Development of a Novel Piezo Actuated Release Mechanism

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Abstract

The Caging Mechanism (CM) is one of core devices of the LISA Technology Package to be flown on the LISA Pathfinder Mission in 2009/2010, a technology demonstrator for the LISA mission. The Caging Mechanism (CM) as part of the Inertial Sensor System (ISS) shall cage and constrain a Test Mass (TM) during launch and subsequently, release the TM into a perfect free-fall or Geodesic Orbit within an Electrode Housing (EH), ready to be controlled and measured via electrostatic forces and an interferometer using a DFACS (Drag Free Actuation and Control System).
The two main functions of the CM are to cage the TM which is done by a mechanism called CMSS (Caging Mechanism Sub-System and to release the TM into free-fall which is performed by the GPRM (Grabbing, Positioning and Release Mechanism), a piezo actuated mechanism which is described in detail within this paper

1. Caging Mechanism Introduction

The Caging Mechanism Assembly (CMA) consists of two Caging Mechanisms (CM), one CM for each Inertial Sensor Head (ISH) of the ISS, including the Caging Mechanism Control Unit for both mechanisms.

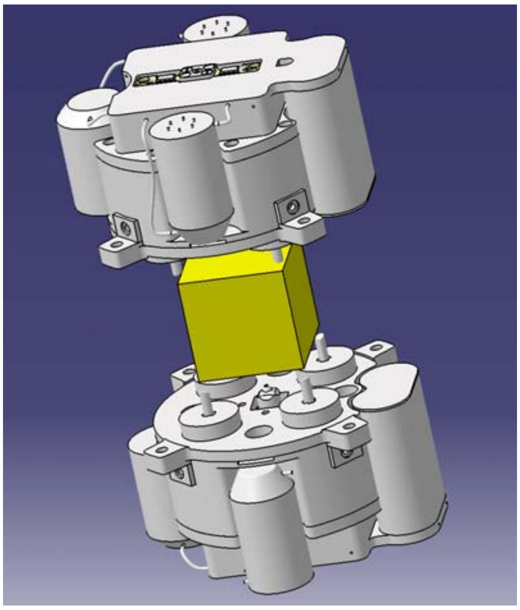

Figure 1: Parts of the Caging mechanism

The Caging Mechanism itself consists of two parts, one (+z) located above the TM and one (-z) located below the TM. Each part of the CM contains two separate and independent mechanisms (Fig. 1), the Caging Mechanism Sub-System (CMSS) and the Grabbing and Positioning Mechanism (GPRM). The CMSS (one at +z and one at -z) cages the TM at its 8 corners with fingers during launch as well as during on ground operation and storage. The loading system of the CMSS is a hydraulic system where 4 actuators apply the preload to the TM by the 4 fingers. Once in the final orbit, the CMSS releases the preload and hands-over the TM to the grabbing fingers of the GPRM, one at +z and one at -z. Following this, the GPRM has to position the TM with a high accuracy and release it into free-fall within the cavity of the electrode housing, which is a few mm larger than the TM. Should the electrostatic suspension system loose control of the TM, the GPRM is able to re-grab the TM, then position and re-release it.

1.1. Initial Technical Requirements

Based upon the demanding requirements of the LTP experiment the CM/GPRM key requirements are as follows:

Requirement	Value
No damage to the constrained TM (body and surfaces)	
TM linear release velocity	< 5 µm/sec
TM angular release velocity	< 100 µrad/sec
TM linear position accuracy	< 60 µm in all axes
TM angular position accuracy	< 60 µrad about 2 axes
Quasi static loads	+/- 75 g for all axes
Random loads	~25 g_{rms} in all axes
Extreme low mass for the CM	<1700gr, <500gr GPRM
Tiny envelope for the CM	ø125 x 65 per CM half
High read-out of positioning sensors	< 5 µm over 2mm range
Extremely high out-gassing and cleanliness requirements	14x 10^9 Pa l/sec (split up for different elements)
Grab the TM from all possible positions w/o help	
Gold coated constraining elements and gold coated TM	
High caging/constraining forces/preloads during launch	
No use of magnetic or ferromagnetic materials	
No noise (creeping, etc) in OFF state of the mechanism	

Table 1: Key Requirements for caging mechanism

From Table 1 it is obvious that not only the accuracy requirements are challenging but also unusual requirements result from using two gold coated, separable in-

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terface surfaces, high preloads at launch, no creation of any magnetic fields, and the ultra-high cleanliness and out-gassing constraints. Furthermore the TM and its surfaces must be delivered in-flight undamaged. These requirements were identified as the main design drivers during the development phase.
The requirements were further broken down for the GPRM.

