# The GRASS Gravimeter Rotation Mechanism for ESA Hera Mission On-Board Juventas Deep Space CubeSat

Matthias Noeker* **, Emiel Van Ransbeeck*** ****, Birgit Ritter* and Özgür Karatekin*

**Abstract**

The ESA Hera mission will follow the NASA DART mission to the binary asteroid system Didymos for detailed investigation of the asteroids and the impact crater caused by the DART spacecraft. The Hera spacecraft will release two CubeSats, Milani and Juventas. In the final mission phase, Juventas will attempt landing on the secondary, Dimorphos. Here, the GRAvimeter for small Solar System bodies (GRASS) will measure the surface gravity. In this work, we describe the design, fabrication and testing of the gravimeter rotation mechanism with its key components. Overall, a gear-motor rotates the sensor head by means of gear train and continuous electrical contact is ensured by a slip ring. The main design drivers were the harsh deep-space environment, especially the cold operating temperature limit of −30°C, and the limited mass (0.38 kg) and volume (1 CubeSat unit U = (100 mm)³) budgets available inside the 6U-XL-CubeSat. While here the presented mechanism is specific to the GRASS scientific payload, it could be used for other future instrument demanding sensor head rotation or pointing.

## Introduction

This paper presents the design, development, manufacturing, integration, and functional tests of the rotating mechanism for the gravimeter on-board the nanosat platform to land on the surface of an asteroid. Juventas will carry the GRAvimeter for small Solar System bodies (GRASS) for surface gravimetry [1, 2] and is part of the ESA Hera mission, which is the first European planetary defense mission, targeting the binary asteroid system 65803 Didymos [3]. Together with the NASA Double Asteroid Redirection Test (DART) mission, it forms the Asteroid Impact Deflection Assessment (AIDA) international cooperation [4]. Here, NASA will perform a kinetic impact to the secondary of Didymos, called Dimorphos, to demonstrate the feasibility of deflecting an asteroid on collision course with Earth. ESA will then embark to visit the same asteroid system for detailed characterization of the system, with special attention to the artificial impact crater. This is necessary to complete the DART test, i.e., by determining the impact momentum transfer, mechanical surface strength, interior structure and asteroid mass. To support this, the Hera parent-craft will deploy two child-craft, the CubeSats Juventas [5] and Milani [6]. In their final mission phases, Juventas, and possibly Milani, will attempt landing on Dimorphos to perform additional surface measurements, most notably the GRASS surface gravimetric measurement.

The landing orientation of Juventas is uncontrolled [7] and the (precise) gravity vector orientation of Dimorphos is unknown. Unlike on Earth, and in absence of a complex levelling mechanism, a 3D-measurement is required for full gravity vector reconstruction. Two gravimeter axes, aligned orthogonally, and the rotation of the instrument sensor heads, in which the gravimeter spring is placed, realize this. The rotation of the spring also allows for instrument bias rejection, similar to the quasi-steady acceleration measurement (QSAM) instrument for spacecraft that inverted the measurement direction by 180° [8]. Therefore, the mechanism rotation is crucial to the experiments success. In this work, we present the GRASS mechanism as designed for flight on-board the Juventas CubeSat forming part in the ESA Hera mission. For this, the one-axis mechanism is presented in detail that is identical for the both combined axes. In addition, the combination of two mechanisms, forming the two-axes GRASS instrument, is described.

* Royal Observatory of Belgium, Brussels, Belgium; matthias.noeker@observatory.be
** Université catholique de Louvain, Ottignies-Louvain-la-Neuve, Belgium
*** VRE Consultancy, Mazenzele, Belgium
**** Royal Belgian Institute for Space Aeronomy, Brussels, Belgium

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The instrument has passed the critical design review (CDR) and first pre-tests on the engineering-qualification model 1 (EQM-1) were successful. The whole instrument, including the mechanism, is designed for the harsh environmental conditions in deep space and on the asteroid surface, as well as for a long cruise phase of up to four years. At this project stage, no noteworthy changes are expected on mechanism level towards the flight model integration and delivery planned for late 2022. The here presented design, hardware and tests belong hence to the EQM, providing the reader with the latest status of the work.

This document first lists the mechanism requirements, followed by an introduction to the working principle of the GRASS mechanism. Next, the instrument architecture, the component selection, mechanism manufacturing, and integration is detailed. Lastly, functional tests with a focus on the cold temperature functionality is presented.

## Mechanism Requirements

The requirements (REQ) for the GRASS instrument relevant to the rotation mechanism are formulated and numbered for reference as listed below. Some of them were already discussed in [9].

The first set of requirements considers the instrument accommodation, demanding an extremely compact instrument design, and the sensor head rotation:

- REQ-001: The overall instrument shall fit inside a volume envelope of one CubeSat unit (1U = $(100\ mm)^3$).
- REQ-002: The total instrument mass shall not exceed 380 grams including margins.
- REQ-003 The sensor head length must be maximized.
- REQ-004: The mechanism shall enable continuous, bi-directional and unrestricted rotation of the sensor head, with a safety factor of at least 3 for the torque.
- REQ-005: The mechanism shall accommodate the sensor head with diameter of 15 mm.
- REQ-006: The mechanical noise induced to the sensor head shall be minimized.
- REQ-007: The sensor head rotation shall allow slow rotation (<10 RPM) and incremental rotation.

The environmental requirements concern the mechanism regarding the temperature:

- REQ-008: The mechanism shall operate in the temperature range from −30°C to +50°C [243 K to 323 K].
- REQ-009: The mechanism shall comply with the non-operational temperature range from −30°C to +50°C [243 K to 323 K].
- REQ-010: The thermal contact between the gear-motor and the mechanism shall be minimized.

The lifetime of the mechanism is non-critical, as the rotation is only performed for the surface operation and maintenance:

- REQ-011: The mechanism shall have a minimum lifetime of 43,200 revolutions.

The requirement on the electric contact between rotor and stator remained unchanged from [9], but demanded two additional lines:

- REQ-012: The mechanism shall provide continuous, uninterrupted electrical connection between the instrument back-end electronics and sensor front-end electronics at 8 lines.

