ESA Study Contract Report

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ESA Contract No: 4000122822/18/NL/BJ/gp	SUBJECT: Ceramic Packages for Magneto Resistive Sensors	CONTRACTOR: RSG GmbH (former HTS GmbH)
ESA CR () No: N/A	No. of Volumes: 2 This is Volume No: 1	CONTRACTOR'S REFERENCE: CEPA-RSG-RP-004

ABSTRACT:

EXECUTIVE SUMMARY REPORT

In Europe typically two different types of angular encoders are used in mechanisms, either potentiometer for coarse position feedback or sophisticated, costly optical encoders for highest position knowledge and highest accuracy demands. Since 2015 RUAG Space Germany, together with Sensitec GmbH (SST), develop a sensor system called “Magneto-Resistive Angular Sensor for Space Applications” (MRS), which is an angular sensor based on the Magneto-Resistive effect, specifically developed for the use in spacecraft mechanisms.

The MRS consists of a rotor assembly, which is a magnetic pole ring attached to the moving part of the mechanism, and the sensor assembly, which includes the magneto-resistive sensor and the pre-amplification stage. In the frame of this activity ceramic packages for carrying the MRS under space environment has been developed, designed, manufactured and tested. The main challenges were:

- High demands on manufacturing tolerances of the package to meet the performance requirements of the sensor
- To produce hermitically sealed vias for electrical contacting of the chip in the ceramic package
- Package closure by soldering

The final performance tests provided evidence in terms of high precision manufacturability of ceramic packages. It can be stated that the accuracy of 0.1° [+/-0.05° linearity error] can be achieved under all tested environmental conditions. Room for improvement showed the full package leakage test based on the soldering process for package closure.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.

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CEPA
Executive Summary Report

Contract Closure Documentation

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1 GENERAL

1.1 Change record

Iss./Rev.	Date	Responsible	Description of change
1 / 0	5.5.2020	Christian Melzer	Initial Issue

1.2 Referenced Documents

RD 1	CEPA-RSG-RP-002 Issue 01. 28.04.2020

1.3 Applicable Documents

N/A

1.4 Abbreviations

AD	Applicable Document
AMR	Anisotropic Magneto Resistance
CIL	Critical Item List
EAR	Export Administration Regulations
ECSS	European Cooperation for Space Standardization
ESD	Electro Static Discharge
GMR	Giant Magneto Resistance
GSE	Ground Support Equipment
IMAPS	International Microelectronics and Packaging Society
ITAR	International Traffic in Arms Regulations
LCM	Lithography based Ceramic Manufacturing
LTCC	Low Temperature Co-fired Ceramics
MMC	Metal Matrix composite
MR	Magneto-resistive
MRS	Magneto-resistive sensors for space applications
N/A	Not Applicable
PDR	Preliminary Design Review
RD	Reference Document
RID	Review Item Discrepancy
RSG	RUAG Space Germany GmbH
SST	Sensitec GmbH

T3DP	Thermoplastic 3D Printing
TBC	To be confirmed
TBD	To be defined

2 PROJECT OVERVIEW

2.1 Background

In most spacecraft mechanisms used today, the angular position is measured using potentiometer or optical encoders. On the one hand, potentiometers provide moderate performance at very low costs, however are often characterized by low reliability. Also the friction in the sensor poses additional burdens to the mechanism as additional torque capability needs to be provided by the actuator to overcome the friction torque, potentially leading to an over-design of the actuator.

On the other hand, optical encoders provide very high performance but are rather sensitive to radiation. In addition costs are significant. In many cases the superior performance of optical encoders is not even needed actually. However, there are only few products and proprietary, mission specific solutions in between these products. In effect many space mechanism suppliers are required to integrate over-sized, costly optical encoders, as they are lacking actual alternatives.

2.2 Technical Objectives

The MRS sensor system presented above is intended to fill the gap in between potentiometer and optical encoders in terms of performance and costs. The market impact could even be increased, if only the sensor head would be small enough and production and verification costs could be reduced to fit in applications which are currently equipped with potentiometers.

In turn, the longer-term objective for the targeted application area is to increase the market share of the MRS sensor system by improving the competeveness of the product, ultimately resulting in superseding potentiometers in most space applications, and thereby reducing technical and schedule risks imposed by those to space projects. In particular this shall be achieved by implementing the following key design logic:

- Achieve a more compact, smaller sensor head to allow for applications where today’s design does not fit in
- Increase competitiveness by reducing production costs using modern and efficient manufacturing methods
- Increase competiveness by reducing verification and acceptance test efforts by developing a “easy to test” product and implementing a lean production and verification stream

Therefore ultimate technical objective of the proposed de-risk project is the design and demonstrator test of a novel, compact and robust sensor head for angular sensors for space mechanisms, using modern and advanced materials and manufacturing methods.

