Project : **Integrated Flex Pivot Position Sensor**

EXPOSITION

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TABLE OF CONTENTS

TABLE OF CONTENTS

(Continued)

TABLE OF FIGURES

TABLE OF TABLES

SCOPE OF THE DOCUMENT

This document resumes the complete Exposition project, from the technical background, the design, analysis and the results of the Engineering Model Test Campaign.

ABBREVIATIONS

ACRONYM	MEANING
AJP	Aerosol Jet Printing
AM	Additive Manufacturing
BB	Breadboard
AMFB	Additive Manufactured Flexible Blade
COTS	Commercial Off-The-Shelf
CTE	Coefficient of Thermal Expansion
EGSE	Electronic Ground Support Equipment
FEA	Finite Element Analysis
GF	Gauge Factor
RD	Reference Document
SLM	Selective Laser Melting
SoW	Statement of Work
TBC	To Be Confirmed
TBD	To Be Defined
TRL	Technology Readiness Level
TSM	Temperature Sensor Meter

APPLICABLE & REFERENCE DOCUMENTS

Applicable Documents		
Doc. Id.	**Document Nr.**	**Document Title**
[AD 1]	ESA-TRP-TEC-SOW-017526, Iss.1, Rev. 1	Statement of Work

Reference Documents		
Doc. Id.	**Document Nr**	**Document title**
[RD 1]	211-ES.2314, Iss.1, 4.7.20	Exposition proposal
[RD 2]	EXP-CSE-TN-01	Technical background information and high-level requirements
[RD 3]	EXP-CSE-TN-02	Preliminary concept definition and performance requirements
[RD 4]	EXP-CSE-TN-03	Preliminary Concept Design – Integration of sensors in flexible AM & Laminated blades
[RD 5]	EXP-CSE-TN-04	Critical element detailed design and test plan
[RD 6]	EXP-CSE-TN-05	Test report

1 PROJECT GOALS

A technology development was performed for the design, manufacturing and testing of Aerosol Jet printed strain gauges and commercial thin film strain gauges on different demonstrators: Additive Manufactured flexible blades and laminated sheet flexible spring blade. The flexible structures are representative of compliant mechanisms such as flexible pivots and tape springs for deployment mechanisms.

2 FLEXIBLE PARTS WITH PRINTED SENSORS

Two different breadboards were designed to address various needs typically found in compliant mechanisms. An additively manufactured (AM) flexure blade representing a large angle flexible pivot and a tape laminated spring as used on deployment systems were designed and manufactured to be used in the test campaign.

The **AM blade** design with a thickness in the range of 160 µm which was challenging to ensure with Laser Powder Bed Fusion (LPBF) additive process and required several optimization iterations. The design was improved with the addition of an additively manufactured electric connector for a direct measurement of the strain gauges.

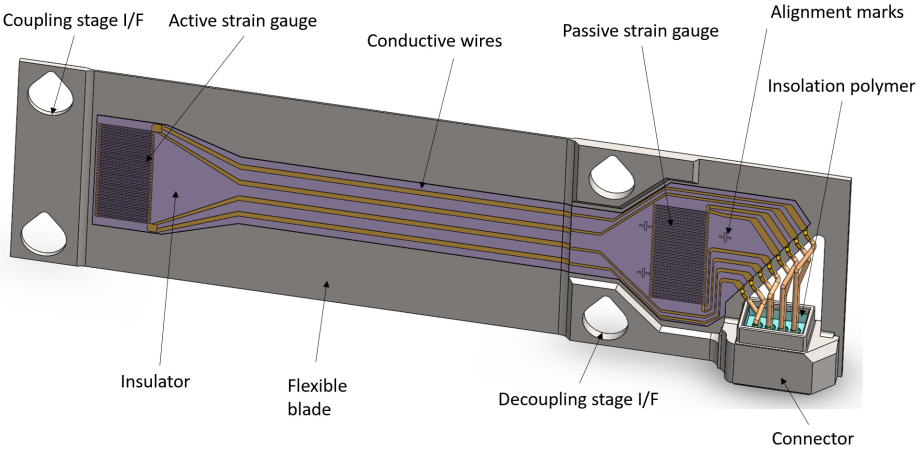

Figure 2-1: CAD view of the AM blade with integrated strain gauge

Figure 2-2: AM blade with AJP gauge and integrated connector

The **Tape hinge** breadboard design represents large angular stroke joints found in mechanisms used for solar panel or antenna deployment booms. The tape hinge is machined from a stainless-steel sheet and a long strain gauge (100 mm) is printed on it to obtain an angular sensor able to assess the correct deployment.