2. GPRM Design

2.1. General Design Features

The GPRM as a part of the CM, has been designed and produced by RUAG Aerospace (Fig. 2). It is located in the centre of the caging mechanism and surrounded by the hydraulic actuators of the CMSS, with the actuator positions being defined by the size of the TM (46x46 mm^2). The GPRM receives the TM from the CMSS, grabs, positions, and releases the TM into free-fall under zero gravity condition.
The GPRM consists of two main sub-assemblies: the actuator and the grabbing finger unit.

The three main functions of the GRPM are:

- Grabbing
- Centring/positioning
- Release

The grabbing function ensures that the TM can be grabbed from any position or attitude within the EH cavity. The TM can freely float within the cavity of the EH within linear distances of only 3.5-4 mm from the EH sides. The maximum angle w.r.t. the GPRM finger that the TM can achieve before it touches the guard-rings of the EH is 9.6°. The grabbing is performed with two plungers (fingers) interfacing the TM at a specially designed area (see 2.1.2) on the z surfaces
The centring function shall position the TM in the centre of the EH for release while a positioning function provides an off-centring of the TM. For release in-orbit, the TM shall be positioned in the centre with accuracy smaller than 60 µm in all translational axes while the rotational accuracy is set to ±780 µrad about all axes. For the optical verification of the interferometer on ground, an angular accuracy of 60µrad about two axes is needed.
The release function is performed by the release pin, a separately actuated pin situated in the centre of the Grabbing finger and designed to minimise the contact area to the TM and therefore the induced velocity to the TM due to residual adhesion at the contact. Once the TM is correctly positioned, a hand-over process from the finger to the release tip is performed. Subsequently, the release will be performed by accelerating the release tip using a stack piezo actuator and retracting the plungers away from the TM; leaving the TM with a residual speed of less than 5 µm/sec and 100 µrad/sec.
After release, the grabbing finger waits in the vicinity of the TM whilst the DFACS confirms the successful release. Once this is confirmed, the command is given to move into the retracted position for switch off, where the tip of the plunger is retracted approx. 8.3 mm behind the inner surface of the EH electrodes. In science mode the CM is completely switched off. Should the release not be successful the grabbing fingers re-grab the TM for a new release sequence.

During S/C safe mode, the GRPM grabs the TM and stores it with a low preload between the grabbing fingers. Furthermore an electrical biasing of the TM has to

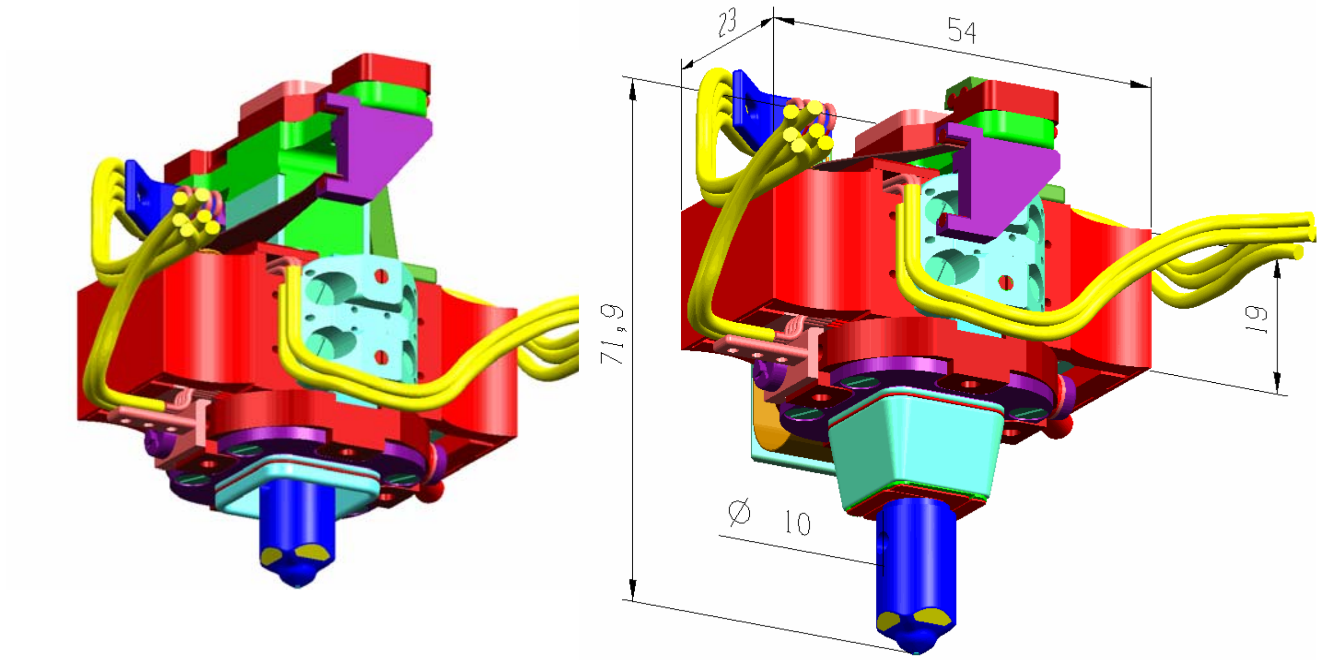

Figure 2: General GPRM design in retracted and extended grabbing finger position

be performed with the grabbing fingers, which are therefore completely electrically isolated.

