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DEVELOPMENT, TEST AND LESSONS LEARNED FOR A DEPLOYMENT AND POINTING MECHANISM

K. Zajac[*], A. Alegre Cubillo, C. Raum, R. John
Beyond Gravity Germany GmbH, An der Walze 7, 01640 Coswig, Germany

Abstract

The objective of the project was to develop a deployment and pointing mechanism as a core component for antenna pointing in future spacecraft for institutional and commercial applications. The main technological objectives for the development of this deployment and pointing mechanism were the optimization and design iteration by building and testing a breadboard mechanism model as well as the production of a mechanism demonstrator by means of additive manufacturing processes.

The project included the consolidation of the technical requirements and the identification of the main requirements as a basis for the development of the breadboard mechanism model and the additive manufacturing demonstrator. The relevant requirements were verified by building and testing the models. A development status corresponding to TRL5 was achieved for the breadboard mechanism model. For the additive manufacturing demonstrator, a development status between TRL3 and TRL4 was achieved. As part of the work on the additive manufacturing demonstrator, extensive investigations were also carried out on material behavior in relation to additive manufacturing regarding manufacturing processes, materials, material properties, post-treatment processes and tests for characterization and verification.

Test conduction and results of the test campaigns will be presented with focus on functional and environmental tests as well as lessons learned.

Keywords

Deployment, Pointing, Mechanism, Antenna, Additive Manufacturing

1. INTRODUCTION

The project aimed to realize the development of a mechanism for the pointing and tracking of high-power antennas, especially Ka-band, in future spacecraft for institutional and commercial applications. Other payloads that require fast and accurate pointing and tracking (e.g. booms) can also be equipped with such a mechanism. The previous project was successfully completed in August 2016 [1, 2].

In this follow-up project, the design of the existing mechanism should be improved, an improvement in terms of assembly and integration effort should be achieved, and a cost reduction by reducing the cost of purchased parts and the assembly time (e.g. by applying additive manufacturing methods) should be achieved. Furthermore, by focusing on the optimization of manufacturing costs in design and production, the future potential of the mechanism, also for NewSpace applications, should be achieved. The concept of the mechanism should be modularized and extended to enable low earth orbit (LEO) and geostationary orbit (GEO) applications in order to lay the basis for the broadest potential future market access.

In this paper we present a mechanism based on conventional manufacturing as well as additive manufacturing for deployment and pointing of antennas. The mechanism design with the main functionality, the manufacturing and assembly of the conventional manufacturing as well as additive manufacturing demonstrator and the results of the test campaign including lessons learned are presented hereafter.

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2. MAIN REQUIREMENTS

In a first work package the technical requirements were derived to design a fully European mechanism following the ECSS design rules and margins [3]. The initial step was to systematize the results of the preliminary project and the new information with regard to the typical properties and parameters as well as the commercial use of the antenna deployment and pointing mechanism (ADPM). The main areas of the specification were design requirements (function, redundancy, mass, dimensions, cables, etc.), application (configuration, performance, lifetime, etc.), environment (thermal requirements, vibration requirements, shock, etc.), interface (I/F for mounting, I/F for electrical, thermal I/F), and materials and processes (outgassing, corrosion, coating, ECSS processes). Furthermore, meetings were held with antenna suppliers to identify the typical application areas and their associated parameters and to amend the

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[*] corresponding author – kai.zajac@beyondgravity.com, phone +49 3523 775614

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specification accordingly. A selection of the key requirements which have driven the development and verification effort is given in TAB 1.

TAB 1: Key requirements for the mechanism

Requirement	Value
Pointing range	360°
Angular resolution	0.5°
Pointing velocity	3°/s
RF Interface	X- and Ka band
Mass	≤ 3 kg
Life	25'000 Min
Operational temperature range	-40°C / +80°C
Non-operational temperature range	-80°C / +110°C

Another major design requirement was a change of usage in the direction of LEO applications compared to the preliminary project. To comply with application in LEO missions an appendage (antenna) of 1.5 kg mass and specified dimensions as well as interfaces for rotary joints for X- and K-band antennas were defined. A further major design requirement addressed the exported micro vibration. Exported micro vibration excitations shall be lower than 0.1 Nm/0.5 N over a frequency band between 0.1 and 100 Hz.