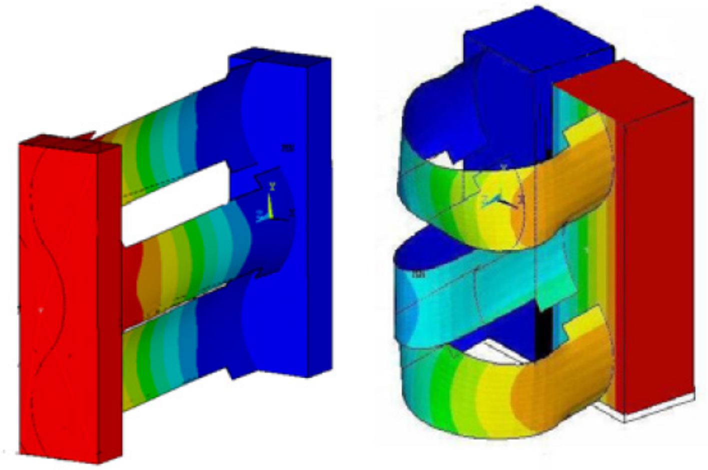

Figure 2-3: Typical Tape Hinge Carpentier joint in deployed and stowed position

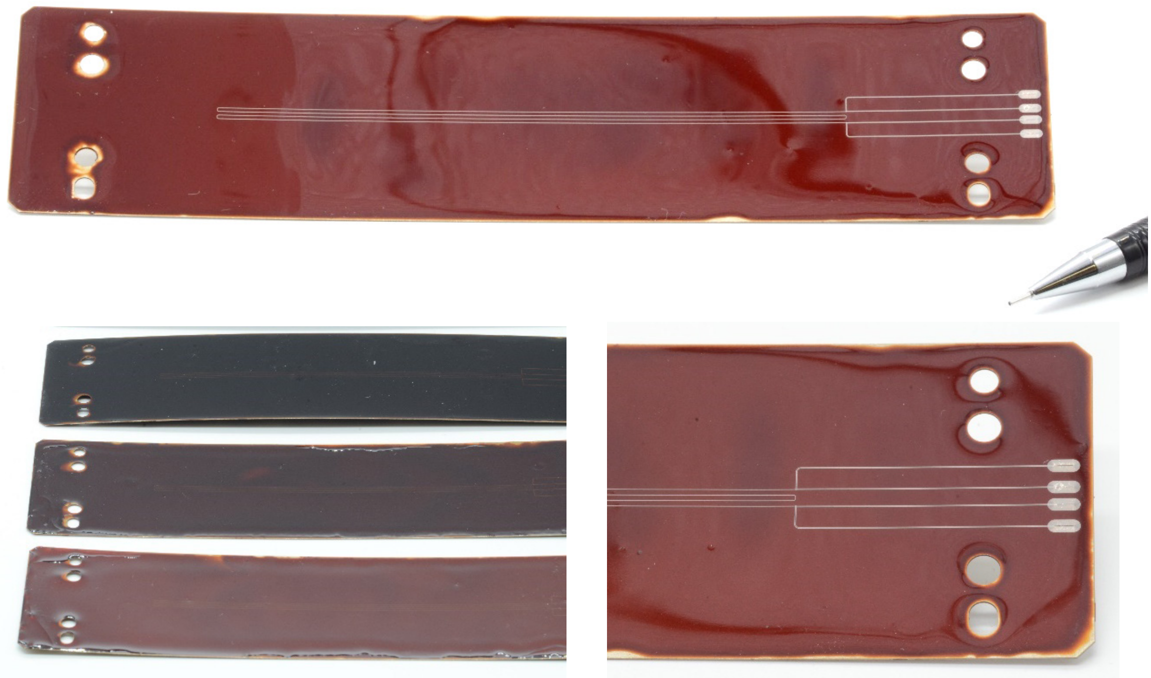

Figure 2-4: Tape hinges with AJP gauge pictures

2.1 TESTING

2.1.1 AM blade test bench design

The AM blade test bench induces a representative deformation of LAFP flexure blades, as shown in Figure 2-5. On the AM blade, either an AJP strain gauge or a glued COTS sensor are monitored as a function of the rotation angle. The single flexure blade has the characteristic dimensions of AM flexure blades, and the imposed deformation is identical to the LAFP configuration (±18° on the single blade motorized wheel corresponds to the ±72° on the full pivot). The flexure blade is fixed on one side in a rotating hub linked to a stepper motor through a coupling flexure and the other side is fixed to a linear decoupling stage. A rotation is imposed on the flexure blade rotating side while the integrated sensor output is read on dedicated electronics. The linear decoupling stage allows the flexure blade to shorten while rotating.

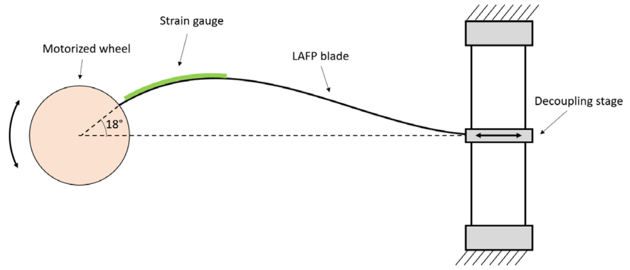

Figure 2-5: Schema of the AM test bench

The CAD model of the test bench is shown on Figure 2-6.