2.1.1. Actuator Unit

The actuator bracket forms the interfacing part between the CMSS I/F flange and the GPRM's Nexline®. The Nexline® is a custom made piezo actuator, with a similar working principle to the inchworm. For the GPRM the Nexline® provides a total stroke of 16.9 mm. The Nexline®, driven in frequency control instead of voltage control, is able to position the grabbing finger with a resolution of 2 µm in a single step which is measured by the specially designed beam position sensor.

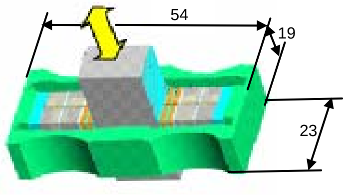

Figure 3: Nexline ®

The Nexline® (Fig. 3) provides 8 clamp Piezo-elements, 4 on each side where two of the stacks (each side) are in contact with the grabbing finger at any one time and the other two are retracted. On top of the clamping piezo stacks, shear Piezo-elements are installed. Actuated, these shear Piezo-elements provide the movement of the grabbing finger. The redundant Piezo-elements are installed in series within the piezo stacks.

The rectangular linear runner of grabbing finger unit is guided in one lateral-direction by the Nexline®, whilst in the other lateral direction, the guiding is composed of preloaded rollers rolling on the grabbing finger and a limiter which prevents the turning of the grabbing finger with off-centred loads. The piezo stacks of the grabbing finger are running on a ceramic plate bonded to the linear runner of the grabbing finger unit.

The position sensor provides the information of the grabbing finger position for approx. 3.5 mm around the centre position of the TM within the EH, with a resolution of 1 µm. The position sensor is made of a thin blade (beam) carrying strain gauges which provide the calibrated position signal. It works in both directions such that the grabbing position and the retracted position can be measured. The retracted position has to be determined accurately due to gravitational constraints.

2.1.2. Grabbing Finger Unit

The grabbing finger unit (Fig. 4) is the movable sub-assembly that includes the linear runner for the Nexline® piezos, grabbing finger for grabbing and positioning, a force sensor on the top and the release mechanism formed by the release tip with piezo stack actuators for fast release, assembled inside the hollow grabbing finger.

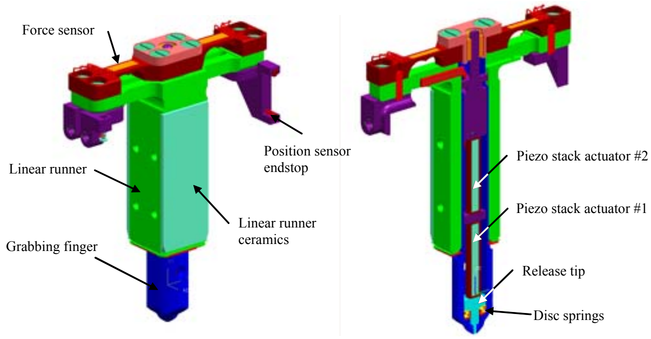

Figure 4: Grabbing finger unit with force sensor and release tip

The grabbing finger tip (Fig. 5) provides the interface to the TM recess. One grabbing finger of the CM is equipped with a pyramidal shape in order to provide the guiding for the TM attitude orientation. The opposite grabbing finger tip provides a conical shape such that the TM is rotationally constrained by the pyramidal shape only.

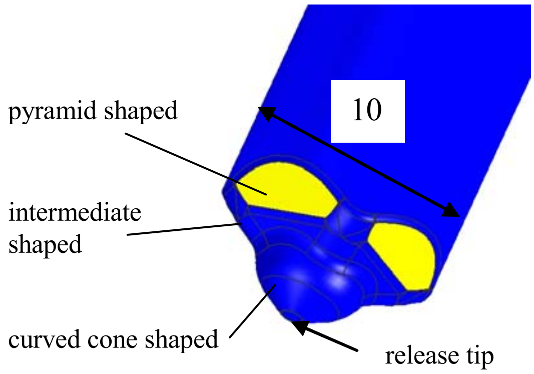

Figure 5: Grabbing finger with pyramidal shape

The grabbing finger is elastically fixed to the rectangular linear runner which provides the interface to the Nexline®. The linear runner provides, at the top, a T-shape interface for the force sensor. Any force acting on the grabbing finger tip will create an output signal at the force sensor beam, which is welded to the grabbing finger. The force sensor output signal is provided by bonded strain gauges at the most thin part.