3. BREADBOARD MECHANISM

The following sections describe the design of the breadboard mechanism and ground support equipment (GSE), the performance of the mechanical and thermal analyses, and the fabrication and testing of the breadboard mechanism.

3.1. Mechanism Design

Based on the requirements as well as the main function and performance, a first design concept was created as an arrangement of the components for the breadboard mechanism. Based on the design of the arrangement of the components, four different concepts were designed and evaluated in terms of their advantages and disadvantages. Based on this initial evaluation, the designed concepts were detailed to the level that a comparative assessment was possible. Based on the assessment, advantages for two concepts became apparent (see FIGURE 1 and FIGURE 2).

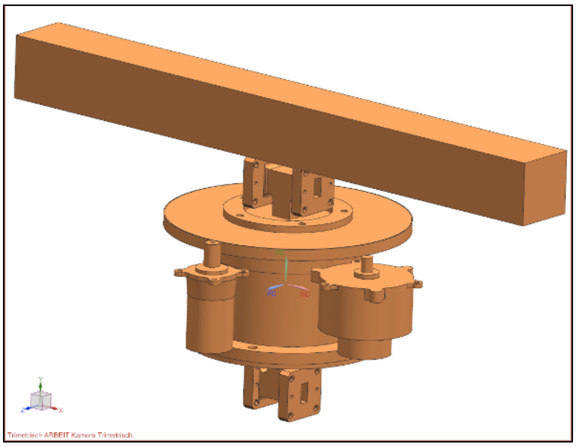

FIGURE 1. First concept for detailed design phase

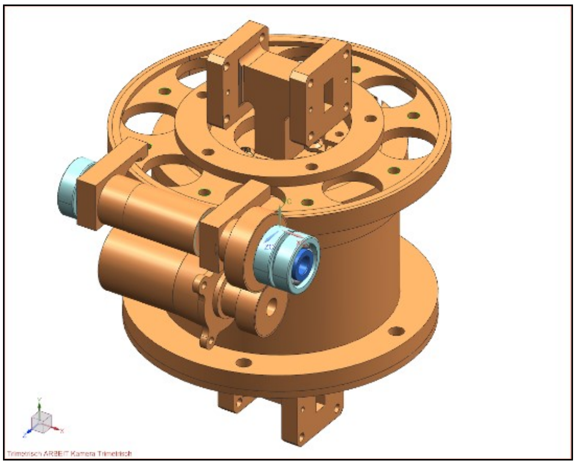

FIGURE 2. Second concept for detailed design phase

For the two concepts selected, the necessary drive and bearings were chosen, and the design was detailed in terms of radio frequency (RF) technology, materials, as well as loads. In addition, both concepts were detailed in terms of motorization, use of commercial off-the-shelf components, sensor technology and harnessing. Following the detailing of the two concepts, further evaluation and selection of a concept for the breadboard mechanism took place. During the detailing and evaluation of the two concepts, the second concept was selected for the final design and the final design review. It became apparent that the first concept could only be implemented in its proposed design with a large amount of effort due to the requirements for RF technology and the need for a holding mechanism for the launch loads (launch lock).

In the detailing of the second concept, the biggest challenges were in the loads on the components. Due to the small size and the required loads, some compromises had to be made in terms of materials and wall thicknesses with regard to the overall mass. In the final breadboard mechanism design (see FIGURE 3), the detailing of the structure including bearings, the materials and surfaces, the drive including motor and gearbox as well as the sensor technology took place. In addition to the mechanical design, the electrical components and the corresponding interfaces were also defined and designed. The nominal and redundant sides are identical.

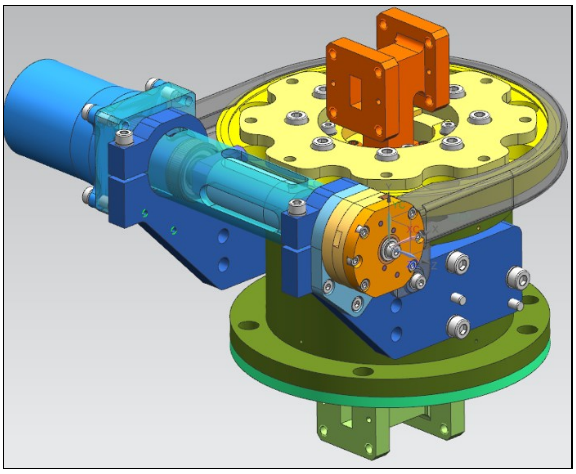

FIGURE 3. Breadboard mechanism design

Based on the assembly and test plan, the necessary mechanical and electrical GSE was also designed for the planned test program. As shown in FIGURE 4 the GSE includes the mounting plate (at the same time adapter for vibration and thermal test), the protection device for the RF components as well as an antenna dummy.