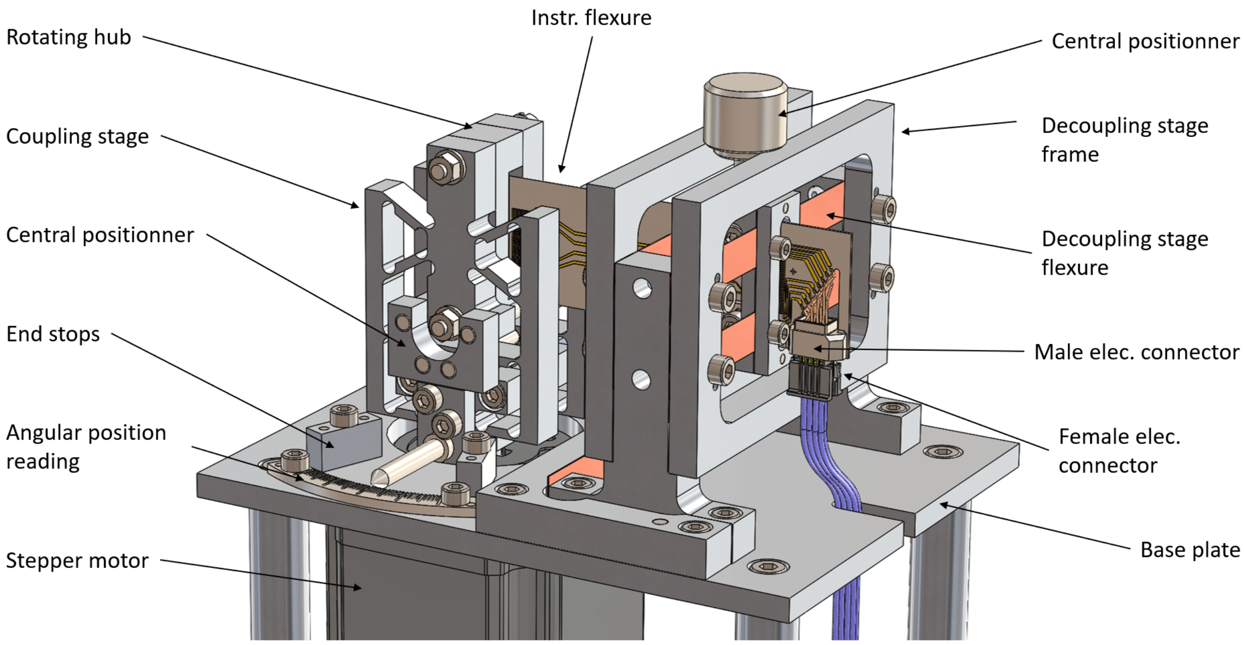

Figure 2-6: CAD view of the AM blade test bench

2.1.2 Tape hinge test bench design

This test bench is composed of a linear stage linked with one extremity of the tape hinge. The other extremity of the tape hinge is clamped on the rotational arm. The linear stage is equipped with a micrometer screw to ensure a more precise location of the linear stage at any position. For bigger displacement, reference gauges are used. The