REGULATED DEPLOYMENT MECHANISM FOR A PANEL LIKE APPENDAGE

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ABSTRACT

The definition of a cost effective deployment mechanism to deploy 180º panel like appendages in a safe way and with minimum end stroke deployment shock has been a challenge that led the design to achieve a low cost, light, compact, simple, flexible, modular, and low power demanding configuration. This mechanism is composed of an active hinge, that includes an optimised helical torsion spring with a deployment regulator in parallel, and a passive hinge, that includes the end stop and the monitorisation. The main functions of the mechanisms are decoupled in order to make the mechanism as flexible as possible to be adapted to very different needs such as different deployment torque, deployment angle, stiffness, interfaces, monitorisation, etc. The deployment mechanism is provided with a very compact novel deployment regulator based on the progressive melting of a band made of a low melting temperature metal alloy, that is cylindrically disposed. The deployment mechanism has been subject to a qualification test campaign including an extensive characterisation of the deployment regulator.

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1. INTRODUCTION

Spacecraft usually include in their systems several appendages that during launch are stowed in order to guarantee their survival to launch loads, and require to be deployed once the launching phase is finished. Those appendages require deployment mechanisms that cover a large range of applications at spacecraft subsystem level and at payload instruments level. It means that the use of a simpler, lighter, compact and cost effective device could have an important advantage over the current technologies used to deploy spacecraft appendages.

With that aim a baseline configuration was selected, and this baseline is shown, defined, and described in detail. The described deployment mechanism is simple, low cost, light, simple, compact, reliable, low power demanding and modular and flexible in configuration to be adapted to different payloads and applications.

Deployable antennas, reflectors and rigid panels will benefit of this developed mechanism that provides high work output capacity and small size.

Furthermore, this deployment mechanism is adequate not only for panel like appendages (requiring active and passive hinge) such as thermal radiators, solar array panels, reflectors, covers, etc., but for boom like appendages (requiring only the active hinge) such as antenna booms, experiments on masts, etc., and even for sequential deployable systems (controlled deployment sequence) such as tridimensional structures, big deployable antennae, etc.

Satellite deployable appendages deployed by motor springs provide, once released, an uncontrolled movement of the appendage up to reaching the deployment end stop. At that time, the spring energy transferred to the appendage, as kinetic energy is significantly high, meaning a significant angular velocity at the end of deployment. When the appendage reaches the end deployed position hits the end stop, transmitting an important shock to the spacecraft, endangering the spacecraft stability, the appendage base structural integrity, and the survival of near delicate electronic and radio-frequency equipment. In order to solve that problem, a new concept of deployment regulator is here included and presented, to make negligible such end deployment shock.

2. DESIGN REQUIREMENTS

Additionally to the aim of developing a cost effective deployment mechanism, the most relevant requirements used for its design are the following ones.

- Deployment angle: up to 180º, with manual adjustability between 135º and 180º, existing possibility of simple adaptation to other angles.
- Deployed appendage positioning: better than ±1º, with possibility of simple adaptation to reach values of ±0.01º.
- Deployment time: Between 20 seconds and 25 minutes.

- Characteristics of item to be deployed: panel like appendage with a mass < 20 kg, and a moment of inertia about hinge axis < 30 kg·m^2 (other values are not excluded).
- Locking latch: maintain in position the appendage once deployed.
- End deployment shock: appendage rotational speed at the end of deployment < 4 º/s.
- Output torque: ≤ 5.4 Nm. One or both hinges can be powered to provide the necessary deployment torque.
- Hinge axis position: two hinges in line locating the rotation axis at 45 mm from the fixation plane.
- Mass: ≤ 2.0 kg (for the case of one active hinge plus a passive hinge).
- Maximum power consumption: ≤ 40 W
- Temperature range (qualification):
  - Pre-operational: from –50 ºC to +75 ºC
  - Operational: from –40 ºC to +65 ºC
  - Post-operational: from –50 ºC to +85 ºC
- Quasistatic loads: 20g in any axis.
- Sine qualification level:

In any orthogonal axis [2 oct/min]	
5–20 Hz	11 mm (0-p)
20-100 Hz	20 g

- Random qualification level:

In any orthogonal axis [2.5 min]	
20–100 Hz	+ 10 dB/oct
100–200 Hz	2.49 g^2/Hz
200–2000 Hz	- 16 dB/oct
Overall Level	20.52 g_{RMS} (61.58 g 3σ)

3. DESIGN CONCEPT

In order to achieve a cost effective design, the main functions of the mechanism (such as torque source, hinge bearing, latching, deployment regulation, hinge structure, load carrying distribution, deployment monitoring, etc.) were analysed in detail, studying all potential alternatives for each function, and studying also the compatibility between the potential design solutions for all functions.

