocity profile has been also considered as an input from mission level, as it has been defined to guarantee that the tether shape is close to its local vertical after deployment (a constant profile will not work and a dedicated "nose shape" profile is required). The following figure shows the tape velocity profile.

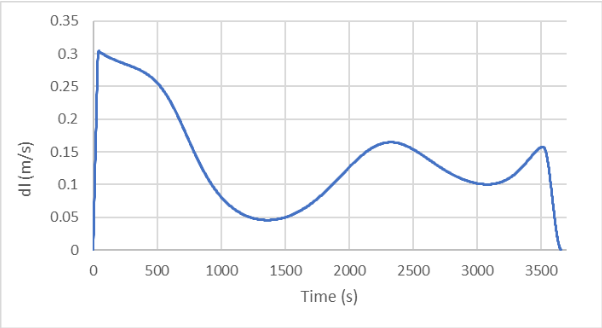

Figure 7.- Tape velocity profile from mission analysis

With this tape velocity profile and the deployment mechanism kinematics, the orbiter velocity profile has been included in the simulation. Fig. 8 shows the result of the simulations plotting the two modules deployment trajectory and the tape linkage (in dotted line). Moreover, Figure 9 shows the deviation angle from the vertical verifying that the tape does not entangled during deployment due to a high instability of the module and the uncentered tape exit of the orbiter.

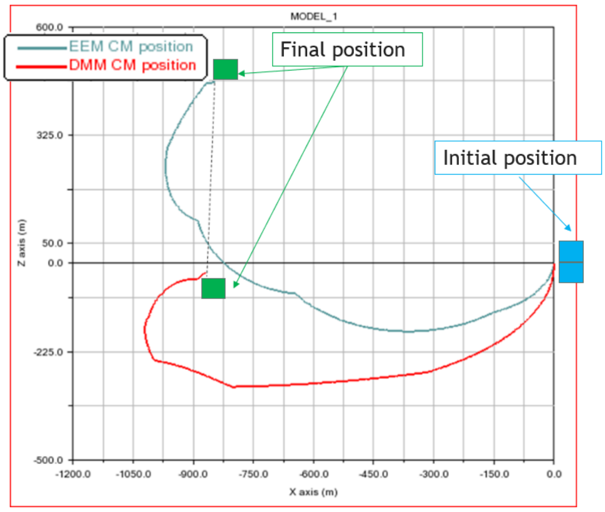

Figure 8.- Deployment trajectory and total length of the tether (dotted line)

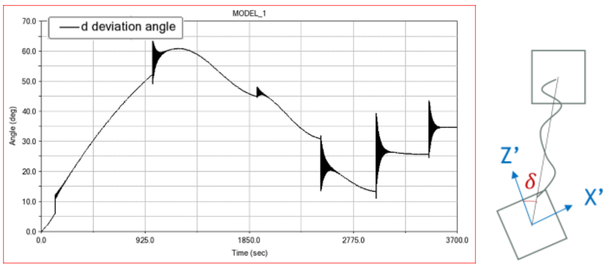

Figure 9.- Attitude of the EEM module during the deployment

Some key points are identified from these simulations. First, the deviation angle, although converge to a considerable low level, is quite high. To optimize it, some modifications in the deployment profile could be done or an attitude control could be implemented during deployment. Second, to damp the tension peaks and to obtain the presented results, a low spring is required at one end of the tape. This spring will reduce the tension peaks and avoid an unstable deployment. The behaviour of the 30N/m stiffness spring and the tether tension is shown in the following figures with the corresponding rebounds. Rebounds could be optimized with the small tuning of deployment profile.

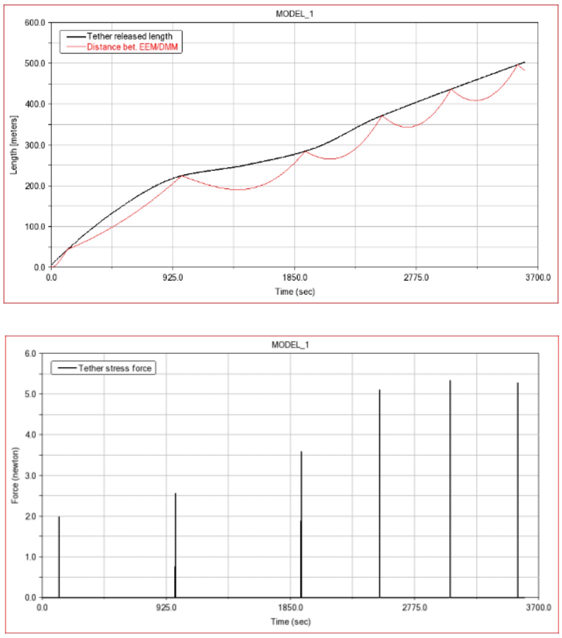

Figure 10.- Tape deployed and distance between modules (Top) & Force on the tether along the deployment (Bottom)