rotational position is measured by an optical system with a resolution better than 0.1mrad. Simultaneously, the linear and rotational positions as well as the electrical resistance of the gauge are recorded.

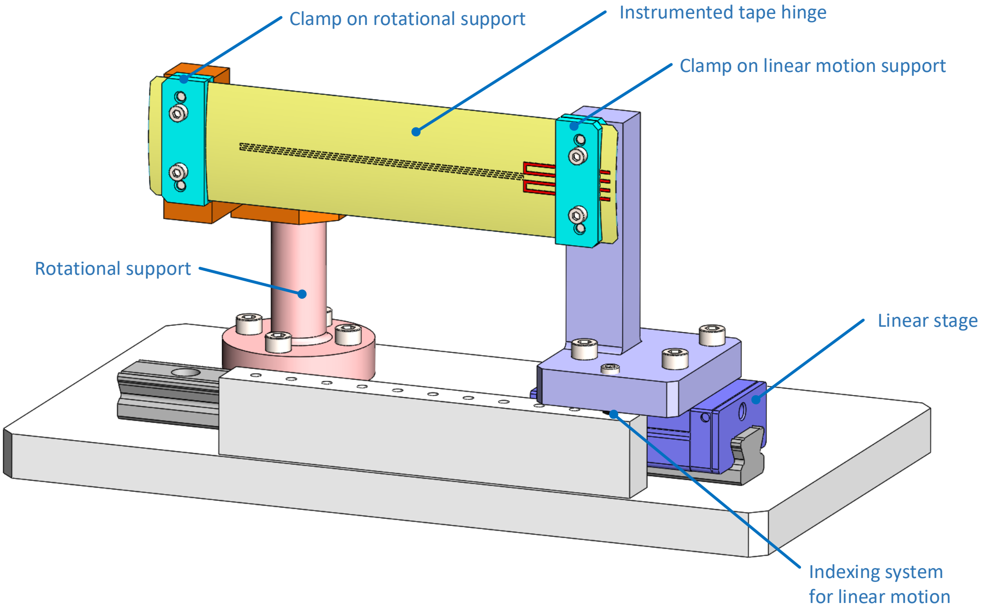

Figure 2-7: Tape hinge performance test bench overview

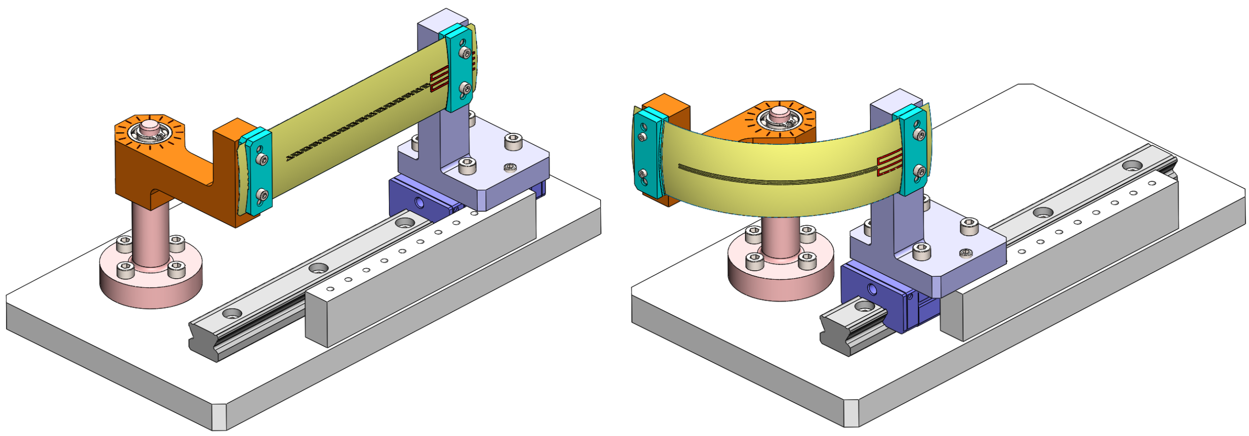

Figure 2-8: Tape hinge performance test bench with hinge in nominal (left) and 90° deflection (right) configurations