After that exhaustive analysis, and without forgetting about a simple and also cost effective assembly and integration process, the baseline configuration was defined.

The selected concept was based on the following guidelines:

- Hinge line composed by an active hinge and a passive hinge, distributing the load carrying capability between both as to makes it compatible with potential appendage thermoelastic distortions.
- Optimised helical torsion spring to provide the necessary torque. In principle, only one, with possibility of using one per hinge.
- Hinge bearing based on the use of self lubricated low friction journal bearings.
- Deployment regulation performed by a device without gear train, being necessary the design and development of a new deployment regulator concept.
- Reduction of the necessary structure to a minimum, providing simple interfaces.
- Maintain functions as decoupled and independent as possible to provide high modularity and flexibility to make the mechanism easily adaptable to any other needs (interfaces, torque, stiffness, etc.).
- Make the mechanism for a simple assembly and for an easy resetting without consumables.

Those guidelines drove to the following design concept:

Active Hinge.

- Helical torsion spring optimised in terms of envelope and mass.
- End deployment shock minimisation based on a novel deployment regulator based on the use of fusible alloys.
- Construction prepared to support radial loads.
- Compatible with appendage thermoelastic behaviour.

Passive Hinge.

- Adjustable end stop.
- Status monitoring based on micro-switches, monitoring start and end of deployment. Potentiometer could also be implemented under specific request.
- Construction prepared to support radial and axial loads.

Of course the design is also open to add options such as:

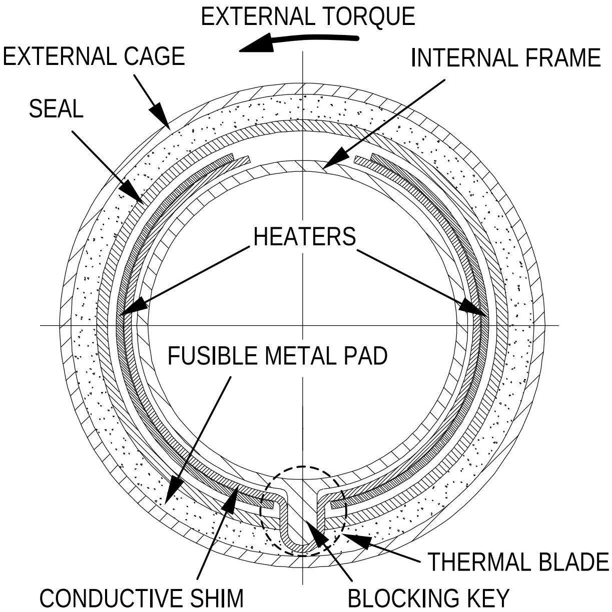
- Additional adjustable end stops.
- Additional mechanical latches.
- Additional monitoring (e.g. potentiometer).
- More quantity of helical torsion springs.
- ….

Although, developed for a panel like appendage requiring two hinges, the active hinge here defined is also adequate for deploying in a regulated way a mast or a slender element (antenna boom, long payload, payload boom, …). Even more, if the appendage requires more actuation torque both hinges could be active, and the selection of the adequate configuration will depend on the required motorization.

As consequence of the exposed guidelines, and the subsequent design concept, a specific development effort was necessary for the deployment regulator, which is the real novel technology to be implemented in the deployment mechanism.

The selected concept for the deployment regulator was based in the progressive fusion of a strip (disposed as a cylinder) of low melting temperature metallic alloy (fusible alloy). But that fusion should be performed in a thermally efficient way in order to make the mechanism not to demand high power. Figure 1 shows the conceptual definition of the deployment regulator (patented).

Figure 1 Deployment Regulator Concept



The deployment regulator concept consists of the following main parts:

1. Outer housing (or external cage) with internal grooves axially disposed.
2. Fusible metal pad cylindrically disposed joined to the internal face of the cage.
3. Internal frame with a blocking key
4. A shim of high thermal conductivity material covering the key. This part acts as a thermal blade fusing selectively and progressively the part of the fusible metal that makes contact with it.
5. A cylindrical seal covering the internal frame in those places different from the blocking key.
6. Heating devices disposed on the high thermal conductivity material shim, which is extended in between the sealing cylinder and the internal frame structure to both sides of the key.
7. An output shaft connected to the external cage and supported by self-lubricated flanged bush bearings.