In principle, with these minor modifications, the deployment is stable and successful. However, looking at the criticality of the deployment and considering the uncertainty on the damping coefficient during the deployment (deployment stability is highly dependent on the damping coefficient assumed in the simulations), at mission level it has been decided to implement an attitude control system in both modules. After several trade off, and considering magnetorquers not enough to prevent instabilities, a cold gas system with active valves and control law was implemented in the Demonstration mission design, details are described in [3].

4 BBM VERIFICATION

In the frame of the mission E.T.PACK-F project includes two models, 1xEQM and 1xFM. The EQM will be subjected to a full qualification campaign including mechanical vibration, thermo-vacuum cycling, radiation tests, magnetic characterization and all necessary fluidic test. The qualification campaign is scheduled to finish before ending 2024. At the moment of paper preparation, the EQM is under manufacturing phase.

To handle with potential design changes in the early stages of the technology development, a Breadboard Model has been manufactured. In this BBM critical performances of the DK has been performed. Mainly, performance tests with the deployment mechanism and vibration tests have been carried out.

4.1 Deployment tests

The main objectives of the tape deployment tests are:

1. Verify that the two motors can follow the defined tape velocity profile
2. Simulate the first steps of the separation phase and the linkage of all the components together

With the tether velocity profile as an input and the kinematic gear chains analyzed, the rotation velocity for each motor has been calculated. The rotation velocity profile for each motor is represented on the following figure.

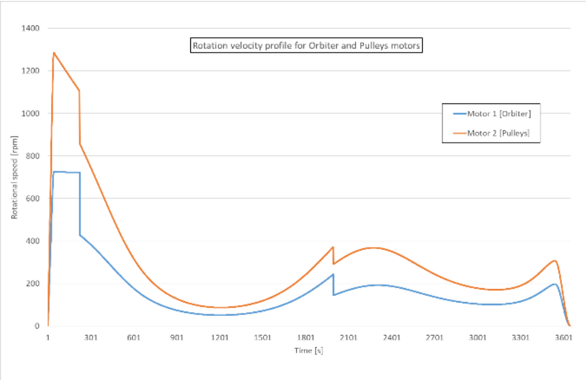

Figure 11.- Rotation velocity profile for each motor

Once the profile has been sent to the EPOS micro-controller EGSE, a complete deployment tests have been run in order to find any sources of error or incompatibilities between different systems.

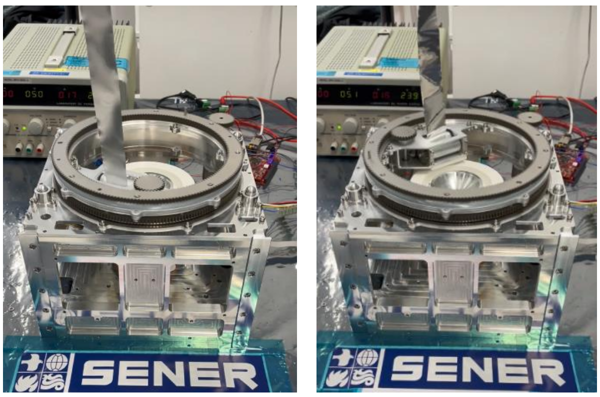

Figure 12.- Motors velocity profile and deployment sequence

After performing several trials, it has been identified the necessity of including a guidance element to route the tape stacked from the central reel to the pulleys. Otherwise, the pulleys tear the tape and break it. Finally, thanks to a dedicate guidance element linked to the orbiter, the tape moves smoothly until it reaches the pulleys in correct direction and the test deployment tests were performed successfully.