2.1.3 Electronic measurement system

The electronic measurement system aims to measure gauge resistor variation to characterize and validate the gauge. Both gauge and reference resistors are measured using a 4 wire acquisition configuration with a current path and two voltage directions.

The system is composed of:

- A current source (up to 20mA) controlled either with a digital bus (SPI) or with an analogue input
- Four multiplexers to switch the acquisition between the gauge resistors, reference resistor and calibration resistors
- A differential amplifier with a selectable gain to measure voltage drop at resistance terminals
- An offset subtractor (bus and voltage controllable) and an amplifier with a selectable gain to measure resistance variations
- A multiplexer and a high precision ADC
- A fixed low side voltage to ensure operation outside of the rail
- Two high precision and stability calibration resistors
- Several measurements points to be able to characterize gauge connector/wires
- An analog output
- A low noise high precision power supply
- Digital interface for a controller board and interface for PLC

The system is designed with precision, low noise components and a high-resolution ADC to characterize as precisely as possible the gauges but also to provide key points to design future or space acquisition electronics. The system is designed to acquire more than 1k samples per second with a resolution of at least 25 000 LSB/Ω. The system is compatible with all kinds of gauges (e.g. printed flexure blades and tape hinges).

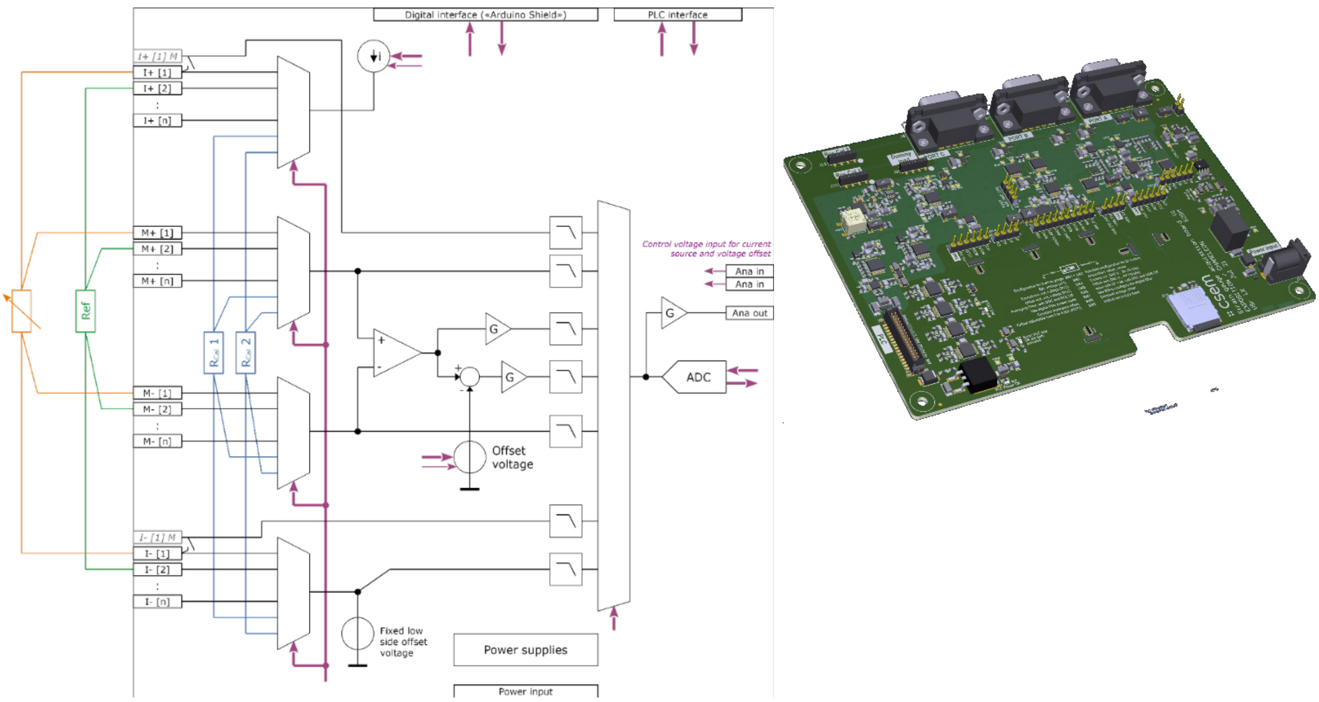

Figure 2-9: Electronic measurement system diagram

2.2 TEST RESULT RESUME

2.2.1 AMB test results conclusions

- **Epoxy insulating layers were significantly thicker** (19-180 µm) than expected when compared to the model (20-30 µm) and dispersion is important.
- When correction is applied to the **gauge factor** calculation (considering the higher insulation thickness), the values are **standard** (~2).
- **All the samples survived the voltage degradation tests**, even when experiencing very high temperature up to 120°C.
  - No crack was initiated in the epoxy layer when applying voltage on passive gauge (SN11).
- **Cracks occur at low temperature**, and/or when high thermal gradient is applied (dT/dt).
- **Thermal sensitivity of AMB AJP gauges is much higher** than COTS sensor (~200 x).
- All the samples **survived the 5k cycling test**, without performance degradation.
- All **performances** except linearity (and thermal sensitivity) **are better on the COTS gauge.**

2.2.2 Tape Hinge test results conclusions

- **Epoxy insulating layers were significantly thicker** (54-249 µm) than expected when compared to the model (20-30 µm) and dispersion as well as local variations are important.