The angular position requirement was tightened compared to the prototype requirement [9], now reading:

- REQ-013: The mechanism shall provide continuous information about the absolute angular position of the sensor head, with an accuracy better than 0.5 degree and the rotation direction.

The instrument mounting requirements are not only concerned with fixing the instrument inside the spacecraft, but also with non-deformation of the instrument, the knowledge of the instrument orientation and the combination of two axes:

- REQ-014: The instrument shall be mounted with countersunk screws following the specified hole pattern.
- REQ-015: Two identical rotation mechanisms shall be combined orthogonally without inducing additional stresses to either mechanism.
- REQ-016: The mounting inside Juventas shall not influence the orientation of the two orthogonal instrument axes.
- REQ-017: The thermal contact between the instrument and the satellite shall be minimized.

With the mechanism requirements formulated above, the mechanism development is described in this work. As will be shown, it was possible to fulfill all of the formulated requirements.

**Working Principle**

This Section describes the mechanisms overall concept. A gear-motor is aligned in parallel with the sensor head and the torque is transmitted by a gear train (REQ-004). Continuous power and signal transfer from the instrument to the rotating sensor head (REQ-012) is realized with a slip ring.

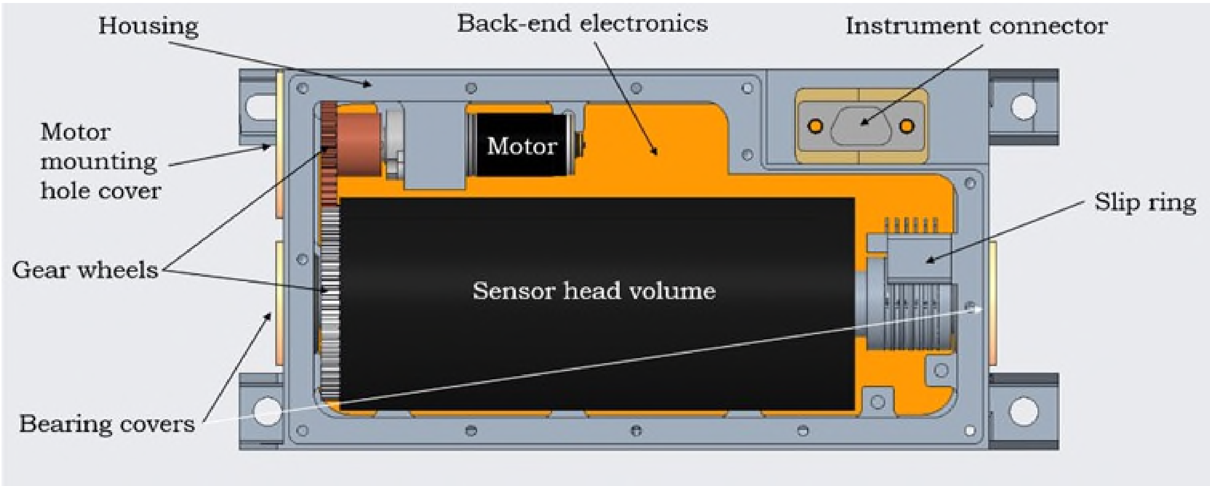


*Figure 1. Working principle of the GRASS mechanism prototype, forming the basis of the here presented mechanism. Figure from [9].*

The working principle of the spring-based GRASS gravimeter mechanism prototype was described in [9], which formed the basis for the continued development. The design included a large degree of adaptability, allowing to test a large range of gravimeter sensor head configurations (i.e., different bending springs, sensing electrodes, front-end electronics, etc.). The prototype consisted only of a single-axis instrument and the constraints on volume and mass were less strict than for the flight model design. Obviously, it is well possible to align two of these instruments orthogonally, e.g., by using a mounting plate as described in this work. The mechanism working principle is shown in Figure 1, allowing to retrace the subsequent development, strongly driven by the need of an extremely compact design, as described with the requirements REQ-001 and REQ-002.

## Mechanism Development

The mechanism development consists of two parts. Firstly, the main part is the one-axis rotation mechanism description. Secondly, the orthogonal mating of two rotation mechanisms is described with special attention to REQ-015 and REQ-016. The used components are detailed in the next Section.

### GRASS Rotation Mechanism

Before providing more details, the top-level mechanism architecture is described in the following as shown in Figure 2. Core element of the mechanism is the rotating sensor head (REQ-004 and REQ-005). Supported by two flanged bearings, the sensor head is rotated by a gear train connected to a gear-motor. The arrangement of the motor in parallel to the sensor head allows maximizing the sensor head length (REQ-003). Electric contact between the rotor and stator (REQ-012) is ensured by means of a slip ring, arranged in-line with the sensor head. The slip ring output harness is passed through protective harness bushes towards the inside of the housing for connection with the back-end electronics (BEE). The BEE also drive the mechanism by controlling the gear-motor, and receive the angular position data. This data is recorded by an absolute encoder (REQ-013), which monitors the angular position of the sensor indirectly, as it reads the position of the motor gear. For this, the encoder is positioned and clamped inside the housing and the encoder magnet is placed inside the motor gear. Driven by REQ-010, the motor mounting piece is machined in titanium and fixed with titanium fasteners. Furthermore, the contact area of the piece to the housing is minimized, all aiding to keep the motor warm in the cold temperature regime down to −30°C (REQ-008 and REQ-009).