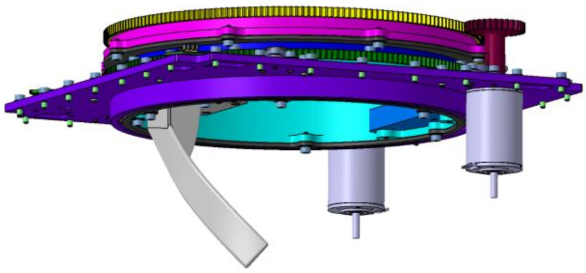

Figure 13.- Mechanism guide element and counterweight

Besides, during the test at top speed, it has been also identified the necessity of balancing the orbiter. A counterweight was implemented placed at orbiter level (at the opposite point where the pulleys are located) to counterbalance the decentralization of the pulleys. Otherwise, the pulleys generate an important vibration that could imply instabilities during deployment.

For the second test, deployment of just the first 2 m of tape were carried on. This length was concluded to be enough to verify the behavior and connections in the first steps of the deployment. For the test execution, a frame structure with two pulleys and a counterweight has been built. To simulate the tape pulling force during the first steps of the deployment, basically the 0.2N of the cold gas, a counterweight concept with the pulleys has been performed. The counterweight includes the mass of the EEM, the friction effect of the pulleys, and the extra 0.2N force of the Cold gas. The following figure shows the configuration and the test setup execution.

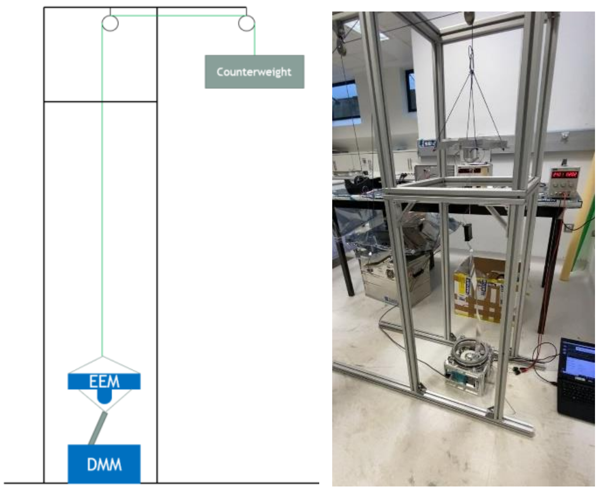

Figure 14.- Basic sketch of deployment test for the first phase (Left) & Real set up for deployment test of first phase (Right)

4.2 Vibration tests

ETPACK BBM has been subjected to sine and random vibrations. The equipment was mounted on shaker by using a dedicated vibration GSE, which represents the Demonstration Mission configuration. Accordingly, the configuration is compatible with a 12U canisterized launcher dispenser interfaces, by means of 2 clamped tabs along the modules to guarantee an invariant load path along the payload.

The first resonance frequency of the assembly was at 240 Hz. Sine qualification level vibration loads were up to 17g in lateral axis and 10gs in longitudinal in the frequency range of 20Hz to 100Hz. Random qualification level was 10gRMS. No notching was required.

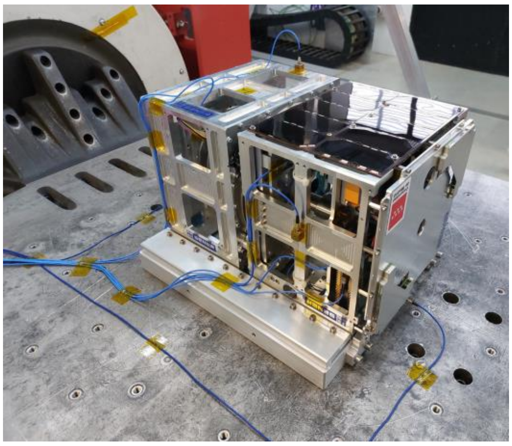

Figure 15.- Photo of E.T.Pack attached to the shacker with all the accelerometers placed

5 CONCLUSIONS

Nowadays, with the appearance of the mega-constellations and the new space, a deorbit system based on an electrodynamic tether could represent a game changer thanks to its reduced mass, low power consumption, high performance and its propellantless nature. The tape deployment mechanism play a key role in the deorbit system allowing the tape storage in a reduced volume and a safe tape deployment. The mechanism presented in this paper is a reliable, adaptable, and totally scalable solution for tape deployment. It is based on a two degree of freedom orbiting structure with motorized pulleys. The uncentered rotation of the pulley's assembly unroll the stacked tape and the pulleys extract the tape outside the module. Simulations and preliminary tests demonstrate that the design fulfil the mission requirements. Implementation of the lessons learned after the performance and vibration tests lead to a more robust design mechanism. A full qualification of the mechanism it is foreseen to be performed in the frame of E.T.PACK-F project during 2024.

6 ACKNOWLEDGEMENTS

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