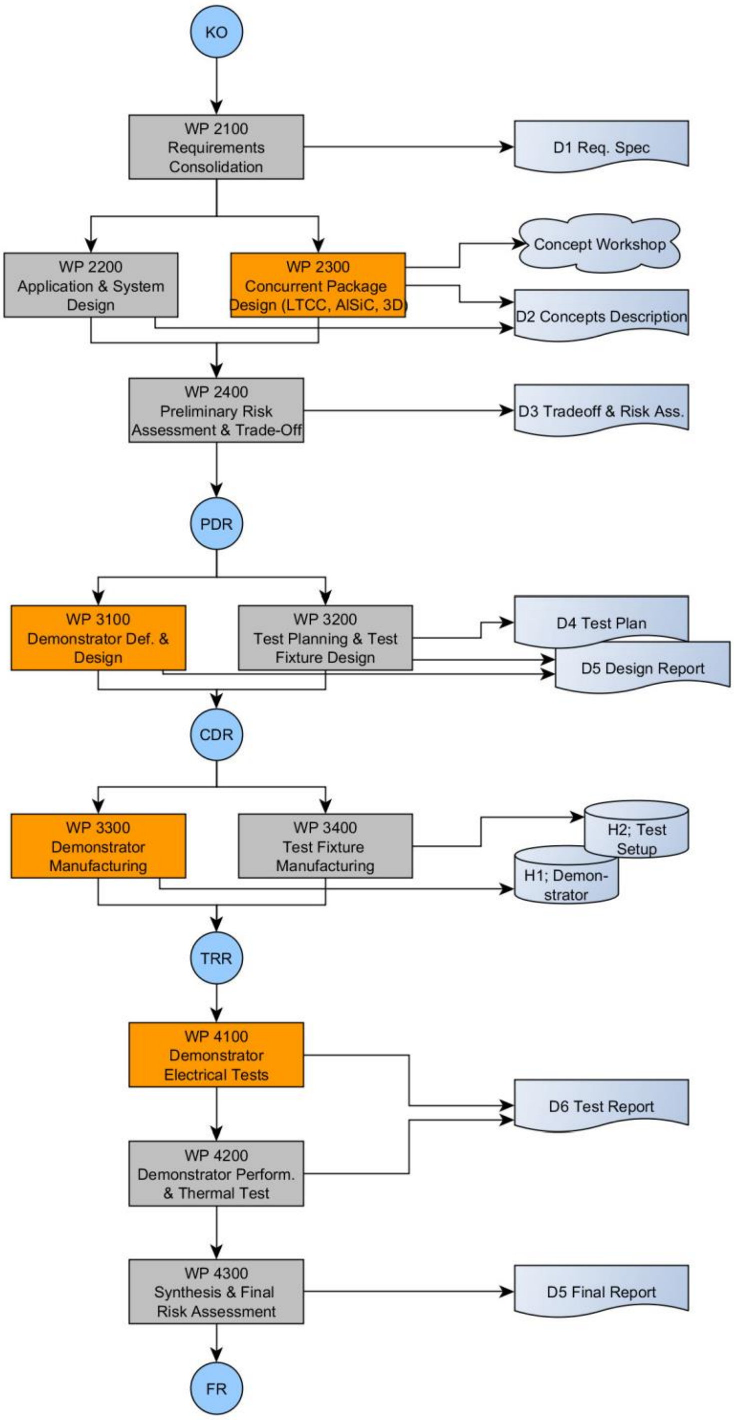
As a pre-cursor study this project is intended to cover the initial design, analysis and bread boarding activities in order to fully identify and understand all technological and programmatic risks associated with the development, qualification and commercialisation of such a sensor package for future space applications.

This objective can be broken down into the following technical approach of the project:

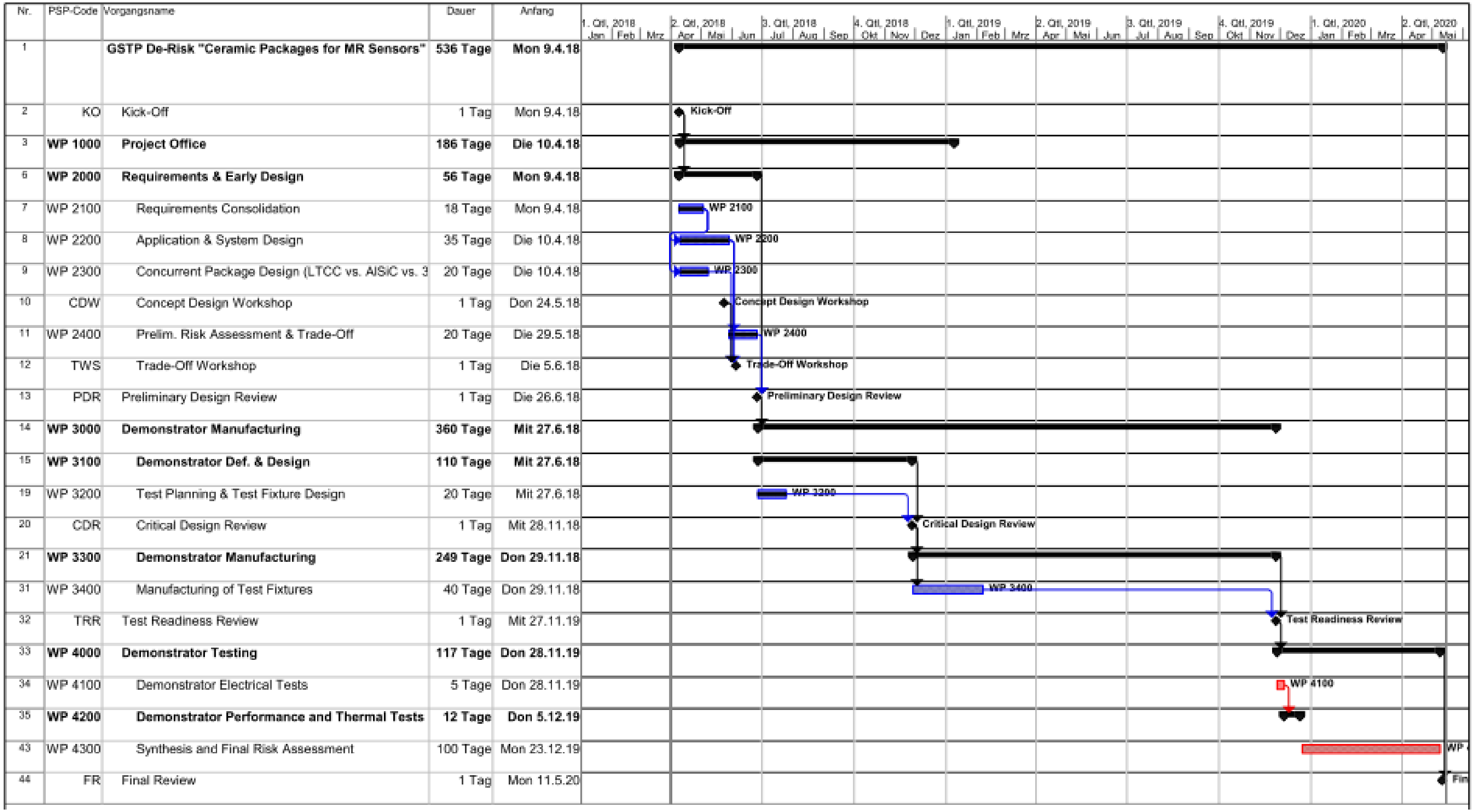
- Elaboration of possible sensor system package designs for manufacturing with LTCC, AlSiC, and ceramic 3D printing technologies
- Evaluation of potential benefits and drawbacks of the candidate concepts
- Identification and detailed analysis of the technical risks concerning development, qualification and application using the new manufacturing approaches
- Perform a concept trade-off and design an early demonstrator model (breadboard)
- Build and test a functional breadboard
- Evaluate test results and consolidate the risk assessment