2.1.3. Release Mechanism

Within the grabbing finger, the preloaded release tip and 2 piezo stack actuators (primary and redundant) are housed (Figs. 5 & 6).

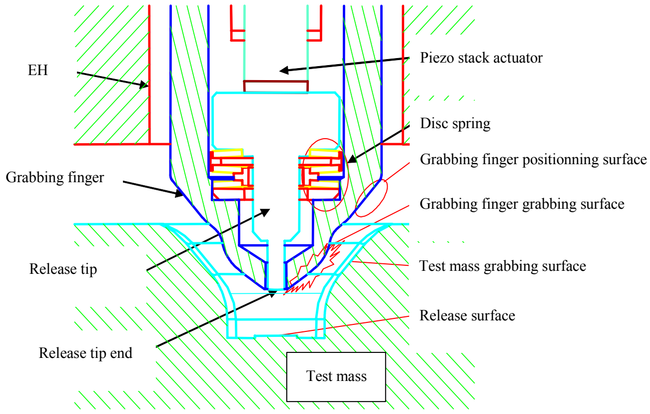

Figure 6: Grabbing finger with release tip

The stack actuator together with the release tip performs the release of the TM by fast retraction (inertial release of the TM).

2.1.4. Hand-over and Release Sequence

After completion of grabbing and centring, performed by the Nexlines® actuating the grabbing fingers, the holding of the TM is handed over to the release fingers. Within the hand-over the preload between the GPRM and the TM will be lowered as the residual adhesion force depends upon the preload applied. After this hand-over phase the TM is ready to be released.

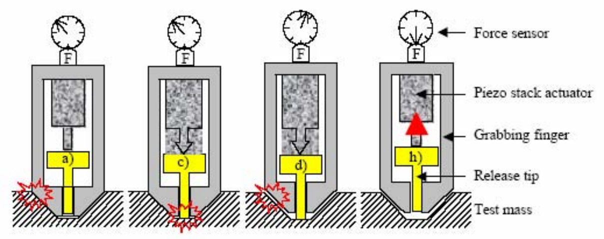

Figure 7: Hand over and release sequence

The Nexline® actuator displacement is controlled by fixed steps increments. The piezo stack actuator is powered during a defined time of the hand-over and release sequence. The process is visualised in the sketches above (Fig. 7).

The individual steps are:

Start: TM grabbed with the grabbing finger and positioned.

a) Move the grabbing finger backwards by one step (the contact with TM is not lost due to the moderate stiffness of the force sensor).
b) Start increasing the stack actuator voltage. This causes the release tip to extend/push the TM. The release tip extends until the force reaches a defined level conditioned by the Nexline® fixed step size.
c) The grabbing finger is moved one step backwards again, followed by a new extension of the release pin until the defined force level is reached again. This is continued in a cyclic operation until the release tip reaches its maximum extension.
d) The adhesion force between grabbing finger and TM is then broken by a controlled slow retraction of the release pins, followed by an immediate extension to re-contact the TM with low force.
e) **TM release** is performed by a simultaneous action of both GPRM located on opposite sides of the TM by powering off the stack actuator. The stack actuator retracts in the grabbing finger within less than 1 ms, simultaneously on the upper and lower mechanisms.
f) The release is immediately followed by the retraction of the Nexline® with full speed over a small distance to avoid interference with the TM.
g) If the TM residual movement/velocity is small enough to be stabilized by the electrostatic control, the grabbing fingers are fully retracted. Otherwise, the grabbing and release is repeated.

End: TM released

3. Development Test of the GPRM

Due to tight schedule and a high development risk some tests have been performed within the development phase with either a breadboard or Engineering model development tests.

3.1. Breadboard & EM Testing

3.1.1. Nexline® Vibration Testing

The Nexline®, as a new industrial component, was vibration tested to ensure that it can withstand the environmental loads applied. The vibration levels for the Nexline® were mainly driven by the random spectra during launch. Whilst the Nexline® performed well during vibration testing, the linear guiding of the grabbing finger failed when vibrated in Y direction. Instead of being centred after vibration the grabbing fingers was off-centred w.r.t. to the guiding in this axis. For the QM the design has been modified to prevent the axial movement.

The test was successful and clearly demonstrated that the Nexline® held the grabbing fingers and even after the large misalignment in one axis the Nexline®, performance was within the specification.

3.1.2. Hand-over Testing

Within the first BB testing, the hand-over process was tested to verify the functioning of the principle. The grabbing finger was brought in contact with a thin blade under a certain load (Fig. 8). The release tips were extended to simulate the hand-over process. The grabbing finger was pushed backwards by the release pin (protruding pin). The blade remained in position which indicated that the force did not change.