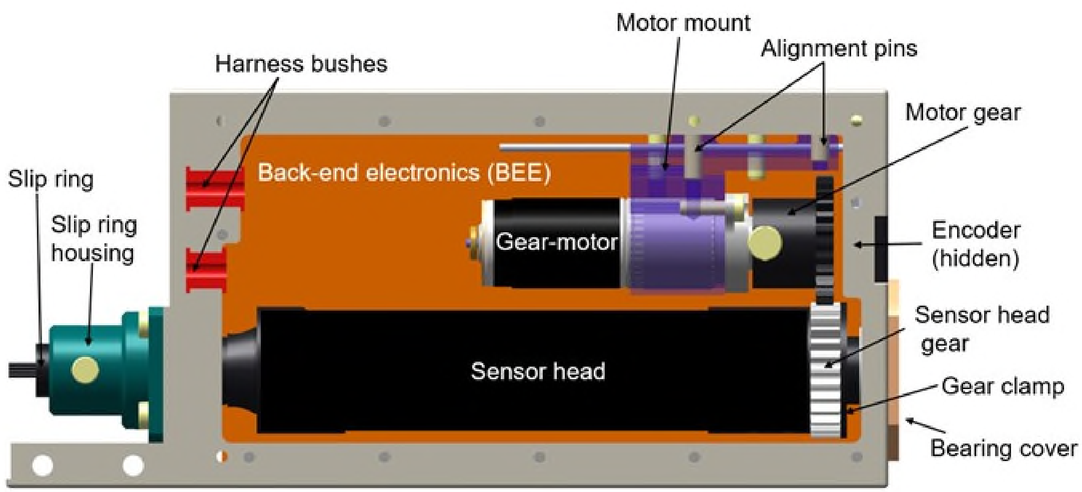


*Figure 2. GRASS mechanism architecture. A global cover covers the open front and slip ring.*

### Two Axes Arrangement

For flight, two of the above presented mechanisms are required (for gravity vector reconstruction) as stated in REQ-015. We have accounted for the orthogonal combination of two identical mechanisms, forming the GRASS instrument. Looking at Figure 2, it is easy to imagine that two mechanisms can be combined by flipping one upside down and merging them at the part of the slip rings. Like this, the two slip rings are stacked above each other at 90°, allowing to meet the maximum length constraint of 100 mm in both dimensions (REQ-001). This arrangement is shown in Figure 3. The second harness bush (Figure 2), allows the interior interconnection of the two instruments, e.g., making it possible to control the full instrument with only one set of BEE, while here the baseline design considers individual communication between spacecraft and each rotation mechanism. For this, each BEE is equipped with an individual connector for power and data connection. A global L-shaped cover on the outside closes the open side of the two mechanisms and the intersection with the two slip rings and harness (Figure 8). Like this, the instrument with its two mechanisms is fully enclosed.

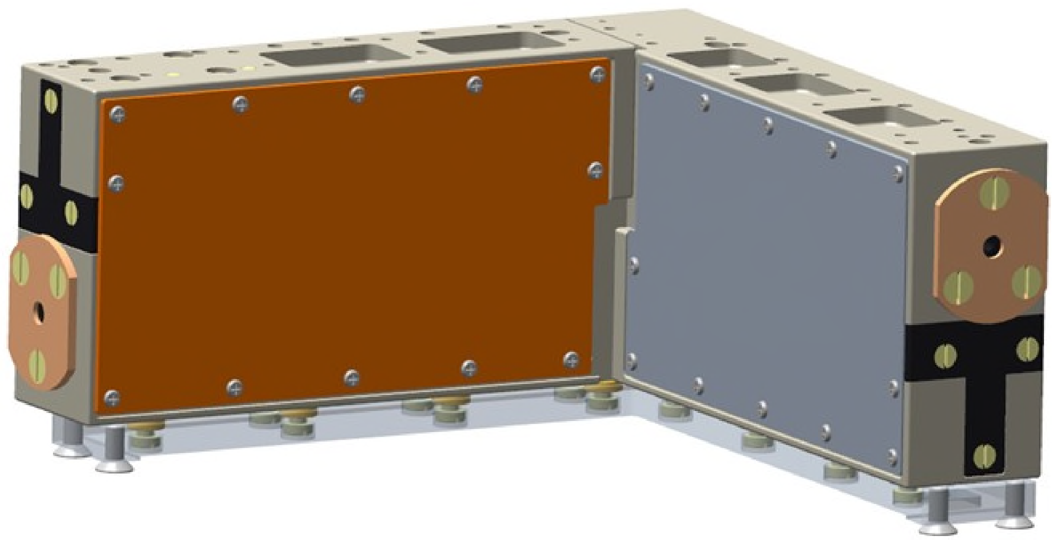

*Figure 3. Combination of two GRASS gravimeters to form an orthogonal setting. Clearly, the instruments appear identical but stacked upside-down to allow maximizing the length of the instrument. The two axes can be differentiated by the back-end electronics shown in orange and grey, respectively. On the bottom, the common mechanical interface plate is shown with the considered mounting screws for the Juventas CubeSat.*

In principle, the mechanism, single or double, can be directly mounted inside the spacecraft. However, the orientation between the two mechanism axes must not be altered (REQ-016), and no mounting stresses shall be induced to the mechanisms (REQ-015). Provided that countersunk screws are used (REQ-014), any misalignment in the screw holes on the housing or the spacecraft (even within the machining tolerances), will induce stress, as the countersunk screw heads force themselves into their sunk position. Therefore, an L-shaped mounting plate is used on which the two-axes mechanism setup is fixed using cheese head screws. This screw type does allow for some lateral play, absorbing any mounting stress (REQ-015 and REQ-016) by the counter sunk screws, used to fix this mounting piece. Furthermore, the thermal insulation of the instrument mechanisms is improved, as the mounting piece is made of titanium and the contact area towards the spacecraft is limited to the surrounding of the screw contacts. The thermal contact is reduced further by using again titanium screws between the mounting piece and the housings, and by using thermal Vespel-SP3 washers, avoiding direct contact of housing and titanium piece. These washers also compensate for the differential thermal expansion of titanium and aluminum. Bending along the mechanisms length is avoided by using shims during the satellite integration, if necessary.

## Components

In this Section, the key (purchased) components forming part of the mechanism are presented together with applied customizations, where they were necessary. Starting here, we present lessons learnt of the presented work, indicated by a → symbol.