Heaters heat mainly the shim. As shim is the only heated piece in contact with fusible metal, only the part of the fusible metal in contact with the shim fuses. This system concentrates the heating point, fusing progressively the fusible metal, rotating accordingly under the torque provided by an external torque source (e.g. a spring). As that external torque source pushes the fusible metal against the shim (blocked by the blocking key of the frame) the fused part of the fusible metal gets enough pressure to pass the thermal blade through a gap disposed to this purpose. Both ends of the cylindrical seal on which the cage slides are provided with means to avoid the liquid metal to get out.

The progression of the fusing, meaning the energy rate provided to the fusible alloy (latent heat of fusion), gives the progression of the rotating movement. Rotation speed is defined by the quantity of heat provided per time unit to the shim located in the blocking key.

Once the fused metal passed the blocking key, it reduces its temperature up to reaching a moment when it gets solid again. So, the system has full rotation capability.

The use of fusible metal alloy means no outgassing in vacuum conditions (no generation of contaminants).

Some of the main characteristics of this deployment regulator are:

1. The concept is not based in the global heating of the fusible material. Thermal blade fuses only the small portion of fusible metal which makes contact with it.
2. Heat fluxes to the fusible metal concentrated in an only point (not generically to the entire low melting temperature alloy). It means a minimisation and drastic reduction of the energy required to start the movement (lower energy required) and/or to start fusing a local part of the fusible alloy.
3. This deployment regulator makes the appendage deployment time independent of the available acting torque (once a positive acting torque is guaranteed).
4. The appendage deployment velocity can be adjusted changing the power provided to the heating elements.
5. The developed deployment regulator is compatible with any rotational angle, being ready for a new operation without any actuation on it. Therefore the deployment end stop should be implemented outside the device.
6. The used concept makes unnecessary another kind of mechanical latching system, as once the appendage is deployed and the heating is off (meanwhile the remaining actuation torque pushes the appendage against their mechanical end stop), when the temperature slow down below the fusible metal melting point, it solidifies, blocking the hinge and providing the required latching function.
7. The used concept does not require any special resetting of the deployment regulator different from the solidification of the fusible alloy.
8. The appendage manual resetting is easy. Only the decoupling of the deployment regulator is needed; then the appendage retraction to its stowed configuration can be performed by hand, and then the re-coupling of the deployment regulator can be done easily.

A demonstration model was design, manufactured and successfully functionally tested, following that concept. It provided high experience to develop a new fully flight representative deployment regulator, improving the demonstrator design in terms of mass, compactness and thermal efficiency, and making it fully compatible with the developed deployment mechanism.

The described concept provides sufficient deployment control in a reliable and self standing way, making the deployment regulator simple, cost effective, light, compact, reliable, and flexible in configuration to be adapted to different payloads and applications just playing with a small quantity of parameters:

- The selection of the adequate fusible alloy to provide the adequate thermal and mechanical characteristics.
- The definition of the effective section of the fusible alloy band to be compatible with the maximum pressure acting on it when solid.
- The diameter at which that fusible alloy band is disposed to be compatible with the maximum torque induced in the deployment regulator.
- The heating power necessary to get the desired fusion rates, and consequently deployment time.

4. DEPLOYMENT REGULATOR DESIGN

The deployment regulator main function is to regulate the deployment movement to minimise the shock at the end of the deployment, acting as an angular displacement regulator and not as an angular speed regulator. Its output performance depends only on the deployment regulator temperature at its activation, and on the voltage provided to the heaters, provided that there is available some positive torque (whatever is the positive torque value). It means that under the same thermal conditions and under the same provided power, the output is similar independently of the positive torque available.

The proposed deployment regulator envelope dimensions are ∅ 39 mm x 70 mm length, having a total mass of about 240 gr. The selected design parameters are the following ones:

- The selected fusible alloy is an eutectic alloy that melts at 70 ºC, providing relatively high mechanical performances.
- The selected section of fusible alloy is about 50 mm^2 .
- The selected diameter is 30 mm.
- The selected maximum heating power is 20 W (4 units of 5 W), being possible any value between 0 W and 20 W, just selecting the voltage.

The total mass of fusible alloy used for this application is about 50 grams. As its latent heat of fusion is 39.8 J/g, the upper limit of the angular velocity is 3.6 º/s.

The outer housing is made of titanium alloy, and the material selected for the internal sealing cylinder is PTFE. The fusible alloy, when solidifies again after being melted, adheres very well to metals, and very poor to low friction plastics. No pressure is guaranteed between the fusible alloy in solid state and the PTFE cylinder, minimising the friction between them, as the CTE of the different materials are in progression.