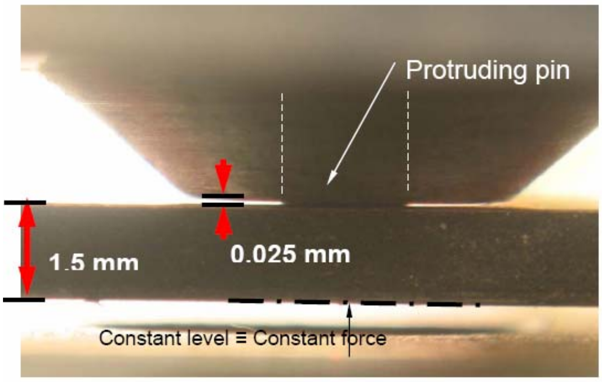

Figure 8: After hand-over - release pin extended

The spring force and position has been measured during the hand-over. The force was kept at a constant level of about 50 mN (Fig. 9). The position of the blade was measured via a laser system and the positional variation was less than 1.1 µm.

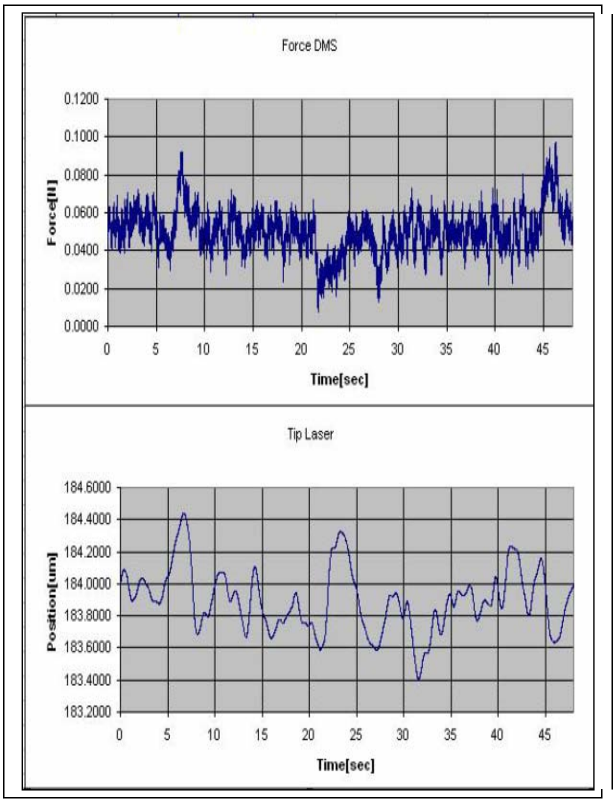

Figure 9: Force and Position read-out during hand-over testing

3.1.3. <u>Friction Tests</u>

Various research through the literature did not reveal a precise knowledge of the friction coefficient between the gold coated contact surfaces. For a reliable grabbing and retraction of the grabbing finger, the angles of the TM indentations are optimized. A friction coefficient of µ=0.7 has been defined theoretically.

The friction of two gold coated surfaces, each coating 1µm thick with a titanium intermediate layer, was tested at ESTL test facilities with a standard pin on disk test. The results are shown hereafter in Fig. 10.

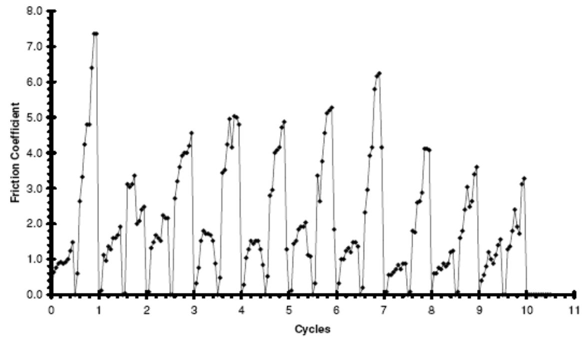

Figure 10: Friction tests results

Due to the extreme high friction coefficient, the gold layer on the surfaces was even removed during this test. The constraints/loads generated by the pin-on-disk test were considered to be much higher than can occur in the actual grabbing. Following this, the test set-up used during the first BB positioning tests was used to demonstrate the feasibility of the grabbing without damaging the gold surface. The only disadvantage was that the test set-up could not be placed in vacuum as the 0-g device was designed with water tanks and floating devices, as can be seen in Fig. 10.