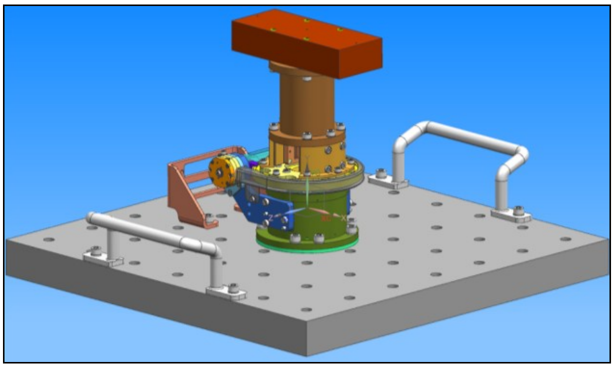

FIGURE 4. Breadboard setup with antenna dummy

3.2. Manufacturing and Assembly

The assembly of the breadboard mechanism was performed according to the assembly procedure and documented as an as-run procedure. The mechanism was assembled starting with the three subassemblies Drive Unit (FIGURE 5), Rotation Unit (FIGURE 6) and Fix Unit. The breadboard mechanism was then fully assembled, including all electrical connections (motor, sensors). In addition to the mechanism, the GSE was assembled, consisting of antenna dummy and transport and test plate.

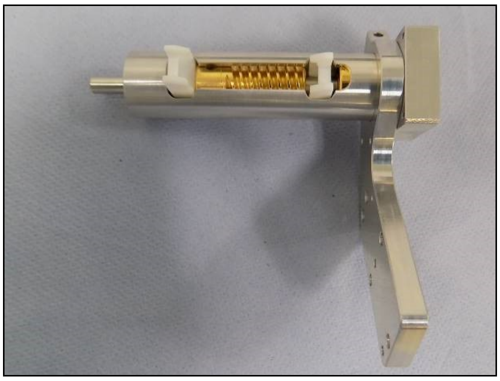

FIGURE 5. Drive unit subassembly

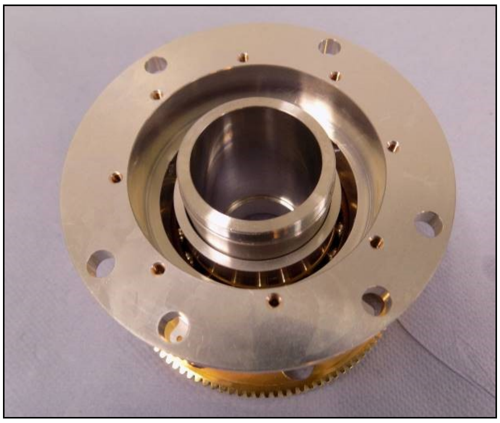

FIGURE 6. Rotation unit subassembly

Due to an anomaly at the breadboard mechanism during the random vibration test of the X-axis (see chapter 6), changes of the design became necessary. The main changes were made to the GSE, which also led to some minor changes to the breadboard mechanism. In addition to the design adaptation, the necessary adaptation of the standard and purchased parts took place. The final assembly of the breadboard mechanism and the GSE, as shown in FIGURE 7 was carried out according to the adapted assembly procedure. After the successful assembly, the test release was performed.

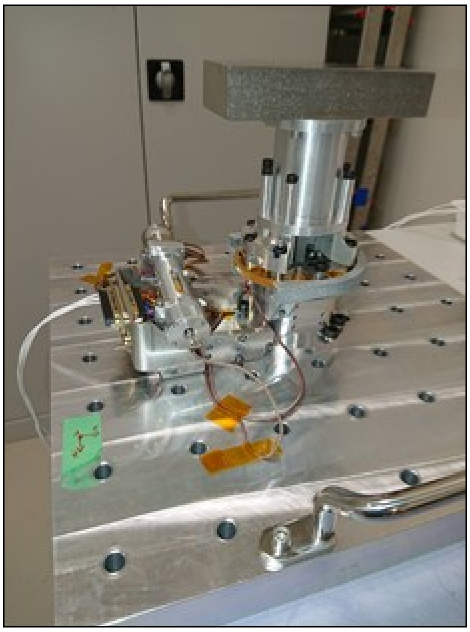

FIGURE 7. Breadboard mechanism with adapted GSE

3.3. Mechanism Test

A breadboard model test campaign for the mechanism has been executed to verify the developed mechanism for space applications with respect to the specification. The breadboard model test campaign started with performance testing focused on verifying functionality and physical properties. Further tests have been sine and random vibration, shock susceptibility and thermal vacuum cycling. The major results will be presented in the following section.