The internal frame containing the blocking key is also made of titanium alloy. The internal frame as well as the outer housing is thermally isolated from the shaft, and from the structure to which it is attached by means of pieces with very low thermal conductivity.

The selected heating elements (four) are kapton flexible heaters prepared to provide 5 W each. They are connected in parallel making the heating system to be failure tolerance as it is connected to two different connectors. If one connector fails, the redundant can provide the necessary power, and if one heater fails the other three can perform the requested operation providing the 75 % of the nominal selected power, meaning only a higher deployment time.

The material selected for the shim covering the key is electrolytic cooper due to its high thermal conductivity Its main function is to transmit in the most efficient way the heat from the heaters bonded on it to the area of the shim covering the blocking key that is in contact with the fusible alloy. The heaters are installed in the part of the shim that extends to both sides of the blocking key, in the cavity disposed between the internal frame and the sealing cylinder.

The sealing cylinder made of PTFE allows the thermal blade (blocking key with the copper shim around it) to protrude out of the cylinder penetrating in the fusible alloy band. That cylinder is provided with all necessary sealing provisions as to maintain the fusible alloy in liquid state in its cavity without any leakage or migration, even when there are relative movement between the cylinder and the outer housing, and even at very high environmental temperature (e.g. 120 ºC).

The shaft is rigidly connected to the outer housing but maintaining both thermally isolated. That shaft rest on two self lubricated bush bearings installed in the internal frame.

Figure 2 shows the deployment regulator, and Figure 3 shows its main components. Figure 4 includes some sections showing the blocks with relative movement, the one that remains fixed to the spacecraft, and the one that moves with the appendage.

Deployment regulator main characteristics are the following ones.

- Compact: < ∅ 39 x 70 mm.
- Low mass: < 240 grams.
- Peak maximum input torque: 20 Nm.
- Continuous maximum input torque: 14 Nm.
- Power: selectable from 10 W to 20 W (depending on allowed maximum deployment time).

- Deployment time adjustable: from 1.5 to 45 min (for 180º), depending on power and temperature.
- Angular velocity (at 180º): from 3.0 º/s (maximum) to 0.5 º/s, depending on power and temperature.
- Full rotation (without limit)
- Resetting for on-ground testing not required (only return to solid state). Re-assembly or refurbishment not necessary, only de-coupling and re-coupling.

Figure 2 Deployment Regulator

Figure 3 Deployment Regulator Main Components

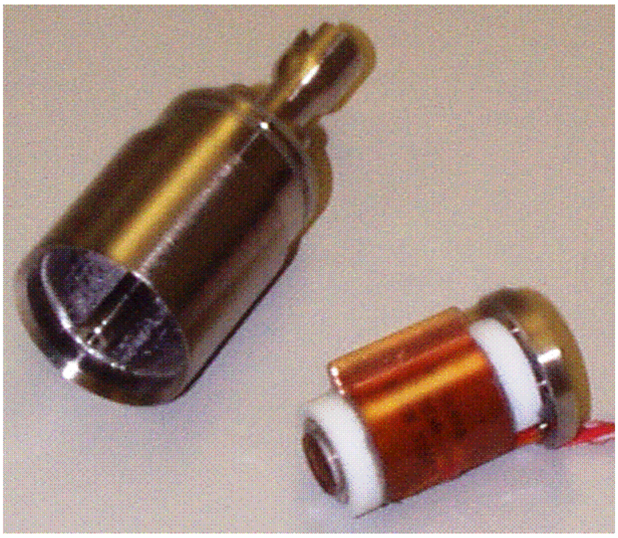
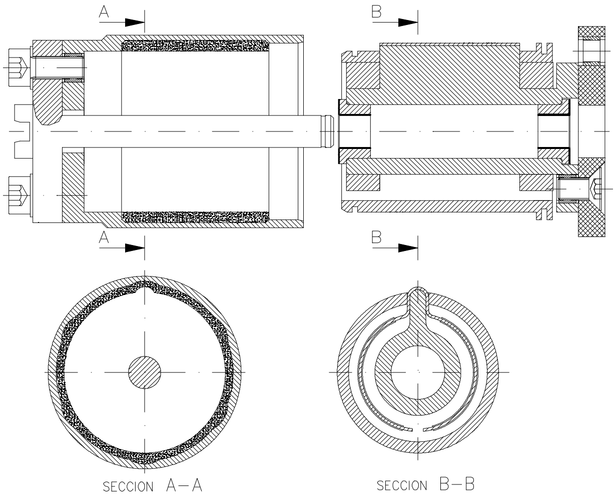