- Define the development and qualification plan
- Consolidate the business case

2.3 Work Logic



2.4 Schedule



Nr.	PSP-Code	Vorgangsname	Dauer	Anfang
1		**GSTP De-Risk "Ceramic Packages for MR Sensors"**	**536 Tage**	**Mon 9.4.18**
2	KO	Kick-Off	1 Tag	Mon 9.4.18
3	**WP 1000**	**Project Office**	**186 Tage**	**Die 10.4.18**
6	**WP 2000**	**Requirements & Early Design**	**56 Tage**	**Mon 9.4.18**
7	WP 2100	Requirements Consolidation	18 Tage	Mon 9.4.18
8	WP 2200	Application & System Design	35 Tage	Die 10.4.18
9	WP 2300	Concurrent Package Design (LTCC vs. AlSiC vs. 3	20 Tage	Die 10.4.18
10	CDW	Concept Design Workshop	1 Tag	Don 24.5.18
11	WP 2400	Prelim. Risk Assessment & Trade-Off	20 Tage	Die 29.5.18
12	TWS	Trade-Off Workshop	1 Tag	Die 5.6.18
13	PDR	Preliminary Design Review	1 Tag	Die 26.6.18
14	**WP 3000**	**Demonstrator Manufacturing**	**360 Tage**	**Mit 27.6.18**
15	**WP 3100**	**Demonstrator Def. & Design**	**110 Tage**	**Mit 27.6.18**
19	WP 3200	Test Planning & Test Fixture Design	20 Tage	Mit 27.6.18
20	CDR	Critical Design Review	1 Tag	Mit 28.11.18
21	**WP 3300**	**Demonstrator Manufacturing**	**249 Tage**	**Don 29.11.18**
31	WP 3400	Manufacturing of Test Fixtures	40 Tage	Don 29.11.18
32	TRR	Test Readiness Review	1 Tag	Mit 27.11.19
33	**WP 4000**	**Demonstrator Testing**	**117 Tage**	**Don 28.11.19**
34	WP 4100	Demonstrator Electrical Tests	5 Tage	Don 28.11.19
35	**WP 4200**	**Demonstrator Performance and Thermal Tests**	**12 Tage**	**Don 5.12.19**
43	WP 4300	Synthesis and Final Risk Assessment	100 Tage	Mon 23.12.19
44	FR	Final Review	1 Tag	Mon 11.5.20

3 TECHNICAL SPECIFICATION

Based on the targeted application area, and based on the objectives outlined above the following technical requirements can be derived for the MRS sensor package:

1. Compact design

   The MRS package shall be smaller than 20 x 10 x 5 mm³ and incorporating the MR sensors, pre-amplification, hermetic sealing and bonding pads to attach harness. The electrical design inside the integrated MRS package shall be compatible to ECSS standards.

2. Thin package walls

   In order to ensure the performance of the MRS, the thickness of the package facing the the magnetic pole ring shall be less than 100-300 µm to allow for sufficiently large magnetic field

3. Radiation hardness

   The sensor assembly inside the novel MRS package shall sustain a total dose of 300 krad to be also compliant to deep space size missions and long term telecom missions in geostationary orbits.

4. Performance

   The performance of the MRS sensor system in the novel package shall be the same as using conventional packaging technology and PCB technologies, i.e. absolute uncertainty of the sensor shall be < 0.1° and the repeatability shall be < 0.002°

5. Sensor output signal

   The sensor output signal shall be the same as in the current MRS design, hence 1 Vpp sine-cosine signals, and compatible to conventional encoder interfaces.

6. Temperature range

   In order to comply with most mechanism applications the MRS sensor system shall survive a temperature range of -60°C to 150°C

7. Reduced production cost

   In order to increase market impact and to supersede potentiometers the production costs shall be reduced by 50 % with respect to the production costs of the current MRS sensor assembly design. This will be possible as the overall number of components and production steps can be significantly decreased by using hybrid electronic technologies rather than conventional PCB technologies. Also the external metallic housing could be obsolete, which also helps reducing production costs and assembly efforts.