- The **gauge factor** value is **standard** (~2.9) for one sensor. The other sensor presented significant drift and electrical noise, probably resulting from a connection problem between the gauge pads and the measurement wires.
- The **angular precision value is 3.3°,** which is lower than the requirements and twice the COTS precision.
- **The samples survived the voltage degradation tests**, when experiencing a temperature up to 47°C (AJP gauge) and 64°C (COTS gauge).
- The sample C **survived the 200 cycles test**, without performance degradation.
- All **performances are better on the COTS gauge except the gauge factor.**

2.3 LESSONS LEARNED BB MANUFACTURING AND GAUGE PRINTING

2.3.1 Breadboard manufacturing (AM blades and tape hinges)

a) Thanks to the AM printed connectors, the connections, and measurements of the AJP gauges on the AM blades were fast and reliable. On the other hand, the connection between the AJP pads and the wires for the tape hinges was problematic. Conductive glue was used but reveals to be very brittle. This connection aspect needs to be carefully considered early in the design process.

2.3.2 Insulation deposition process

a) The activation by plasma of the surface to be insulated is of the utmost importance to avoid de-wetting. Several tools (plasma pen, plasma cleaner chamber) have been used with various results. Especially the activation before applying the second insulation layer over the silver ink which could damage the ink by oxidation. This aspect should be investigated further as next priority.

b) The insulation deposition process still needs to be optimized since the layer thickness is not homogeneous, when done with the robotized spray coater. Deposition with the AJP machine was tried but the process required considerable amount of time which blocked the nozzle. More AJP tests with bigger nozzles and eventually other insulation formulation should be performed. In parallel, other materials, such as polyimide (instead of epoxy) should be investigated to be closer to material requirements for space, such as low outgassing and resistance to radiation.

c) The insulation between the blade metallic structure and the printed tracks is significantly lower than the requirement of 100MΩ. Hypothesis is that the thickness of the insulation layer is locally lower than expected (nominal thickness should be 20-40 µm). Again, the insulation process should be improved.

d) It is not believed that improving further the surface roughness of AM substrate (Ra value around 2 microns) would significantly improve the deposition of the insulation layer. A change in the process is considered as most effective, such as to deposit by AJP with a better control of the insulation quantity and location.