Figure 4 Deployment Regulator Sections



5. DEPLOYMENT MECHANISM DESIGN

Developed cost effective deployment mechanism main components have the following characteristics:

Active hinge

- A titanium alloy helical torsion spring of 5.4 mm diameter circular section wire. It provides at the end of a 180º deployment a torque > 6.3 Nm.
- A deployment regulator based on a low melting temperature metal alloy (as shown), installed inside the spring drum, and disposed in parallel with the spring.
- One set of aluminium alloy hinge supports, containing the hinge self lubricated bush bearings, joined together with the spring internal drum, providing structural support. Spring and regulator are disposed in between those supports in order to provide a self-standing device. The spring is disposed out of outside and the regulator inside the drum. Spring and regulator are disposed in parallel. It means higher compactness, and easy regulator de-coupling for mechanism resetting.
- Two titanium alloy hollow shafts, one per support, to rotate inside the self lubricated bush bearings, connected to the appendage bracket.
- An aluminium alloy bracket embracing both hinge supports, connected to the appendage.
- One titanium alloy coupling piece to connect the appendage bracket to the deployment regulator.

Passive hinge

- One aluminium alloy hinge support containing the hinge self lubricated bush bearings.
- An aluminium alloy bracket embracing hinge support, connected to the appendage.
- A titanium alloy hollow shaft, to rotate inside the self lubricated bush bearings.
- One adjustable end stop.
- Two micro-switches (main and redundant) that provide monitorisation of the appendage deployment status, with two adjustable cams.

As distance between both hinges can be important, the design of the active hinge has been made compatible with potential thermoelastic distortions of the appendage respect to the spacecraft. Therefore, the structural philosophy of the hinge line is that the passive hinge supports axial and radial loads, and the active hinge only withstands radial loads.

The design of both hinges maintains the idea of:

- Easy assembly (simple configuration).
- High degree on modularity as to be easily adaptable to any other requirement.
- Flexibility as to include options such as additional end stops, additional monitoring (potentiometer), more springs, etc.

Table 1 shows the achieved characteristics. Deployment mechanism main characteristics are the ones indicated in the design description of the deployment regulator adding the following ones.

- Low mass: < 1.5 kg (including deployment regulator, interface bolts and redundant electrical connectors). Active hinge < 1.12 kg. Passive hinge < 0.38 kg.
- Compact size. Active hinge: ∅ 75 x 160 mm. Passive hinge: ∅ 65 x 55 mm. (excluding interfaces).
- High deployment angle and adaptability: up to 180º .
- Positioning accuracy better than +/- 1º (+/- 0.01º is achievable).
- Mechanism output torque > 5.4 Nm (180º). If 90º deployment and two springs, torque > 11.7 Nm.
- Panel like appendage: 20 kg, 30 kg·m2, 2 m x 4 m (but not limited to that).
- Collaborates in launch configuration appendage stiffness. Adaptable to different stiffness requirements.
- End deployment shock minimum (deployment regulator): < 10 N·m (depends on appendage eigen-frequency).
- Operational Tª range: –40ºC/+65ºC (qualification).
- Non operational Tª range: -50ºC/+85ºC (qualification).

Table 1 Deployment Mechanism Characteristics

	Requirement	Achievement
Deployment angle	135º - 180º	0º - 180º
Deployment positioning	± 1º	± 0.1º
Deployment time (15W)	0.33–25 min	1.3–18 min
End deployment shock	< 4 º/s	≤ 3 º/s
Output torque	≥ 5.4 Nm	≥ 5.4 Nm
Mass	≤ 2.0 kg	≤ 1.5 kg
Power consumption	≤ 40 W	10 W – 20 W
Pre-Operational Tª	–50ºC/+75ºC	–50ºC/+75ºC
Operational Tª	–40ºC/+65ºC	–40ºC/+65ºC
Post-Operational Tª	–50ºC/+85ºC	–50ºC/+85ºC

Figure 5 shows a global view of the deployment mechanism with a deployable panel (2m x 4m). Figure 6 and Figure 7 shows the active hinge and the passive hinge, respectively in stowed configuration. Figure 8 shows a picture of complete deployment mechanism in deployed configuration.