3.3.1. Functional Test

During the course of the "Physical Properties" procedure, the mass of the subassemblies and the entire assembly was determined, the center of gravity was determined, and the interfaces were measured. Finally, the electrical parameters were determined on the mechanism (including resistance measurement on the mechanism and the individual pins on the connector). Subsequently, the test procedure "Function and Lifetime Assessment" was processed in the subsection Function Test. As part of the function tests, the correct functioning of the motor was checked, various speeds were tested, and the repeatability was determined.

3.3.2. Vibration and Shock Test

FIGURE 8 shows the setup used for the vibration tests. These tests were performed using a dedicated shaker with a slip table. The vibration test was done axis by axis in the sequence sine sweep, sine vibration, sine sweep, random vibration, sine sweep according to the defined levels.

TAB 2: Sinusoidal vibrations loads

Axis	Frequency	Test Level
All axes	5 Hz	± 11mm
	26 Hz	27.0 g
	60 Hz	27.0 g
	61 Hz	6.0 g
	140 Hz	6.0 g
Sweep rate	2 oct./min	

TAB 3: Random vibration loads

Frequency	PSD Input X	PSD Input Y	PSD Input Z
20 Hz	0.0629	0.0629	0.0629
100 Hz	0.3130	0.3130	0.3130
111 Hz	0.3130		0.3130
140 Hz	0.0423		0.0438
168 Hz	0.0423		0.0438
208 Hz	0.3130		0.2633
300 Hz	0.3130	0.3130	0.2633
2000 Hz	0.0134	0.0134	0.0134
Overall level	12.62 g_{RMS}	13.39 g_{RMS}	11.33 g_{RMS}
Duration	120 s		

During sweep the natural frequencies were determined and compared to the test prediction values. The functional integrity of the breadboard mechanism was tested by means of electrical tests in between, before and after every vibration direction. The vibration test was concluded successfully. No difference between pre and post vibration test states of the breadboard mechanism was observed. A successful actuation of the breadboard mechanisms was performed after passing the vibration test.

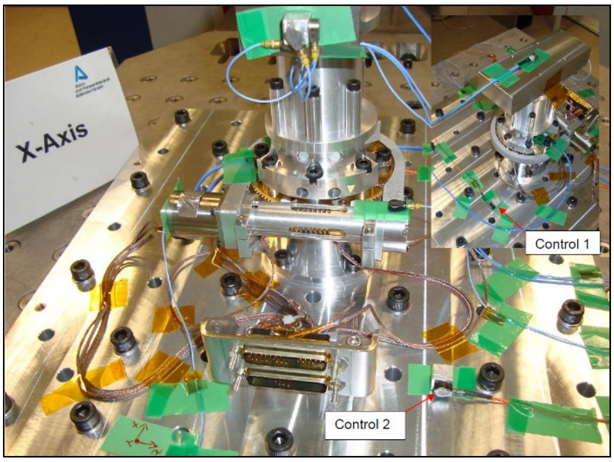

FIGURE 8. Vibration test setup for breadboard mechanism

Following the vibration test, the pyro-shock test was conducted for the three orthogonal axes of the breadboard mechanism with a level shown in TAB. 4. The tested breadboard mechanism passed the pyro-shock test. No visible changes or damages and no changes in resonance behavior greater than 5% were observed. Functional tests were performed successfully after the pyro-shock test.

TAB 4: Pyro-shock test level

Axis	Frequency	Level
All three axes	100 Hz	40 g
	800 Hz	300 g
	1500 Hz	350 g
	4000 Hz	310 g
Shocks per axis	3	
Attenuation	D=5% / Q=10	
Resolution	1/12 octave	

3.3.3. TVC Test

The thermal vacuum cycling (TVC) test was performed in the thermal vacuum chamber of Beyond Gravity Germany GmbH according to the prepared procedure (see FIGURE 9). After installation in the chamber, a bake-out was performed. The breadboard mechanism was baked out at a temperature of 80°C for a period of 24 hours.