### Gear-Motor

The gear-motor (Figure 6) selected for the mechanism is the same as for the mechanism prototype [9], being the *CoograDrive® Space 10 mm - Type 6* from Micromotion GmbH. For the initial selection, a preliminary torque requirement with the required safety factor had been formulated together with limitations on mass and volume. This gear-motor, fulfilled all preliminary requirements without any problem for both the prototype and the design for the Juventas CubeSat and meets REQ-007. The extremely compact design (diameter = 10 mm, length = 36.15 mm, mass = 13 gram), did not drive the mechanism length or depth, as both are smaller than the sensor head (REQ-005), and the part delivers a high nominal torque of 15 mNm. As will be shown in the *Mechanism Verification* Section, this torque satisfies REQ-004. According to the supplier, the part has heritage in space, yet limited to geocentric orbits. Regarding the cruise phase in deep space, two solutions were implemented to minimize the lubricant creep and to ensure proper functioning of the motor, and therefore the mechanism, upon arrival in the binary asteroid system. Regarding a physical creep barrier, this option was discarded, as a well-functioning lubricant seal would come at the cost of torque, which was a critical motor selection criterion. Rather, the output bearing, gear components and motor bearing will be customized by applying epilamization[1], limiting the spreading of the lubricant inside the gear-motor. The second solution is the implementation of a mechanism maintenance procedure, described in detailed in Section *Mechanism Maintenance*. Regarding the minimum operating temperature, the gear-motor has a nominal value of −10°C, which is too warm considering the formulated requirement REQ-008. To verify the part's functionality at colder temperatures, a cold motor starting test is presented below in Section *Mechanism Verification*.

- → The CoograDrive® Space gear-motors provide a very good Torque/(Volume×Mass) ratio for our application.
- → To avoid lubricant spreading, the relevant surfaces should be treated with epilamization.

For performed trade-offs regarding this gear-motor, including the option to include an encoder or a slip clutch in the gear-motor, we refer to [9].

### Slip Ring

The selection of the slip ring to realize electric contact (data and power) between mechanism rotor and stator was driven by similar factors as for the (gear-) motor. An extremely compact design in diameter and length was needed to not drive the instrument width, while limiting the increase on the total mechanism length, respectively. While for the motor a torque as large as possible was desired, the required torque for turning the slip ring had to be minimized. Furthermore, as discussed below in the *Integration* Section, the slip ring had to be without flange, and the harness were not to exceed the part's diameter-bound cylinder. When selecting a slip ring, the nominal torque values often lead to exclusion of candidates. Finally, we have selected the *MMC1189-S08* slip ring from Moflon. The version S08 provides the required 8 lines (maximum number of lines available). This slip ring has again an extremely compact design (diameter = 5.9 mm, length = 11.9 mm, mass = 3.8 gram). The nominal torque (data sheet) was 25 mNm (for 6 lines), which was also too large, but was found much lower in our testing (Section *Mechanism Verification*). This slip ring is sold as military grade, and the finally purchased parts were again customized, here by changing the housing material to aluminum and by adopting the bearing to space conditions by using a bearing without lubricating oil.

[1] http://www.epilamisierung.com/en/, accessed on 12.01.2022.

- ➔ Considering extremely compact slip ring designs, it is hard to find a motor meeting the nominal slip ring torque. However, measuring the torque can reveal that the actual torque requirements is (much) lower than the value stated in data sheets.

Encoder

Driven by REQ-013, positional knowledge only once per revolution as in the prototype [9] was no more an option. Rather, an absolute encoder was integrated in the mechanism design. Here, we use the *RM08 Miniature Rotary Magnetic Encoder* from RLS. The angular position is not measured directly over the sensor head, but rather over the motor gear wheel. As discussed in the next Subsection, the gear ratio is $i$ = 1, thus the angular position translation is straightforward, while the measured rotation direction is obviously inverse. A section-view of the encoder setting is displayed in Figure 4. The gear was adapted to mount a (screw-fixed) magnet bush, in which the encoder magnet is glued. The nominal distance between the magnet and the encoder is 1.0 mm ±0.5 mm. The encoder is clamped with a dedicated encoder mounting bracket into the housing that also covers the encoder harness before it enters the housing. Encoder and magnet mass is <2 gram and 0.4 gram, respectively. The encoder accuracy is rated up to ±0.3°.