Figure 5 Panel with Deployment Mechanism

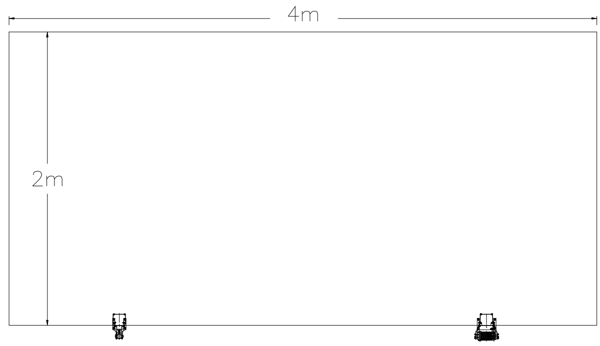


Figure 6 Active Hinge in Stowed Configuration

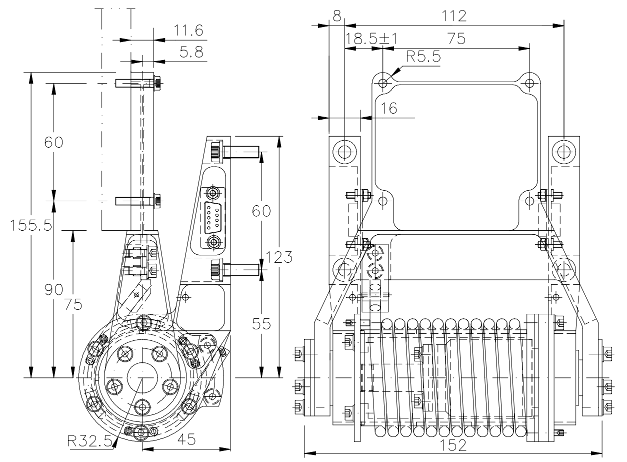


Figure 7 Passive Hinge in Stowed Configuration

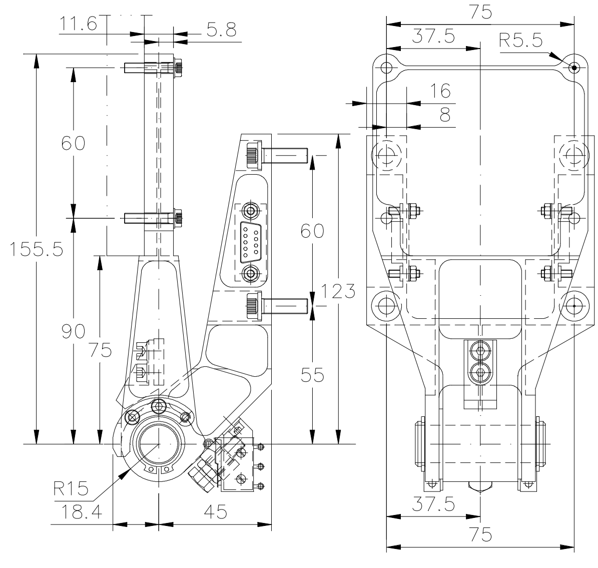
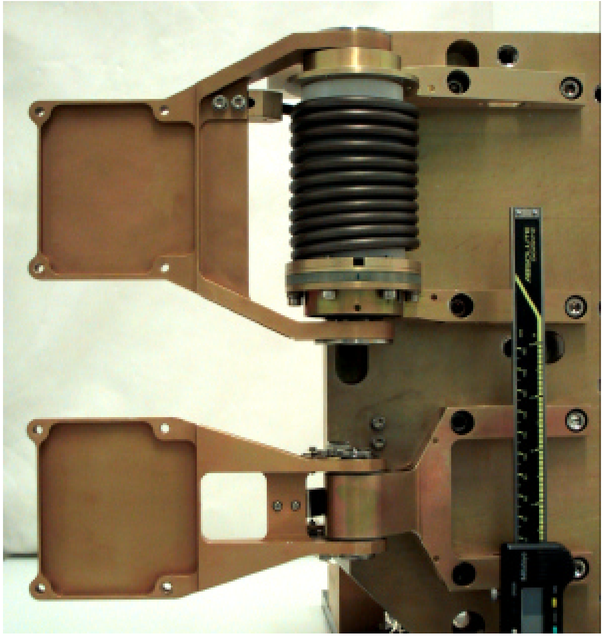