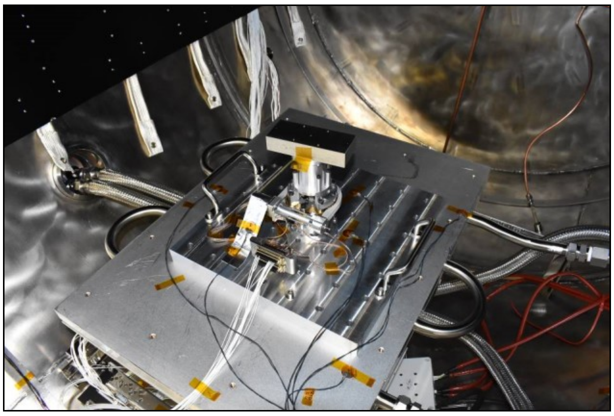

FIGURE 9. Thermal vacuum cycling test setup for breadboard mechanism

According to the procedure, at a pressure < 10-4 mbar, one cycle should be performed at non-operational temperature (-80°C to +110°C) and another nine cycles at operational temperature (-40°C to +80°C). Unfortunately, some problems occurred during the thermal vacuum test. Due to technical problems with the shroud, the positive operational and non-operational temperatures could not be achieved. Therefore, one cycle was performed at non-operational temperature between -20°C and +90°C and another 9 cycles at operational temperature between -10°C to +80°C. The functional tests during the TVC test were performed in the last hot or cold plateau after at least 4 h holding time. The function of the breadboard mechanism was successfully demonstrated.

4. AM DEMONSTRATOR

In the following sections, the work related to additive manufacturing (AM) is briefly described. The design of the AM mechanism demonstrator, the performance of the mechanical and thermal analyses as well as the manufacturing and testing of the AM demonstrator were carried out.

4.1. AM Design

As part of the work on the AM mechanism demonstrator, extensive investigations were carried out at the beginning on material behavior in relation to additive manufacturing regarding manufacturing processes, materials, material properties, post-treatment processes and tests for characterization and verification. Based on the AM research and testing, the first step was to identify the necessary steps for a demonstrator based on AM processes. For example, with regard to the optimization for additive manufacturing processes, restrictions apply such as the retention of functional components or manufacturing options of the manufacturers.

The first step was to select the material. For the optimization and design process, the key assumptions for the AM demonstrator then had to be established. First, all components had to be defined that would not be changed due to functionality, such as gears, bearings, or wave guides. On the other hand, it must be defined which of the components to be changed could be combined in order, for example, to reduce the mass, reduce the assembly effort or increase the stiffness. In the final step before the optimization and design process, the available design space then had to be specified so that the limits of the components could be defined for the gear and the flange unit (see FIGURE 10).

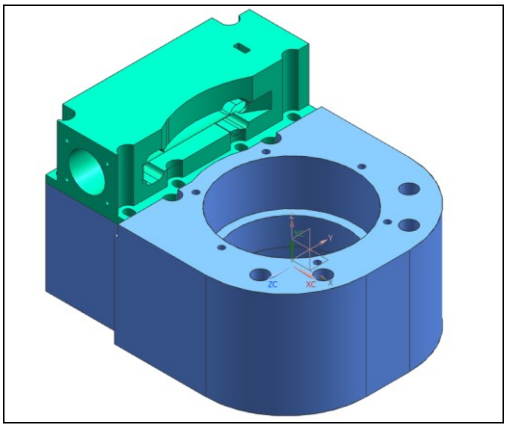

FIGURE 10. Definition of optimization space

The optimization and design process took place in the following sequence: creation of the design space in the CAD program, creation/calculation of the AM components with OptiStruct, analysis of the results, creation of the components in the CAD program. Due to the optimization, the steps were run through several times.