8. Reduced verification effort

   In order to reduce the overall costs of the product, the verification costs, e.g. for lot acceptance tests, functional tests and environmental tests need to be reduced. The design and the production approach shall be such that the verification effort can be reduced by at least 30 % of the current verification costs. In particular, this shall be achieved by streamlining the required verification test approach, based on a dedicated risk assessment.

4 MANUFACTURING PROCESS, MATERIAL AND DESIGN CONSIDERATIONS

4.1 Lithography based Ceramic Manufacturing

Lithography based Ceramic Manufacturing (LCM), developed especially for additive manufacturing of ceramics, works according to the so-called digital light processing principle. This technology is available at Fraunhofer IKTS Dresden, were the CerFab7500 system from Lithoz GmbH is used.

As in stereo lithography, free radical polymerization of the binder system takes place with light of a defined wavelength, causing the suspension to solidify. Via a DLP module, the suspension is selectively irradiated with blue light, whereby all areas to be cross-linked on a given plane are exposed at the same time. The productivity is hence high. Achievable densities following conventional thermal treatment of the AM green bodies are at least 99.4 % of theoretical density for Al_2O_3 and at least 99.0 % for ZrO_2.

Equipment type	CeraFab 7500 (Lithoz)
Build chamber	76 x 43 x 150 mm³
Layer thickness	5 – 100 µm
Lateral resolution	40 µm (635 dbi)
Build speed	2.5 – 10 mm/h

The LCM-technology was developed by Lithoz (Figure 4-1) and is based on the principle of photo polymerization. Ceramic powder is homogeneously dispersed in a light-sensitive organic matrix and selectively structured through mask exposure. The body of the CeraFab system consists of a vat, filled with a photo curable slurry. Through the rotation of the vat, a layer of slurry is applied with a static wiper blade. The vat is transparent so that the slurry can be lit from below. The projected image is generated via a digital mirror device (DMD). The mirror array consists of more than two million mirrors, which are lit by the LEDs, and can be operated individually. Each of these mirrors can be turned on or off separately and simultaneously, which enables dynamic mask exposure. The advantage of this procedure is that the entire surface area is exposed at the same time, making the duration of light exposure independent of the size of the cross section to be exposed.

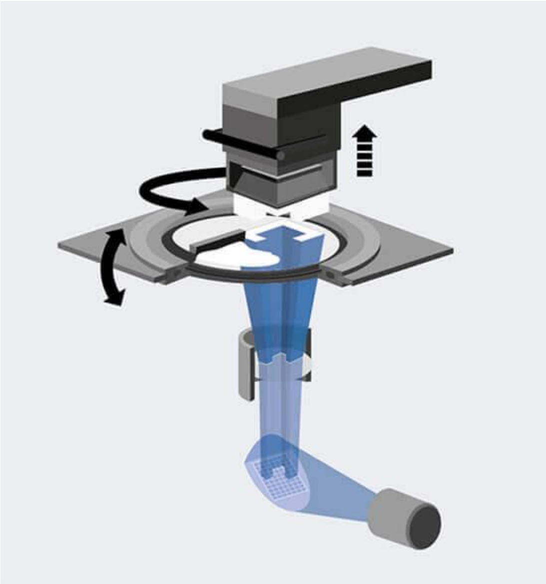


Figure 4-1 LCM Cerafab principle

The main part of the package is the bottom component. It is manufactured in a 3D printing process based on lithographic technology. Build up takes place upside down starting with the large base area. Layer by layer a polymeric binder is solidified by light and is establishing a green body, which is baked in a furnace to the final ceramic. Base material is Al_2O_3.