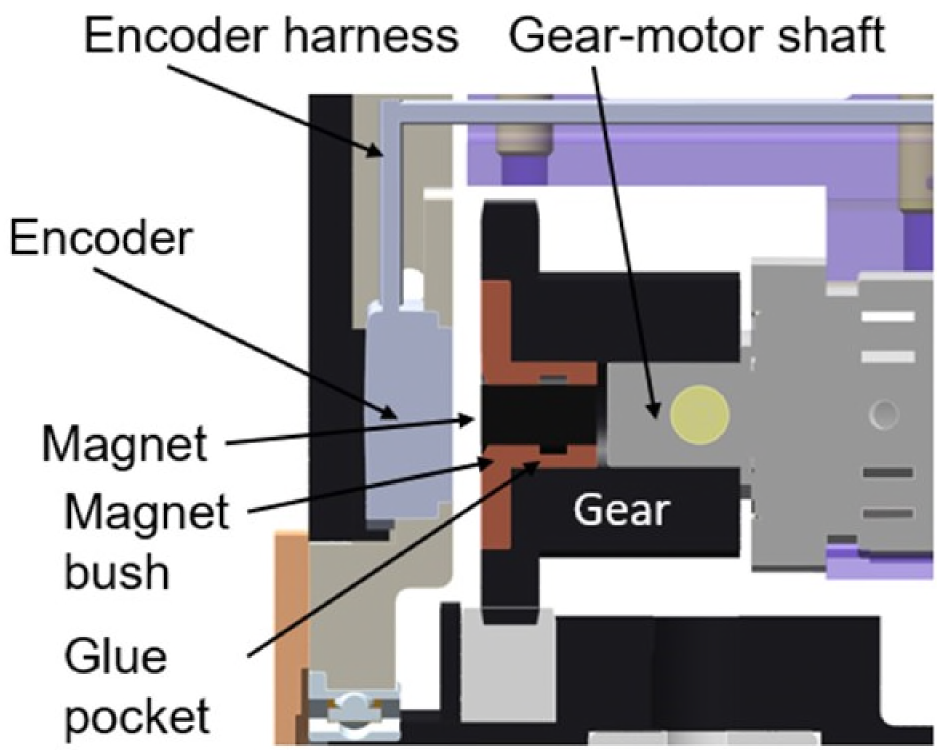


*Figure 4. Section-view of mechanism encoder solution.*

Gear Train

The gear motor torque is transferred by a gear train of two gear wheels to the sensor head. To avoid cold welding of the mechanism, the (gear-) motor gear is made of stainless steel 304L and the sensor head gear of Delrin®. The motor gear with the encoder magnet is visible in Figure 4. Regarding the sensor head gear, we increase the bore hole and mounted it over the sensor head. Initial mounting of this gear, screwing directly in the thermoplastic, lead to problems due to the proximity of the (countersunk) screw holes to the gear teeth profile. Therefore, an aluminum clamp to fix the gear (Figure 2) was added to the sensor assembly. The gear ratio $i$ (output to input) is computed in Equation (1) and the module of the two parts is 0.50.

$$i = \frac{D_D}{D_S} = \frac{14mm}{14mm} = \frac{z_D}{z_S} = \frac{28}{28} = 1 \tag{1}$$

Where $D_{D/S}$ is the reference circle and $z_{D/S}$ the number of teeth of the Delrin (D) and stainless steel (S) gear, respectively. Like for the prototype [9], a gear ratio $i > 1$ would have been desired, however, a reduction of the motor gear was not possible due to the encoder magnet, and a larger sensor head gear would have increased the overall mechanism volume.

Bearings

The sensor head is supported by two identical flanged bearings that are assembled from the outside in the housing. The selected bearing cages are made of non-metallic BarTemp material and machined in one-piece. This material is very well suited for space applications, as it is dry-lubricated, not demanding conventional lubrication. For example, the operational temperature of these bearings ranges from −200°C to +100°C. Dry-lubrication means that the BarTemp cage material provides a lubricating dry-film to the bearing balls during their movement, lubricating both the balls and the raceway. While this is an excellent solution for space mechanisms, the loading on the bearings is limited due to the absence of conventional lubrication. Furthermore, this self-lubricating bearings should have an initial rotation of about 30° in order to distribute the dry-film in the bearing [10], which is another motivation for the mechanism maintenance, described below.

➔ BarTemp bearings provide unique properties for space mechanism, not demanding lubrication and being operational in a very wide temperature range, but they are generally not available off-the-shelf with a very long lead-time of nearly one year in our case.

Wave Washers

For structural reasons, the sensor head was made of titanium Ti-6Al-4V, while the housing is made in aluminum Al-7075-T7351. To compensate for differential thermal expansion between the two pieces, one wave washer (2 waves) has been added between each of the two bearings and the sensor head. This avoids axial play of the sensor head, e.g., in the warm case, when the housing thermally expands more than the sensor head. Furthermore, it avoids rigid contact from the sensor head to the bearing-housing assembly, aiding at reducing vibrations in the sensor head (REQ-006).

Helicoils

Preferably, titanium Helicoils Screwlock Tangfree should be used for fixing the mechanism, to reduce the thermal contact of the mounting, in support of the used titanium screws (REQ-017). However, we were not able to find a Helicoil supplier offering the pieces made in titanium, except one with a minimum order quantity (MOQ) of 5,000 with additional charges on the tooling, making it prohibitively expensive for the project budget.

➔ Titanium (or comparable material) Helicoils could be used in aerospace applications e.g. to further reduce thermal contact between bolted parts, but are currently hard to source on the market.

## Manufacturing

Regarding the manufacturing of the mechanism hardware, this Section focuses on measures to minimize the mechanical noise induce in the sensor head (REQ-006). For this, the machined pieces shall ensure best possible alignment of the two bearing holes, and best parallelism of the two axes of sensor head and gear-motor. The latter reduces the noise within the gear train, with the additional condition that the axis distance is within the specified positive tolerance of $d = 14^{+0.03}_{+0.02}$ mm (accounting for thermal expansion).

For the bearing holes drilled in the one-piece housing, it is required to do all measurement and the machining with respect to the same reference surface. Like this, best alignment of the two bearings and therefore the sensor head rotation is ensured. Relative to the bearing holes, the hole for the encoder is machined, ensuring good positioning of this component. Regarding the axes distance, the machining of the motor mounting piece is key (Figure 6). Here, the machining cannot be done independently from the machined housing. Rather, the machining is done with a positive tolerance on the distance from the motor mounting hole to the contact surface with the housing. Following this, the piece is screwed in the housing using additionally the alignment pins. This two-part assembly is then used for the measurement, focusing on the motor mounting hole *relative* to the bearing holes in the housing. If the distance is measured too small, or the axes alignment is not sufficient due to the geometric tolerances, the motor mount contact surface with the housing is re-machined by grinding. This process is repeated until the required specifications are met.

All aluminum (Al-7075-T7351) parts are treated with Alodine 1200, passivation is applied to stainless steel parts and the titanium (Ti-6Al-4V) parts experience blue anodization. The total instrument was found to have a mass smaller than 330 gram, leaving a margin of 15 % and fulfilling REQ-002.

- ➔ The iterative process of measuring two assembled parts and adapting one part as required, ensured meeting the assembly tolerances, and mitigated the risk when manufacturing and measuring both pieces individually.
- ➔ Adaptation of precision gears must be done by no other means than grinding to avoid burrs in the precision pieces.

**Integration**

The rotation mechanism integration is performed in two steps, firstly the two one-axis mechanism are integrated individually, followed by the orthogonal combination of the two mechanisms and the combination with the mounting plate. These two integrations are described in this Section.

Firstly, the *sensor head subassembly* is integrated, an in-line assembly of the *sensor head* with the *slip ring*, connected by the torque-transmissing *slip ring clamp*. The torque of the rotating sensor head is transmitted to the *slip ring clamp* by fins. Through this hollow piece, the sensor head harness arrives at the rotating shaft of the slip ring that is glued to the clamp. The custom-made precision sensor head gear and the associated gear clamp, as pictured in Figure 5 (it is referred to left/right as in this Figure), complement the assembly. This subassembly is realized to ensure the best in-line alignment of the assembly, e.g. when aligning and gluing the slip ring clamp. During the gluing process, the clamp is fixed with a setscrew to affix the position.