3.1.4. <u>Grabbing Test</u>

The demonstration of the grabbing operations requires the simulation of a free floating Dummy Test Mass (DTM) and the use of a grabbing finger whose displacement is controlled by the force measured by a force sensor. Before this setup could be implemented with the help of the EM Nexline®, numerous test rig adjustments and alignment had to be performed.
The complete test set-up is shown in Fig. 10 with the laser tube on the left and the BB test set-up on the right hand side. A mirror fixed on the TM reflects a laser beam onto a position sensitive array. A rotation of the TM generates a displacement of the reflected beam on

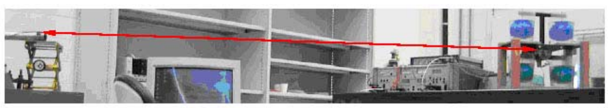

Figure 11: Grabbing test set-up

the sensor surface leading to a proportional signal that can be recorded. The total distance between the laser and the mirror of is 2.5 meters, so that the total optical distance is 5 m, resulting in an angular resolution of 1 µrad.

The vertical stiffness of the anti-g device is significantly dependent on the water level in the 4 reservoirs containing the floating balls (Fig. 11). When the water levels are set correctly, a nearly unstable rotational situation of the TM can be obtained and the vertical stiffness becomes small. However, setting the correct water lever is difficult. Therefore, several experiments were performed to determine the ideal water level.

Grabbing Test Results

The performances reported below have been obtained with the use of a lock-in amplifier (set at 10 kHz reference frequency) and a low-pass filter of first order allowing a sampling rate of 1 Hz. The test was run with fixed Nexline® step size of about 2 µm every half second and just before grabbing. Figure 12 shows a typical record of both the grabbing force and finger displacement in Z direction with time.
When the grabbing finger is far from the grabbing position, the force sensor shows very little fluctuations issued from the dynamic resistance of the TM when pushed forward at each step.
At the point of grabbing, the force increases suddenly within 2 to 3 steps. The movement is then stopped by the driver.

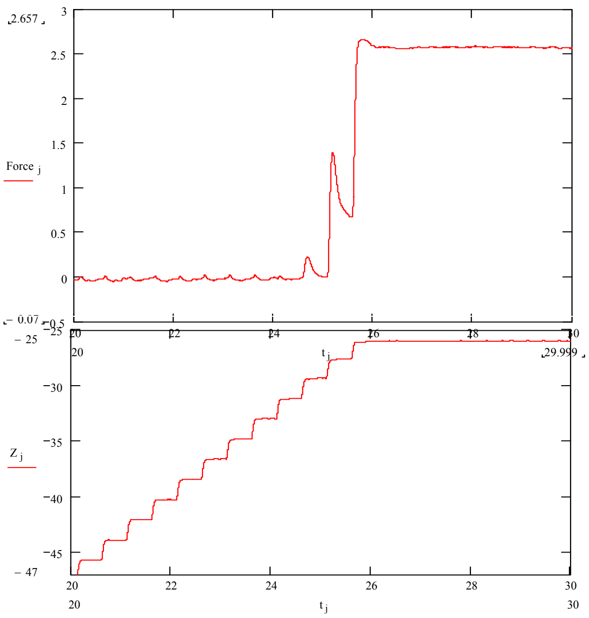

Figure 12: Grabbing finger axial force and displacement at grabbing position

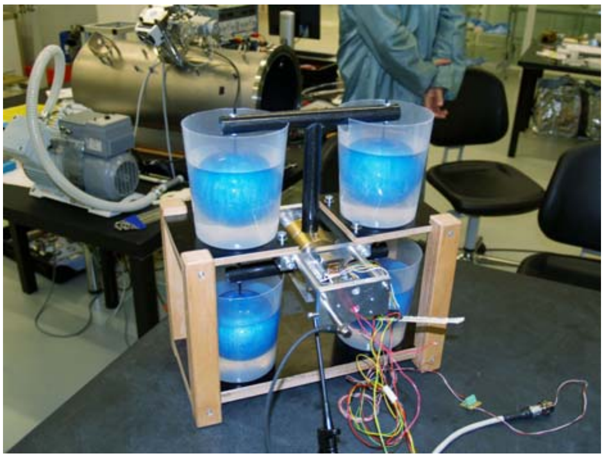

Figure 13: BB TM gravity compensated in water

The rotational movement of the TM during the grabbing is also measured. A typical record is presented in Fig. 14. Shown is a case where the water level defined a good alignment of the grabbing finger and the TM. The record shows the angular position instability of the free floating TM. Here, the vertical force produced by the floating device was minimal.

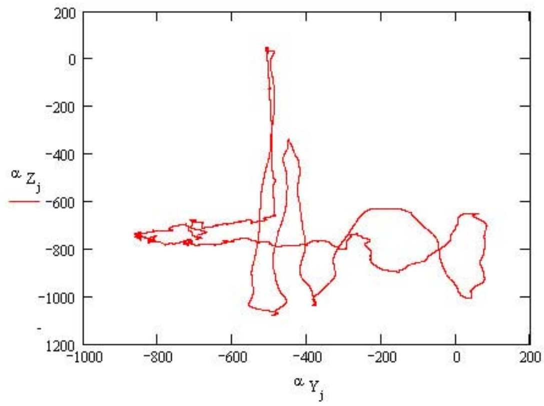

Figure 14: Rotational movement of the TM during grabbing approach (α_Z and α_Y are rotations in µrad around Z and Y respectively).