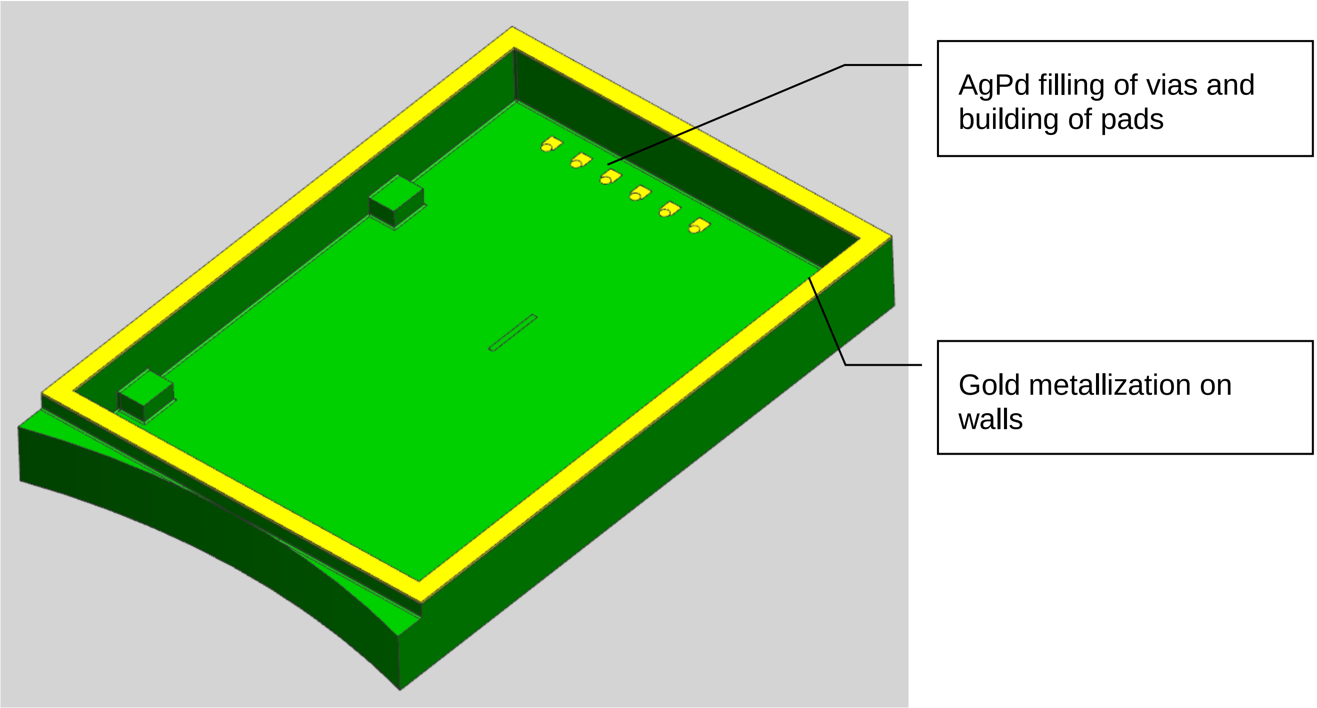


Figure 4-2 Package bottom 1

Functionalization is done afterwards to provide two things:

- Gold metallisation for lid closure soldering
- Provision of electrical conductor lines.

The package lid is also manufactured by the same lithographic 3D printing process from the same material. It provides a physical marking on the top side and a gold metallisation[1] on the bottom side. This metallization is needed for the closure by soldering.

As a backup process a glass paste might be used for hermetic closure. In this case the metallization is obsolete. This backup will be considered if the metallic soldering is causing technical issues (e.g. soldering temperature of gold is not bearable by electronics, hermeticity is not achieved, etc.).

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[1] As a backup process a glass paste might be used for hermetic closure , if soldering temperature of gold is not bearable by electronics

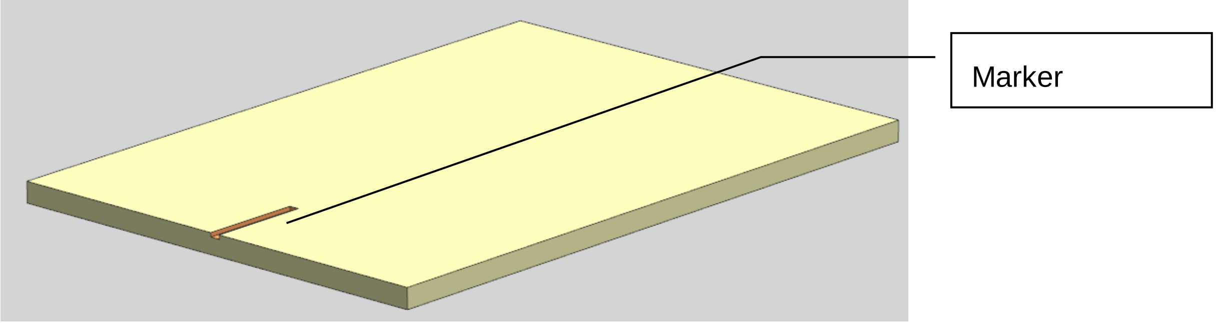


Figure 4-3 lid top side

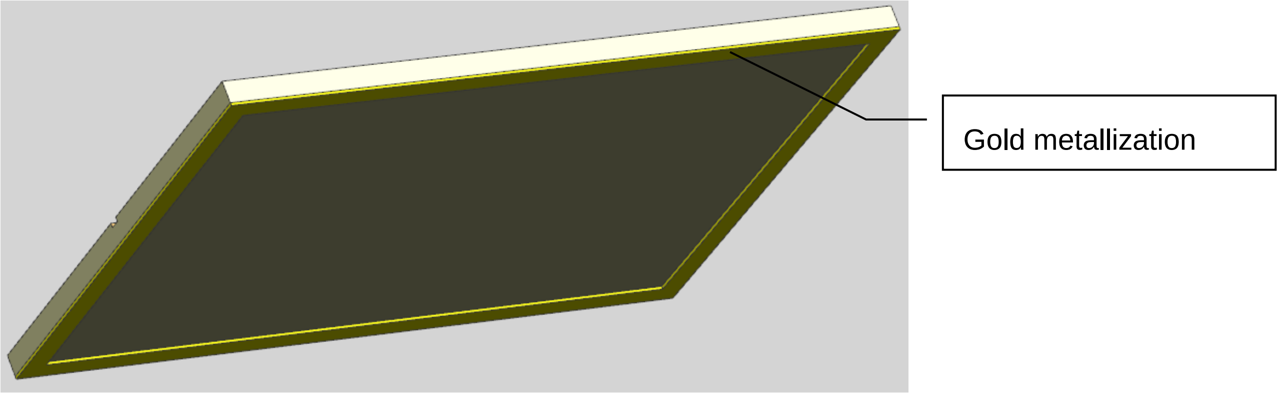


Figure 4-4 lid bottom (inner) side

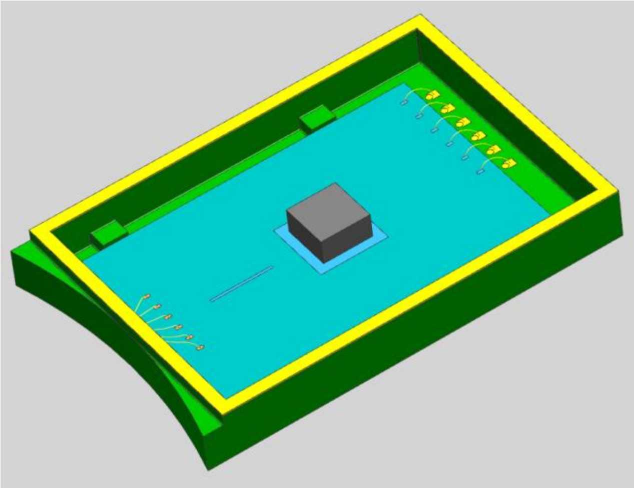
4.2 Electrical feedthrough

Electrical feedthroughs have to be implemented in order to enable contacting of the electrical signals. The main objective is to maintain the hermeticity. The technologies available shall be selected suitable for the main package manufacturing process. A compatibility assignment is given in Table 4-1.