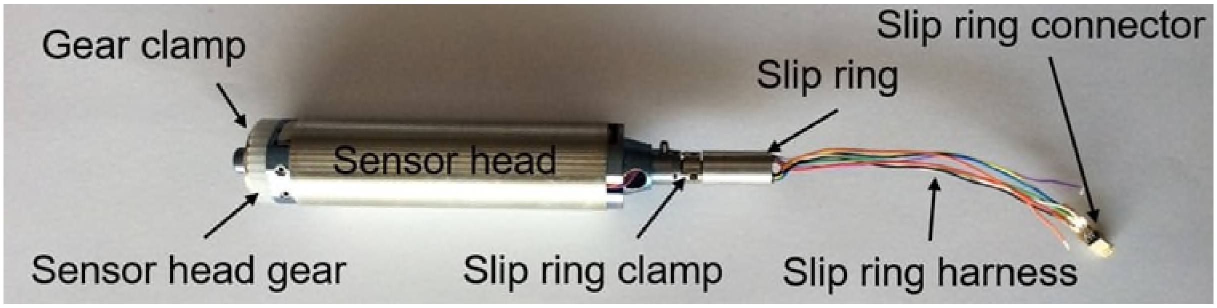


*Figure 5. Integrated in-line "sensor head subassembly" for integration into the housing. Note that the slip ring clamp is not yet glued in the shown setup.*

This pictured subassembly is then introduced into the mechanism *housing*. With the housing being in one piece, the design allows to introduce this setting laterally with the chamfered shoulder of the sensor head temporarily entering the bearing hole, thus allowing the leftmost shoulder to enter the second bearing hole. This assembly is then positioned with the two flanged bearings mounted from the outside. Here, it becomes clear why the slip ring outer diameter was limited, as the bearing is slid over the slip ring and its clamp to the sensor head bearing shoulder on the right. The left bearing is secured with the *bearing cover* and the right bearing is secured by the *slip ring housing,* serving therefore twofold. The second purpose is the support of the slip ring stator, which is glued and screw-clamped in this housing. At this stage, the rotational torque of this subassembly is measured below in the *Functional Tests* Section.

After this, the second half of the one-axis mechanism assembly concerns the assembly of the *gear-motor* and the *encoder* setup. Firstly, the encoder is placed inside the housing and its harness enters the housing through the dedicated hole. Using the *encoder clamp*, the encoder is fixed in its position and the external part of the harness, as well as the harness hole are covered by this piece (Figure 6). Second, the *gear-motor assembly* is prepared as shown in Figure 6. The *encoder magnet* is glued inside the *magnet bush*, which in turn is screwed in the *motor gear*. The gear motor is put inside the *motor mount* and its gear is then screwed on the shaft of the gear-motor. This subassembly is then introduced into the housing, while the alignment is ensured using two alignment pins during the fixation (identical to the mounting during machining, see above).

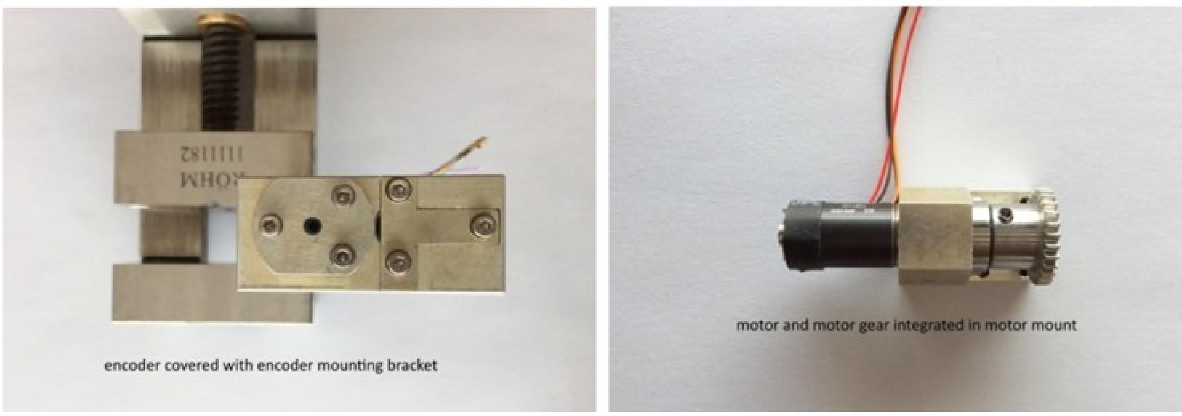


*Figure 6. (Left) Bearing and encoder cover on side view of the mechanism. Note that countersunk screws have replaced the screws on the bearing/encoder covers. (Right) Motor mount with integrated gear-motor and motor gear.*

As a last step, the *back-end electronics (BEE)* of the instrument are mounted, which closes the mechanism off on one side. The gear-motor and slip ring harness are connected to the BEE, while the latter harness is guided inside the housing through one of the harness bushes. For the BEE (and cover, introduced below) fixation, special SNZS pan head screws are used to limit the width of the mechanism. The fully integrated mechanism is shown in Figure 7.