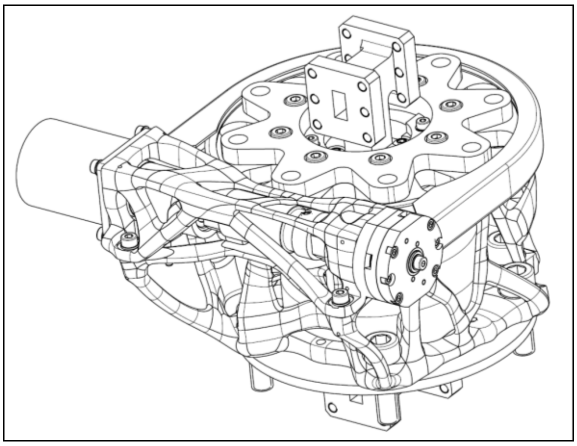

FIGURE 11. CAD Modell of the AM mechanism demonstrator

In parallel to the optimization and design process, the components were analyzed to determine the applied loads. For this purpose, the AM design was created as a finite element model and subsequently analyzed in several iterations with the AM design.

4.2. Manufacturing and Assembly

At the end of the optimization and design process including definition of the build-up direction in the print job, an optimized AM structure was available, which was then finally clarified with the corresponding manufacturer regarding manufacturing and postprocessing due to drawing requirements. For this reason, the optimized AM component was processed in the CAD program to mark all relevant functional surfaces such as screw connections, bearing surfaces or interfaces to other components.

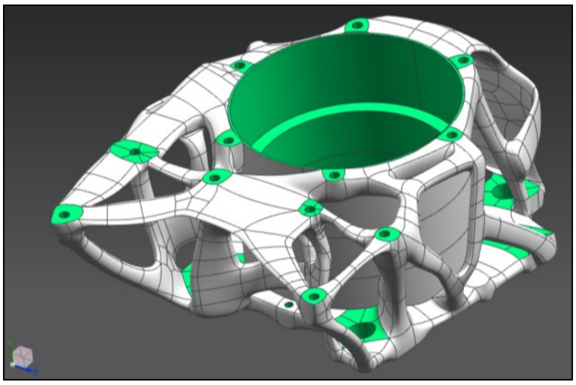

FIGURE 12. AM component Flange after optimization and clarification with manufacturer

After the order for the production of the AM components was placed at the selected manufacturer, continuous monitoring of the production process was carried out to ensure the required quality.

FIGURE 13. AM component Flange after additive manufacturing

FIGURE 14. AM component Flange with post-processing during incoming inspection

For the assembly of the AM mechanism demonstrator, the assembly procedure was adapted and updated. This procedure was kept and documented as an as-run procedure during assembly of the demonstrator. The assembly of the mechanism was done starting with the two subassemblies Gearbox and Flange (see FIGURE 15). This was followed by the complete assembly of the AM demonstrator including all electrical connections (motor, sensors) as shown in FIGURE 16.

FIGURE 15. Partial assembly AM subassembly Flange

FIGURE 16. AM mechanism demonstrator after final assembly

4.3. Mechanism Test

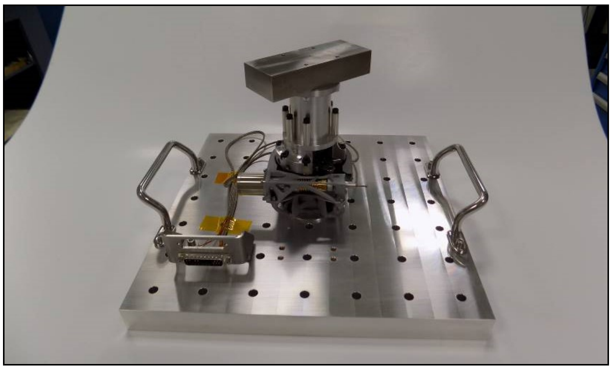

FIGURE 17. AM mechanism demonstrator with GSE and antenna dummy

The individual procedures for the AM mechanism demonstrator were carried out in accordance with the test plan. Within the scope of the "Physical Properties" procedure, the mass of the subassemblies and the entire assembly was determined, the center of gravity was determined, and the interfaces were measured. Finally, the electrical parameters on the mechanism were determined including resistance measurement on the mechanism as well as the individual pins on the connector.

This measurement reveals a severe problem with the bearings. The torque of the motor was not sufficient to move the mechanism, which led to the abortion of the test with a corresponding Non-Conformance Report (NCR). Since the remaining time of the project did not allow a complete elimination of the error, the further tests (e.g. procedure "Function and Lifetime Assessment") were cancelled. Consequently, vibration tests, shock tests or thermal vacuum cycling tests could not be carried out with the AM mechanism demonstrator.