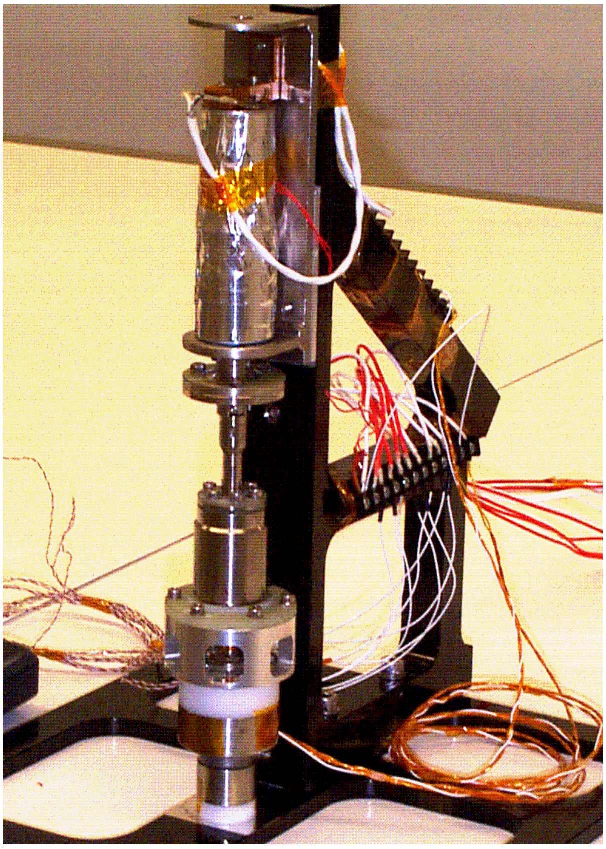
Figure 8 Deployment Mechanism Deployed.



6. TESTS

As the deployment regulator was the only device in the deployment mechanism with novel technology, a set of functional tests with very different conditions (180º) were performed. The test set-up is shown in Figure 9.

Figure 9 Deployment Regulator Test Set-up



The parameters used to characterised the deployment regulator design were the following ones:

- Electric power: 10 W, 15 W, 20 W.
- Temperature: -40ºC, -25ºC, +20ºC, +65ºC.
- Environment: in air, in vacuum.
- Actuating torque: 2 Nm, 5 Nm, …

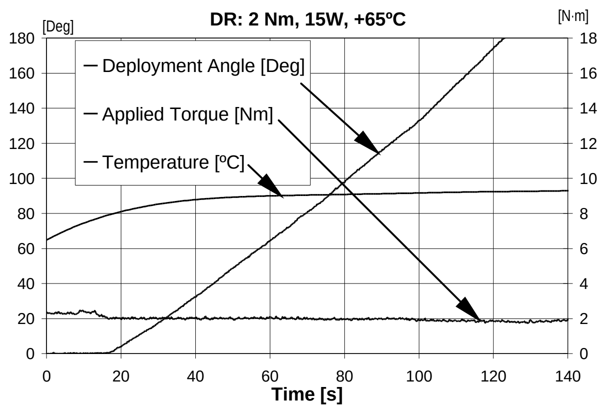
A chart showing the angle versus time is recorded in each functional test. This chart shows a curve similar in all cases to the one included in Figure 4. Also the temperature in the heating element has been recorded.

From each chart four main values are derived:

- The total time (TF)
- The time to start the deployment (TI)
- The deployment time (DT= TF-TI)
- The angular velocity at 180º deployment (AVF)

Figure 10 shows a typical chart obtained in an operation of the deployment regulator. It shows the progression of the deployment angle with time (potentiometer), the torque applied (torquemeter), and the temperature achieved in the cooper shim (thermocouple).

Figure 10 Typical Chart of Deployment Regulator Functional Test (E.g. 15 W, 65 ºC in air)



The following Table 2 shows the results obtained in air at different conditions of power and temperature.

Table 2 Deployment Regulator Performance

Power [W]	Tª [ºC]	TF [s]	TI [s]	DT [s]	AVF [º/s]
10	-25	1781	1309	472	0.5
	+20	567	276	291	1.1
	+65	148	18	130	1.8
15	-25	780	545	235	0.9
	+20	329	150	179	1.5
	+65	123	17	106	2.2
20	-25	487	286	201	1.4
	+20	192	66	126	2.2
	+65	92	15	77	3.0

Figures 11, 12 and 13 shows the total time, the time to start, and the deployment time, including the potential value dispersion, for different supplied power, and different environmental temperature in air. Figure 14 shows the angular velocity at the end of deployment as function of power and temperature, in air.
Additionally, the deployment mechanism has been subject to the following test campaign

- Sine vibration: 20 g (qualification).
- Random vibration: 20.5 g_{RMS} (qualification).
- Steady: 20 g (qualification).
- Thermal vacuum cycling and function (qualification).

Functional test with different actuation torque shows that the torque value has almost not influence in the deployment time, having a small impact in the time to start, that in principle can be considered negligible. Functional test in vacuum shows, as expected, a higher thermal efficiency than in air, reducing slightly the deployment time. In fact to have an idea of the deployment regulator in vacuum conditions, provided charts (in air) should be reduced in about a 23 % for the Total to Start, 18 % for the Total Time, and 15 % for Deployment Time. For each case, the 180º end deployment velocity increases about a 15 %.