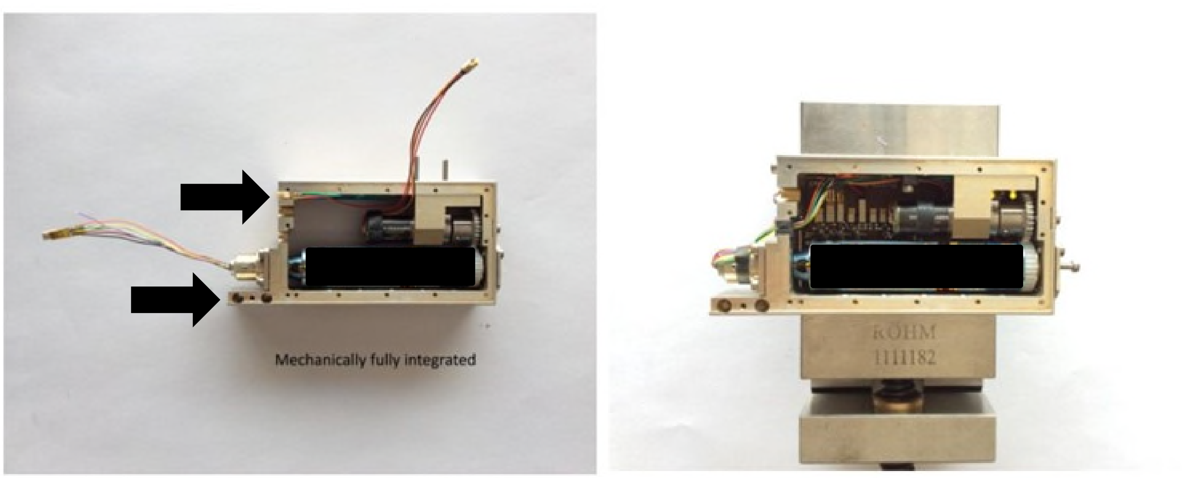


*Figure 7. Manufactured and assembled EQM GRASS instrument showing the main characteristics of the payload mechanism. Black arrows indicate the interface for two-axes assembly.*

The combination of the two individual mechanisms to form the orthogonal instrument mechanism (Figure 3) is straightforward. The two identical mechanisms are combined orthogonally by stacking the two instruments such that the rotation axes are skewed with the slip rings lying above each other (Figure 8). Per axis, two screws enter the respective other housing, as indicated in Figure 7. As shown in Figure 3, the inside of the instrument is closed off with the BEE, while the outside is covered with a L-shaped *global cover* made from a single sheet material bent at 90°. With this cover, the instrument is fully enclosed, including the junction with the two slip rings, aiding to avoid EMC problems and covering all moving parts of the mechanism(s). Finally, this setting is mounted on the Titanium *mounting piece* with *thermal washers* to complement the full instrument. After allowing for some stress relaxation time, the alignment of the two axes is measured by obtaining the orientation of defined reference planes that have previously been defined with respect to the sensor head rotation axis. This is a specific requirement coming from the gravity vector reconstruction, and might not be needed for other science payload applications. It allows further confirming that the alignment between the two axes was indeed not altered during the instrument mounting (REQ-016) as should be avoided due to the mounting piece.

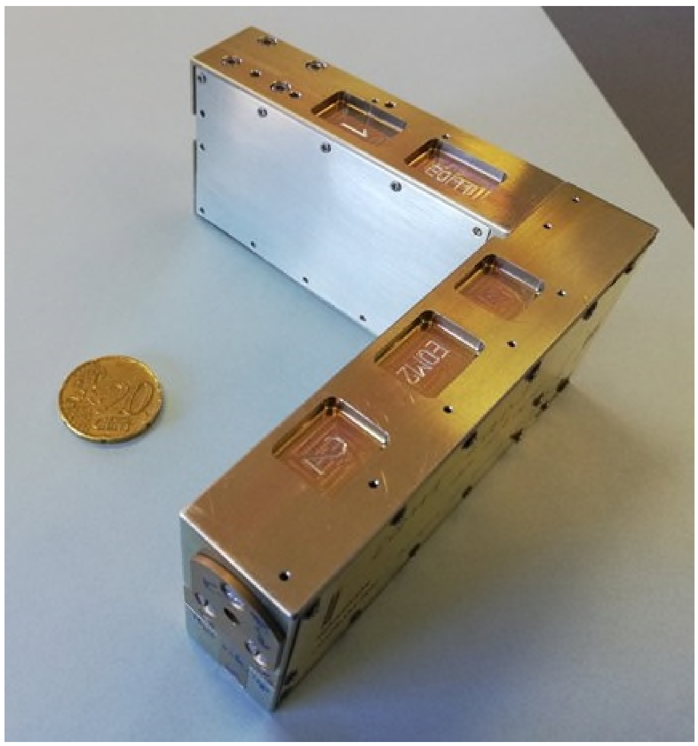


*Figure 8. Integrated two-axes GRASS instrument (without satellite interface and dummy BEE on the inside). Engraving in the mass reduction pockets allows clear identification of the instrument axes (1 and 2), as well as the instrument version (here: EQM). In the front, the bearings and encoder covers are visible. 20 cent euro coin for size-reference.*

## Mechanism Verification

In order to verify the mechanism design, two functional tests regarding the sensor torque after integration, and the functionality at low temperatures have been performed. The qualification testing of the EQM at instrument level, thus including the mechanism, is ongoing and not reported in this paper. First pre-tests show favorable results regarding the here presented rotation mechanism. The below reported sensor torque test has been re-measured after a pre-vibration test, and no measurable increase in the torque was observed. Regarding REQ-011, no lifetime test was foreseen, as this requirement was found non-critical regarding all used components affecting the rotation (gear-motor, slip ring, bearing, and gear train) considering their individual lifetimes and recalling the low rotation speed (REQ-007).

Sensor Rotational Torque

In order to verify the safety factor of the torque (REQ-004), the torque of the sensor head sub-assembly (bearings, slip ring, moment of inertia) has been measured. The value of the tested torque $M_{T,start}$ for both directions, was found to be 1.2 mNm.

With the gear ratio $i$ = 1 (Equation (1)) and an assumed gear efficiency for the precision gears of $\eta = 0.9$, the nominal input torque of the motor of 15 mNm yields an output torque at the sensor head as shown in Equation (2).

$$M_{T,out} = M_{T,in} \cdot i \cdot \eta = 15 \text{ mNm} \cdot 1 \cdot 0.9 = 13.5 \text{ mNm} \tag{2}$$

With this, the safety factor $S$ can be computed as in Equation (3).

$$S = \frac{M_{T,out}}{M_{T,start}} = \frac{13.5\ mNm}{1.2\ mNm} = 11.25 > 3 \tag{3}$$

The safety factor of 11.25 is much larger than the minimum required value of 3, and therefore, no problems in the gear train are expected.