3.1.5. Step Size Verification

The aim of the step size verification test was to identify very early on that the chosen/designed control strategy with a fixed step size of the Nexline® provides the required performance w.r.t. position accuracy and setting of the correct pre-load for the TM release.
The final TM position statistics have been acquired over repeated grabbing operations. Figure 14-16 show the distributions obtained after 119 grabbing operations:

- Final Z position dispersion (standard deviation): σ(Z)= 0.6 µm

- Final angular dispersion
  around Y: $\sigma(\alpha_Y)$= 42 µrad
  around Z: $\sigma(\alpha_Z)$= 8 µrad

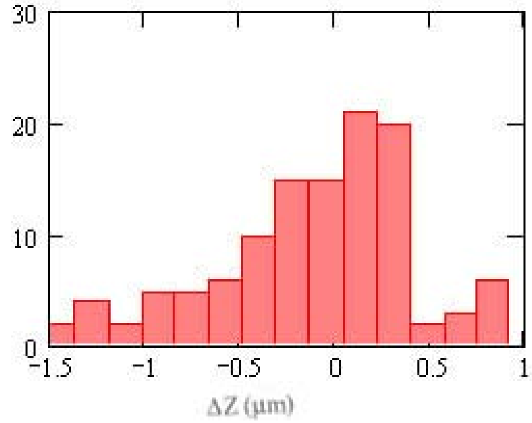

Figure 15: Histogram of final axial position dispersion of the TM (sample: 119 grabbing's)

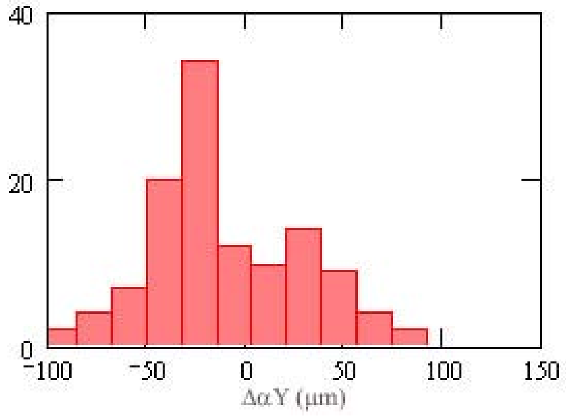

Figure 16: Histogram of final angular position dispersion about Y of the TM (sample: 119 grabbing's)

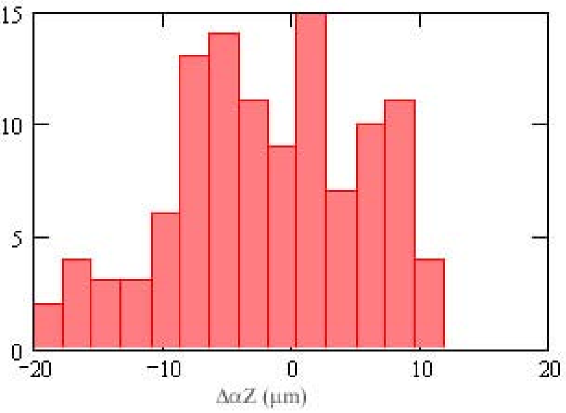

Figure 17: Histogram of final angular position dispersion about Z of the TM (sample: 119 grabbing's)

3.1.6. Pre-LifeTime Testing of the Grabbing

The pre-lifetime test demonstrated that the chosen thickness of the gold coating (1 µm) of the interfacing surfaces are only slightly affected by the friction between grabbing finger and recess (Figs. 18, 19).

- Recess shows local friction marks without gold damages.
- Grabbing finger remains essentially gold plated over its complete surface with gold removed only at the points where friction always occurs i.e. the contact points between the recess and the finger that provide the final position. The estimated size of the uncoated marks is << $1mm^2$.