Figure 11 Total Time for 180º Deployment

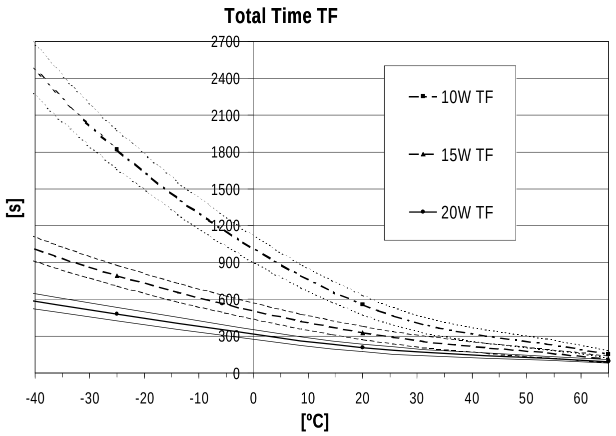


Figure 12 Time to Start Deployment

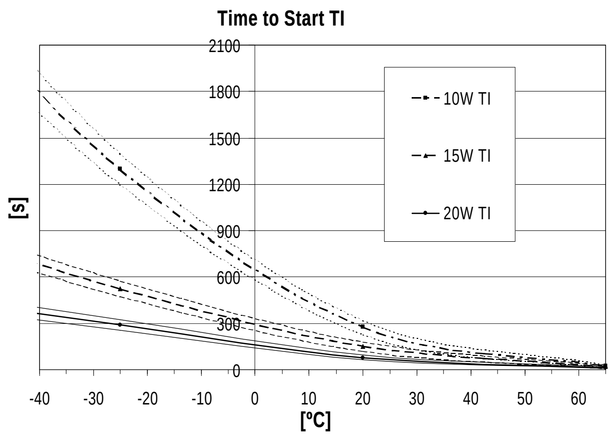


Figure 13 Deployment Time

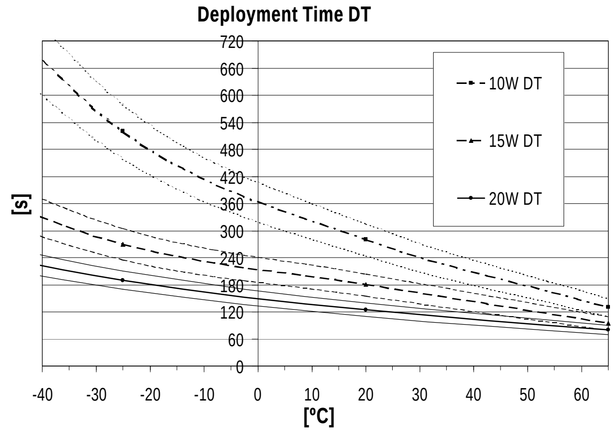
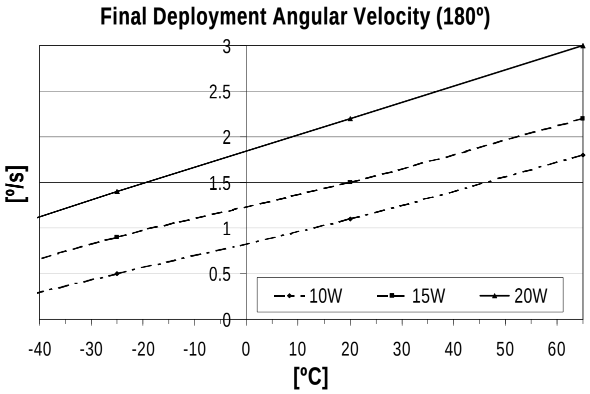


Figure 14 Angular Velocity at 180º Deployment



7. CONCLUSION

Presented deployment mechanism has been designed, manufactured to flight standard, and tested to qualification levels. It has proved to be a cost effective solution for deployable appendages being at the same time compact, simple, light, low power demanding and modular and flexible in configuration to be adapted to different payloads and applications. Although in principle it has been developed for panel like appendages, the active hinge can be used to deploy boom like appendages. Its functional performance is mainly based on a novel deployment regulator developed for spring driven deployable appendages. That deployment regulator has been extensively characterised under very different scenarios (temperature, power, air/vacuum, . . .). The deployment regulator minimises the shock at the end of the deployment, acting as an angular displacement regulator. Its output performance depends essentially on the environmental temperature at its activation, and on the voltage supplied to the heaters, provided that there is available some positive torque.

The obtained results show a promising future for both, the deployment mechanism and the deployment regulator.