2.3.3 Gauge printing process

a) At least 16 AM blades of the last design have been printed, but finally, after all printing and insulation processes, only three have acceptable gauge resistance values around 120 Ω. The AJP process is currently not mature enough to ensure reproducible results.

b) The gauge resistance is not reproducible. Especially the deposition width is not constant.

c) Moreover, the resistance varies along the multiple step process, such as the second insulation layer deposition and curing. Sedimentation of the silver particles was observed.

   More work should be done to improve the repeatability of the ink deposition process.

d) The chosen insulation and ink require multiple curing at 250°C. This aspect shall be considered to verify that the parts are not affected by these operations. Lower temperature curing would be more suitable in future, even if curing time is increased.

e) The silver ink is stable only for 2 to 4 hours after homogenization process. The pattern of the gauges and conductive lines has been modified to accelerate the deposition and respect this time, at the cost of less homogenous and precise tracks.

f) The current equipment has limited positioning features, so a precise alignment between each AJP layer requests time and is not repeatable. This aspect should be improved with the new equipment. In parallel, printing on 3D surfaces should be investigated.

3 FUTURE APPLICATION POSSIBILITIES

3.1 Possible applications of flexible pivots with integrated sensors

As the next generation of pointing mechanism will be subjected to more and more stringent µ-vibration requirements, making old designs based on stepper motors and ball-bearings obsolete and requiring new solutions. A flexible pivot with integrated position sensors provides the possibility to remove not only the ball bearings but also the stepper motor. The latter could be replaced with a closed-loop controlled brushless DC motor or a voice-coil actuator. This concept can minimize exported disturbances with a compact design, as the sensor is integrated within the pivot. The only down-side is a more complex controller.

Depending on the configuration, we can envision the following advantages by implementing **integrated sensors**:

- the printed gauge avoids the complex integration, alignment and need for a separate monitoring of an external position sensor, e.g. a potentiometer
- redundancy of the position if more than one blade is equipped with a sensor
- possibility to have a direct information of the flexure blade health and to implement methods for faults identification and management
- information on the temperature of each blade if the blades are equipped with printed thermal sensors

One of the most streamlined applications is a pointing mechanism where the elevation stage is composed of two large angle flexible pivots with integrated position sensors.

3.2 Possible applications of tape hinges with integrated sensors

Tape springs are very thin (0.1mm to ~1mm thick) metal strips (mostly manufactured from spring steels) that have an imposed curvature around their longitudinal axis. The larger the curvature of the tape spring, the more robust it is in deployed configuration and the higher the force to coil them up (higher preload required to remain coiled).

The most common application for tape spring hinges is frictionless deployments e.g. of booms or panels. Basically, the tape springs allow two different kinds of deployment:

- Linear deployment as per a winding meter concept.
- Rotary deployment: Here often a pair of shorter tape springs are used to connect the deployable part to the structure. This concept benefits from the tendency of tape springs in the coiled state to exert force to unfold themselves due to internal stresses. It is often used for "binary" systems that only require the deployed and stowed states.

An **integrated position sensor** could detect and confirm the successful deployment and the reached end position. The position or change of position could be measured indirectly via strain gauges that detect the deformations and additionally as a health monitoring indicator while in the stowed position. Integrated position sensors (also distributed) could allow for a better characterization and monitoring of the tape spring highly non-linear deployment process, both during on-ground testing correlation activities, and the in-orbit process.

Another possibility could be to combine the position knowledge during deployment with an active damping system for future missions to minimize disturbances during the deployment. An integrated sensor could be used in closed loop to provide information to an active shape control system to correct deformations in case of sensitive payloads (such as optical cameras, etc) are deployed by means of tape springs.