	Via through holes generated by laser; Filled with conductive paste; fired in oven 	Via through holes generated by laser; conductive tracks in intermediate layer Filled with conductive paste; fired in oven 	Isolating low temperature melting inlays with conductive fired in oven 
Compliance with LCM manufacturing principle	Yes (in dependency of built direction)	No	Yes (in dependency of built direction)

Table 4-1 feedthrough technique assignments

The selected technology is using vias of approximately 500µm diameter and building bond pads on both sides by screen printing. To build solderable pads a thick-film process is needed which in turn requires flat surfaces.



- **Figure 4-5 Package bottom with integrated intercarrier**

4.3 Electrical Circuit Board

The intercarrier assembly is supporting the sensing circuit which is equivalent to the MRS circuit for incremental measurement. The differences lay in two main aspects:

- the AL magneto-resistive chip is bonded directly on the substrate without an additional package
- the amplifier IC is also a chip on board variant

The layout of the intercarrier is to be seen in Figure 4-6. It has the dimensions 17.39mm by 28.2mm. The AL798 MR chip will be places in the middle and 50µm protruding over the substrate edge. This is deemed to have the sensor at closest possible distance from the package wall.

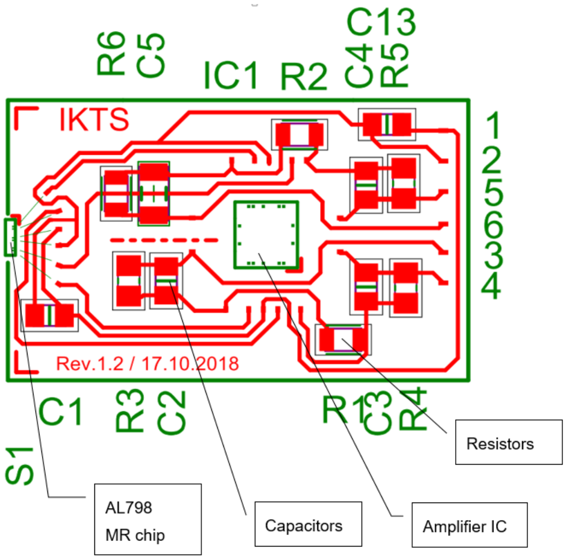


Figure 4-6 Layout of electrical circuit

5 OVERALL PACKAGE DESIGN

From preliminary design and corresponding variants trade off a package concept was selected which consists of the following components with its functions:

Package bottom

- building one half of the hermetic cavity for accommodation of the sensing electronics
- provides a gluing interface with positioning locators
- provides electrical feed-troughs for outside electrical contact
- providing flat wall edges for soldering closure of package

Package lid

- building second half of the hermetic package cavity
- providing a centre mark (prevent transposition of lid sides after production)

Intercarrier assembly

- provides MR sensing electrical circuit
- mechanical interface for integration in package

Package carrier

- metallic interface for screwed connection to different application
- positioning interface (rails) for gluing connection to sensor package
- cut-out for inspection of wire soldering on the package