5. RESULTS

Finally, all requirements that have been verified during the tests of the breadboard mechanism were listed together in the verification control document with a conformance statement and with remarks on compliance. The following table summarizes some of the achieved results from the demonstrator test campaign.

TAB 5: Key requirements for the breadboard mechanism

Requirement	Value
Pointing range	360°
Angular resolution	0.3°
Pointing velocity	5°/s
RF Interface	X- and Ka band
Mass	1.5 kg
Life	not tested
Operational temperature range	-10°C / +80°C
Non-operational temperature range	-20°C / +90°C

Appropriate conclusions could be drawn for the requirements that were only partially fulfilled. For example, the non-operational and operational temperature limits could not be achieved. The main reason was a modification of the thermal vacuum chamber before the mechanism test, which, however, did not lead to an improvement of the thermal characteristics. Another point is the pointing velocity which is higher than required. The selected use of a combination of worm and spur gear made a higher speed possible. The requirements for the AM mechanism demonstrator could not be verified due to the abortion of the test as the motor was not able to move the mechanism.

6. LESSONS LEARNED

The initial Vibration Test performed according to the approved procedure failed with mechanical damage of the device under test. Four Non-Conformance Review Boards (NRBs) were conducted as part of the NCR process. Corresponding tasks were defined to determine the effects and causes of the fault. Among other things, it was decided to disassemble the breadboard mechanism and to evaluate the test results available so far. Investigations carried out in the meantime showed, among other things, that the breadboard mechanism was still functional and that the damage was only to the GSE. Insufficient mechanical strength in the GSE was detected as the cause. This was not detected in time because the personnel resources for a corresponding in-depth analysis including detailed bolt calculations were unavailable. Based on the causes of the anomaly, it was decided to modify the design of the mechanism and to recalculate it including detailed bolt calculation. The GSE structure and bolt strengths were the major points of the design modification. Before reassembly, it was decided to perform a crack test on some of the components of the mechanism to check whether the components could be reused. The NCR process also revealed that early signs of the anomaly have been missed. The plot of the resonance survey on some sensors shows a drop in frequency already during the initial run. For future similar tests, the local test personal should be educated before to be able to act in a timely manner.

In the course of the AM design, it was observed that the use of specific programs for AM topology optimization and analysis represents a greatly increased effort. In addition to the effort for the programs, this also relates to the personnel effort. Furthermore, it was determined that the transformation of existing mechanical manufacturing parts into AM manufacturing parts without a new approach to the design leads to strong restrictions in the optimization process. Therefore, a new design approach is always preferable for further AM manufacturing parts.
For the AM mechanism demonstrator, the torque of the motor was not sufficient to move the mechanism. Three NRBs were conducted as part of the NCR process. It was found that the measured moments of resistance were significantly higher than the calculated values. This indicated a high level of stress. As a result, it was decided to carry out disassembly with additional measurements. It became apparent from the results of the mechanical measurement on the 3D coordinate measuring machine that the bearing seats in the flange were outside the tolerance, in contrast to the measurement protocol supplied. Regarding an assembly, this leads to a strong distortion of the bearings and thus to a high resistance torque.

7. SUMMARY AND OUTLOOK

Beyond Gravity Germany successfully developed and tested a one axis deployment and pointing mechanism demonstrator for space application. Two mechanism demonstrators, one based on conventional manufacturing and one based on additive manufacturing, were designed and built. The test campaign for the conventional mechanism demonstrator has demonstrated its potential as deployment and pointing mechanism for antennas including RF components. A major part of the requirements could be successfully demonstrated for this demonstrator.

With respect to the additive manufacturing mechanism demonstrator the design was successfully completed, and a model was manufactured and assembled. Due to the problems that occurred with the bearings, unfortunately no full functional tests, vibration tests, shock tests or thermal vacuum cycling tests could be carried out. Therefore, it is planned to carry out further work on the deployment and pointing mechanism in order to perform the tests on the demonstrator but also to achieve further advancement in terms of mass, performance, and cost. According to the specification, the design was made for a single-axis mechanism but also considers the option to combine two units to a two-axis mechanical pointing mechanism. As a further step it is planned to design a bracket and flexible waveguides to demonstrate a full two-axis mechanism.

8. ACKNOWLEDGMENT

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