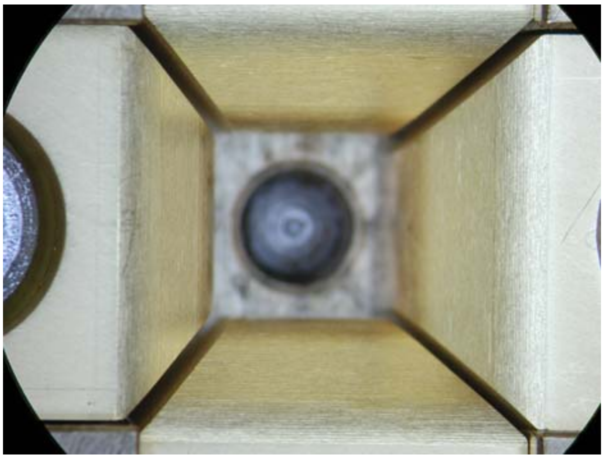

Figure 18: Dummy recess after life test. Gold plating not damaged

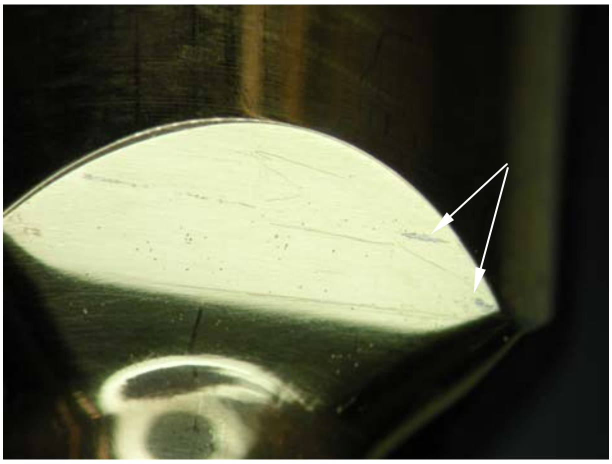

Figure 19: Grabbing finger pyramid after life test, small damaged areas marked

3.1.7. TM Release Testing

The main purpose of the GPRM is to release the TM in-orbit. Testing of an undisturbed TM release is not possible or extremely complex and costly on ground.

To verify this function and its performance, the torsion pendulum at the University of Trento and their knowledge has been used. At the time of writing, a validation of the test set-up and a commissioning phase has been performed. The final TM release testing with applied preload is on-going.

In a vacuum chamber, a reduced mass TM is suspended by a long thin fibre/wire. A dummy release tip, also suspended by a long thin fibre/wire, is connected via a thin fibre to an acceleration unit/actuator. By activating the acceleration unit, the release tip is retracted with a high acceleration away from the TM. The transferred momentum is measured via an interferometer at the reduced TM and the release velocities can be calculated. A detailed description of this sophisticated test set-up is given in an associated paper of this symposium.

4. Design Improvements and Lessons Learnt

Although testing in laboratory does not represent orbital conditions, the following conclusions can be made with a fairly good reliability. They should essentially be considered as worst case with respect to mechanical constraints, except for vacuum, which is a major unknown factor with respect to friction and wear and cannot be tested easily. Further ground testing under vacuum on the fully assembled CM is still necessary and planned to consolidate the first observations made at GPRM level:

- Grabbing and re-positioning accuracy has shown dispersion much lower than expected from the theoretical considerations based upon shape accuracy and friction coefficient.
- Hand-over from the grabbing finger to the release pin was demonstrated on a test rig. The hand-over driven with actuator variable step size could be controlled very accurately after the electrical noise was overcome with the help of a lock-in amplifier.
  The flight hardware will drive the movements with fixed step size. This control strategy was successfully verified for the grabbing and will need further verifications under vacuum for the TM release.
- Small local damage generated on the grabbing finger by friction against the recess has appeared early on during the life testing and remained constant with repeated cycles. Indications show that this situation cannot be improved unless the coating is modified. Unfortunately, the gold coating is imposed by the experimental constraints and is a very strong requirement.
  The extremely small affected area ($< 1\ mm^2$) found only on the grabbing finger has been demonstrated to be stable (at least in air); the adverse effects of these defects should be sufficiently small to be acceptable.
- The extremely high requirements related to cleanliness also appear as a challenge with respect to manufacturing and testing. Classical cleaning processes cannot be applied, severe constraints on material selection are necessary; handling is permanently submitted to non-standard operations.
  Minute production of dust particles by the piezo actuator was considered excessive and required the implementation of a dust trap to isolate the TM/EH operational volume from the actuator. An improvement on the actuator run-in procedure was also defined and reduced the dust particle production during nominal operation.
- The adjustment of the complex interface between the numerous components of the CM imposed a very close and detailed collaboration between the various partners working on this program. The exchange of 3-D models and cross-checking possible mechanical interferences was an unavoidable exercise.

5. Outlook

The highly constraining requirements of the Caging Mechanism for LISA Pathfinder Experiment led to a very compact design associating complex and multiple functions of extreme accuracy in a very tight volume. Dead volumes are almost absent.

The critical aspects related to accuracy, material constraints, and in particular the gold plating, cleanliness and interface have been developed and tested essentially in air. The manufacturing of the GPRM QM's is now ready to be started. Additional testing is still pending, but needs to be done on the assembled CM mechanism under vacuum.