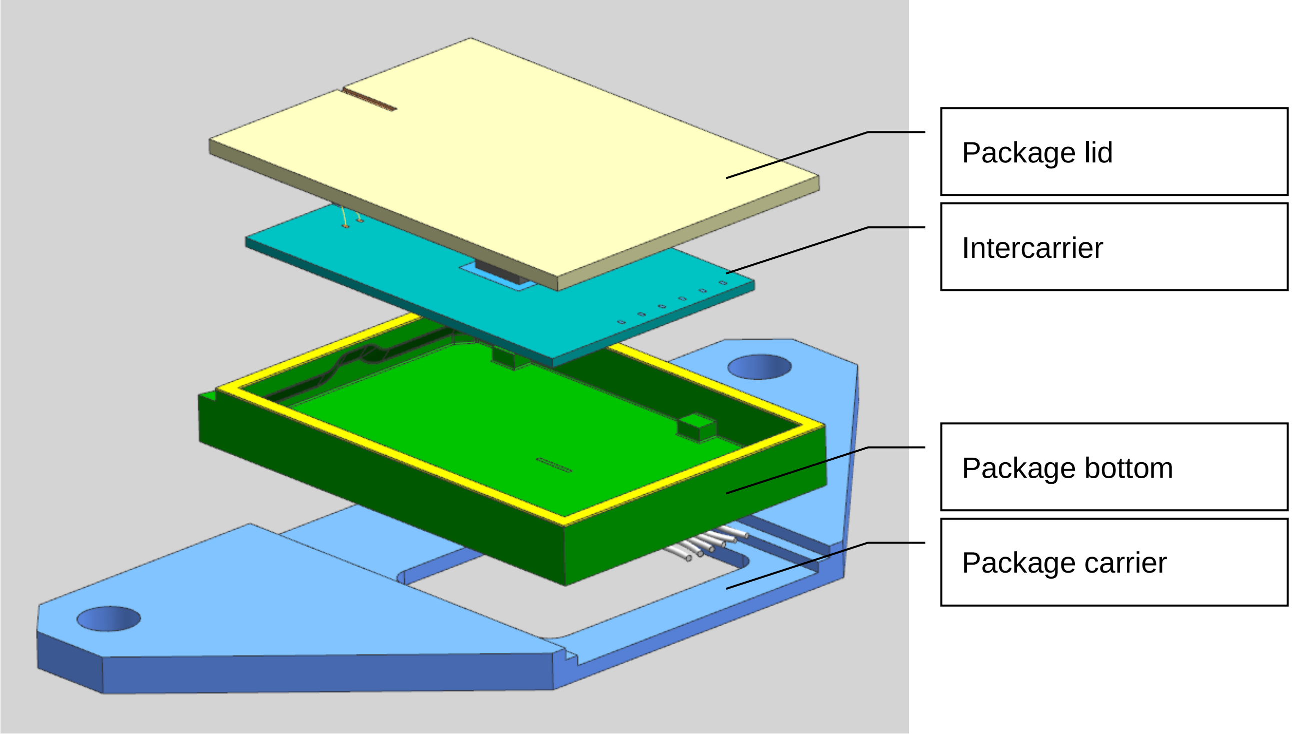


Figure 5-1 CEPA Sensor ASM (exploded view)

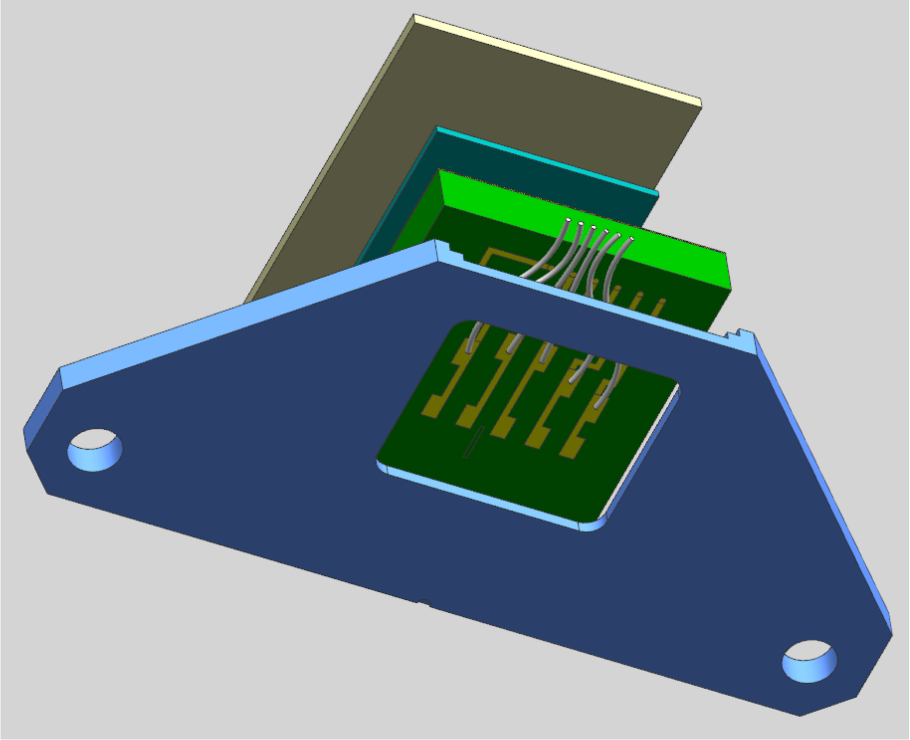


Figure 5-2 CEPA Sensor ASM (exploded view2)

6 DEMONSTRATOR TESTS

6.1 Test sequence overview

Since the test is sub-structured in single test activities a brief overview shall be given in Figure 6-1.

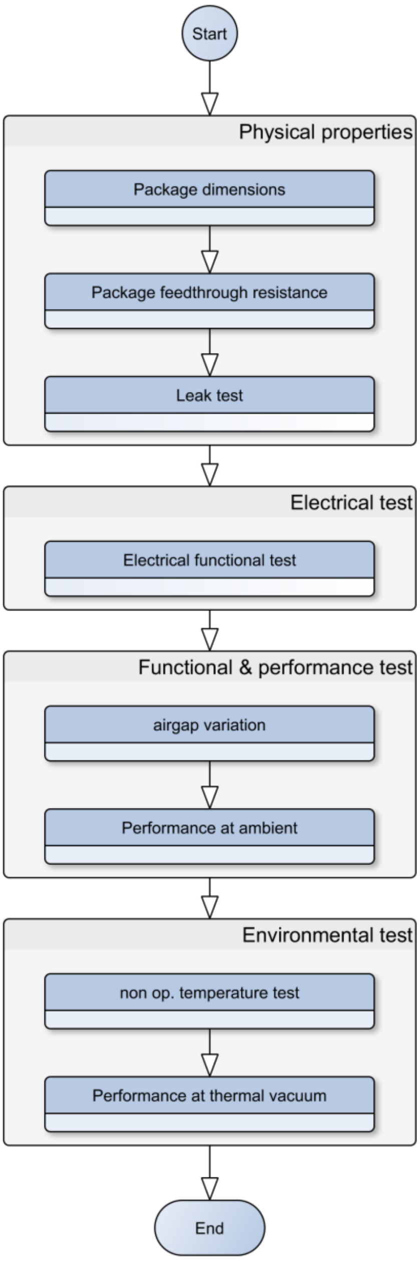


Figure 6-1 Test flow

6.2 Tested Item

The tested item is an electrical full functional demonstrator of a magneto resistive sensor, Sensing elements and circuit is housed in a 3D printed hermetic ceramic package. The unit is attached to a metallic carrier for integration in different applications. All function, performance and environmental tests has been conducted on demonstrator level.