Cold Motor Start

One of the limiting factors of the mechanism in cold temperature was the minimum nominal operating temperature of the gear-motor. The supplier stated that this is due to the reduced viscosity of the lubricant and that additional testing would be required if the range could be extended for the minimum operating temperature of −30°C (REQ-008). For this, a cold motor start had been performed in a thermal vacuum chamber. Specifically for the cold motor start test, the ambient temperature was set to −35°C. After holding this temperature for about two hours, the motor was started at a temperature of about −29°C ± 1°C without problems. This was well confirmed by the encoder reading, clearly showing the expected gear-motor rotation. The delay in reaching the target temperature comes from the functioning of the thermal insulation of the gear-motor (REQ-010). Still, the result was very promising and showed a good behavior of the gear-motor below its nominal minimum working temperature. Additionally to this, the option to power the stepper motor coils, to perform preheating of the gear motor prior to a cold motor start, and the option to add an external heater are considered as additional measures. Based on future test results, it will become clear if these measures are needed. If in doubt, it will be possible to consider one or both options as backup solutions, provided that the mechanism rotation is indispensable to the experiment's success.

## Mechanism Maintenance

Other than for Earth-orbiting mechanisms, the cruise phase of the here presented mechanisms can be up to four years. Additionally, the ground-storage phase of instruments on piggyback-spacecraft, i.e., a CubeSat deployed by a parent-spacecraft, is extended due to two deliveries (instrument to CubeSat, CubeSat to main spacecraft). Therefore, the idle time of the here presented mechanism will be extended. This poses a risk to the movability of the mechanism. Most specifically, it is possible that, despite the epilamization added to the gear-motor, the lubricant creeps and that it leaves the regions to which it has been applied. These are the internal bearings and the gears of the planetary gear forming part of the gear-motor. For this reason, and in discussion with the gear-motor supplier, it was proposed to include a mechanism maintenance to minimize the lubrication creep. This maintenance would exercise the rotation mechanism regularly, monthly, or at least bi-monthly during storage and cruise. In case that this exercise cannot be performed during certain periods, due care will be taken to place two additional exercises as late as possible before such interruption, and likewise as early as possible after the interruption. The rotation of the sensor head during cruise phase will induce a torque $T$ on the spacecraft that needs to be compensated. However, given the small moment of inertia $I_{xx}$ of the sensor head and the low angular acceleration $\ddot{\omega}$ of the maintenance mode, it is shown in Equation (4) that the induced torque is negligible (and that the mechanism cannot be used as backup reaction wheels).

$$T = I_{xx} \cdot \ddot{\omega} = 7 \cdot 10^{-7} \mathrm{kgm}^2 \cdot 0.210 \frac{1}{s^2} = 1.47 \cdot 10^{-7} \ \mathrm{Nm} \qquad (4)$$

Additionally, this mechanism maintenance aids at maintaining the dry-lubrication film of the self-lubricating bearing cages on the bearing balls. Nevertheless, one initial rotation should be considered before entering the incremental rotation/pointing mode, if applicable and possible.

➔ Mechanisms for deep space exploration can be subject to (very) long storage times in cruise. Mechanism maintenance can increase the reliability of a mechanism upon arrival, yet mechanism exercise might not be possible for all kinds of mechanisms and it has to be agreed upon with the operations of the spacecraft.

## Future Mechanism Utilization

While the here presented mechanism has been developed for the GRASS gravimeter and the Juventas CubeSat as part of the ESA Hera mission, it can be adapted to other use cases in space. For example, payloads likewise requiring sensor head rotation or pointing can make use of the here presented system. Together with the larger prototype design [9], a large range of sensor head sizes is covered, and the presented mechanism can be adapted or scaled for other sensor head dimensions. Further miniaturization of the presented CubeSat mechanism will be challenging, but achievable when identifying corresponding smaller solutions for dimension-drivers, e.g., the gear-motor, slip ring. The total mechanism length might be reduced for shorter sensor heads. The mechanism of one axis can work as a standalone instrument with minor modifications to the cover and mechanical interface. The orthogonal arrangement of two axes is the baseline presented in this paper, while other arrangements or a third orthogonal axis (potentially for redundancy) are possible, either with an adapted design or by using one one-axis and one two-axes mechanism in combination.

## Conclusions

Here, we present the complete rotation mechanism for the GRASS gravimeter on-board Juventas CubeSat as part of the ESA Hera planetary defense mission. The requirements were introduced and the design is presented. Compared to the previous prototype development, the main difference is the need for an even more compact design, the compliance with the accommodation requirements in the CubeSat, and the orthogonal combination of the individual mechanisms forming the instrument.

The design drivers, choices as well as component and material selection have been presented in this work. Regarding the individual mechanism components, customizations were applied to the gear-motor and slip ring as adaptations to the space environment, and to prepare the mechanism for a long cruise phase in deep space. Functional tests showed a good mechanism performance and confirmed the presented design. The manufacturing description was focused on ensuring the proper tolerances, specifically concerning the gear train axes distance. Using an iterative machining-measurement process, best results were obtained. After this, a detailed description of the mechanism integration steps and their order has been presented. This was complemented by the description of two functional tests. Both showed satisfactory results with regard to the formulated requirements. Next, a procedure for mechanism maintenance, considering both the long ground storage and deep space cruise phase, has been presented for this mechanism. Lastly, possible future adaptations of the here presented mechanism to other science payloads have been discussed, opening a wide range of possibilities for future science missions demanding sensor head rotation or pointing.

The relevant lessons learned have been formulated throughout this paper in the relevant sections. Without repeating these in detail, it is worth highlighting two lessons learned that were developed specifically for this deep space mission: The gear motor was treated with epilamization to minimize lubricant creep, and furthermore a maintenance procedure on mechanism level has been described. Both aspects address a specific challenge of mechanisms for space missions and might prove particularly valuable for future mechanism developments.


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