4 CONCLUSION

The general conclusions of the project activities are summarized in the sections below:

AM Blade tests conclusion

- Epoxy insulating layers are significantly thicker (19-180 µm) compared to the model (20-30 µm) and dispersion is high
- When correction is applied for epoxy thickness to the gauge factor, the values are normal (~2)
- All the samples survived the voltage degradation tests, even when experiencing very high temperature up to 120°C
- Cracks occurred in epoxy at low temperature and/or when high thermal gradient is applied
- Thermal sensitivity of AMB AJP gauges is much higher than COTS sensor (~200 x)
- All the samples survived the 5k cycles test, without performance degradation
- All performances except linearity (and thermal sensitivity) are better on the COTS gauge

Tape Hinge tests conclusion

- Epoxy insulating layers are significantly thicker (50-250 µm for two layers) compared to the model (20-30 µm) and dispersion as well as local variations are important
- The gauge factor value is standard (~2.9) for one sensor. The other sensor presented significant drift and electrical noise, probably resulting from a connection problem between the gauge pads and the measurement wires.
- The angular precision value is 3.3°, which is lower than the requirements and twice the COTS precision
- All the samples survived the voltage degradation tests with temperature up to 47°C (AJP gauge) and 64°C (COTS gauge)
- The tested sample survived the 200 cycles test, without performance degradation
- All performances are better on the COTS gauge except the gauge factor

General conclusion

- COTS strain gauge gluing is not straightforward…
- Aerosol Jet Printing is a promising technology to ease the implementation of sensors However, this technology needs to be matured as soon as possible
- AMB performances are better on the COTS gauge except linearity
- AMB design of 3D printed connectors saved us from connectivity issues
- Tape Hinge performance better on the COTS sensor except gauge factor

Future plans for this activity need to address difficulties encountered during the development, notably epoxy insulation thickness and homogeneity, performance aspects related to AJP sensor precision, repeatability, resolution, hysteresis and thermal sensitivity. A follow on project at CSEM (EU-ATTRACT) will develop an AM heat pipe with embedded temperature sensor for temperature monitoring in cooling system for advanced detectors.

5 REQUIREMENTS PERFORMANCE

Reqt ref.	Verif.	Description	Requirement	expected value	Measured value	Status
Single Blade						
Req-0002	A, T	BB angular deflection	compatible with a deflection equivalent to ±70°	±18° (representative of ±70° on 4 stages)	±18°	Compliant
Req-0003	R, T	Integrated sensor electrical signal output	Related to the flexible structure absolute deflection.		Linearity error 2.4 to 3.4%	Compliant
Req-0005	A	Lifetime	>12 million cycles	not assessed for the gauge	5'000	Compliant
Req-0006	A, T	Sensing angular precision/resolution	<0.1°		0.05° to 0.1° (resol AJP sensor) 0.02° (resol COTS sensor)	Compliant without thermal aspects[1]
Req-0008/9	R, A	Blade thickness	no direct requirement	160 µm	165 µm (+8/-19 µm) after polishing	Compliant
Req-0008/9	R, A	Blade stiffness	no direct requirement	192 mNm/rad	not measured	NA
Req-0008/9	R, A	Blade torque	no direct requirement	60 mNm	not measured	NA
Req-0006	A, T	Gauge resistor value	no direct requirement	120 Ohm	113 to 122 Ohm	PC[2]
Req-0006	A, T	Gauge factor	no direct requirement	1.73	1.82 to 2.05	~Compliant
Tape Hinge						
		BB angular deflection	+90°	+90°	+90°	Compliant
Req-0003	R, T	Integrated sensor electrical signal output	Related to the flexible structure absolute deflection.		Linearity error 5.4%	Compliant
Req-0005	A	Lifetime	>200 cycles		200 cycles, no degradation	Compliant
Req-0007	A, T	Sensing angular precision/resolution	<4.5°		Repeatability: 2.4° AJP, 0.1° COTS Precision: 3.3° AJP, 0.2° COTS	NC (C for COTS)
Req-0008/9	R, A	Blade thickness	no direct requirement	250 µm	250 µm laminated sheet	Compliant
Req-0008/9	R, A	Blade torque	no direct requirement	320 mNm	not measured	NA
Req-0007	A, T	Gauge resistor value	no direct requirement	120 Ohm	161 to 247 Ohm	NC
Req-0007	A, T	Gauge factor	no direct requirement	1.73 (analytic), 2.18 (FEM)	2.7-2.9	Compliant

[1] The thermal contribution to the accuracy will depend on the number of look up tables that can be implemented over the thermal range.
[2] Some aspects are not compliant, such as the temperature dependance.