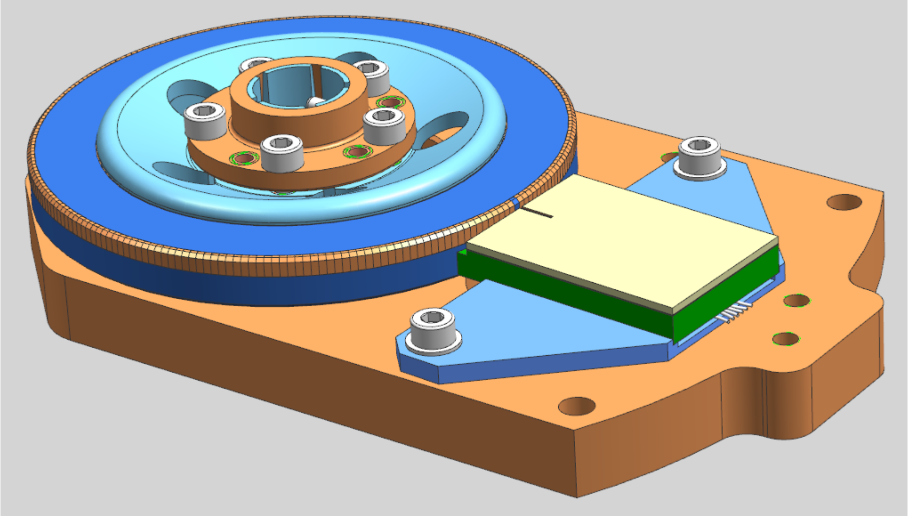


Figure 6-2 Test configuration for environmental tests

Several pre-tests has been conducted on component or package level. For details see CEPA-RSG-RP-002.

6.3 Summary

Dimensions & Interfaces

The length and width dimensions of the package are solely determined by the printing and shrinking process in oven afterwards. The measured values were stable over several measurements with a tolerance of +/-0.05mm. The shifted placement of the lid during closure was not regarded here. The deviation from CAD model tolerances is small in general (<1% for highest deviation).

Leakage

The leakage tests for all tested package units failed. The leakage detected was localised in the soldered connection between package bottom and lid. The X-ray radioscopy suggests that a poor quality of the soldered connection is the reason for the leakage.

Sample tests with different design features and different closing processes tested before show that a hermetic package is definitely possible. The leakage tests on filled vias, package sample with thin walled section and closed sample package were successful.

4 units failing electrical functional test and one was not tested because of poor quality of the lid closure with considerable shift of the lid.

The leakage pre-tests showed that soldering for lid closure is possible and will lead to sufficient hermeticity. The main issue seen is process stability. The lab process with hand applied metallization yielded in rather poor quality of the closing seam.

Secondly, it can be stated that the gluing with a ceramic adhesive can be seen as an alternative. Achieved hermetic closure was comparable level like soldered samples. The possibility to implement larger and non-flat closing contours on the package may further improve that adhesive tightness.

Performance Testing

The performance measurement under ambient condition showed that neither rotational speed nor turning direction have recognizable influence on the linearity error or signal amplitude output. This can also be concluded from the tests in operational temperature range, were also speed and direction was varied.

The exposure to non-operational temperatures showed no degradation in performance. Minor delta in parameters may be addressed to dismounting and remounting tolerance of the pole ring.

The signal amplitudes show a significant dependency on the temperature. Low temperature increases and high temperature decreases the voltage amplitude. In the tested temperature range [110..-65°C] no significant change in the resulting linearity error was observed. This means that accuracy is relatively independent from temperature as long as the signal to noise level is high enough.

It can be stated that the accuracy of 0.1° [+/-0.05° linearity error] can be achieved under all tested environmental conditions.

7 CONCLUSION

The overall project objective was to develop and test a novel sensor package out of a ceramic material manufactured by an additive manufacturing technique. The advantages to achieve by this were as follows:

- Robust design for application in space environment and the associated influences like vacuum, radiation, atomic oxygen exposure and high temperature gradients
- Reduce manufacturing effort in terms of costs and lead times for highly accurate parts
- Reduce the assembling and alignment effort by reducing the number of parts and thus the overall verification effort

Furthermore the project shall confirm the good performance of the MRS system which was already shown in the previous projects MRS and MRS Phase 2.

The redesign and optimization with respect to the change of the manufacturing principles showed benefits. A compact design has been developed with advantages in package mass as well as a drastic reduce in alignment effort of the sensor which is due to the production accuracy and the fact that the sensor has to positioned in a monolithic part.

In terms of functionality was one of the main design drivers the thin wall thickness which is necessary to position the chip sensitive area close to the magnetic measure and receive the signal. The manufacturing was in line with the specification so that function and performance tests of the tested items showed all good results in terms of accuracy. The hermeticity of the thin wall section of the housing could be proven in sample tests. However, it must be mentioned here that only 5 test objects could be tested, since 5 other did not pass the function test after the lid was closed.

To get a hermetically closed package the technology for closure of the cover on the housing has to be further developed. The sealing surface must be evenly covered with solder. The x ray scan showed an uneven distribution. The process parameter needs to be adapted to prevent overheating of the solder.