A MIRROR CONTROL MECHANISM FOR SPACE TELESCOPE

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ABSTRACT

The high resolution optical instruments require more and more stability on the relative position between their different mirrors. The use of a mirror control mechanism (MCM) allows to correct in flight the position of the mirror (in particular the focusing and the 2 tilts). The mechanism described hereafter is designed for a Cassegrain telescope secondary mirror.

The selected concept is based on 3 vertical actuators which produce the focusing and tilts movements, and three horizontal actuators which produce the transverse movements. This architecture offers 5 degrees of freedom which guarantee the absence of rejection for any kind of correction.

After the design phase, a demonstrator was manufactured and characterised by functional and mechanical tests.

This mechanism is able to control any type of axisymmetric mirror within 5 degrees of freedom. The mass of the model presented is 3.5kg with overall dimensions ∅280mm/H77mm (except electronics). This concept can be adapted to smaller versions of mirror requiring an active control, and in a more general way to equipments for which the pointing precision is a key requirement.

1. CONTEXT

The optical instruments for observation at high resolution must have a very important dimensional stability of the structural elements which connect optics together. Two ways of work allows to progress in this direction. The first one consists in using materials having thermoelastic and hygroelastic sensitivity almost null and setting up integration procedures with fine metrological adjustments. The second one consists, in the opposite, to relax the constraints on materials and integration by adding in the instrument an in-flight adjusting device able to correct the optical defects during the mission. Such a device can be placed behind the secondary mirror of a Cassegrain telescope, allowing to minimize the inertia to be moved and to work on the relative stability with regard to a passive primary mirror. The knowledge in mechanisms of precise positioning resulted in drawing aside all the solutions bringing of the tribological contacts (ball screw, kneecaps, ball bearings) because of the non-linear behaviour to the small movements, of problems of performance stability versus time and the potential problem of optics pollution. It was thus decided to work with piezoelectric actuators which are already universally used in ground systems of precise positioning, and to use techniques of guidance by elastic strain to avoid non-linearities

The mechanism described hereafter is designed for a Cassegrain telescope secondary mirror to correct in flight the focusing, the 2 tilts, and the decenters (see fig1).

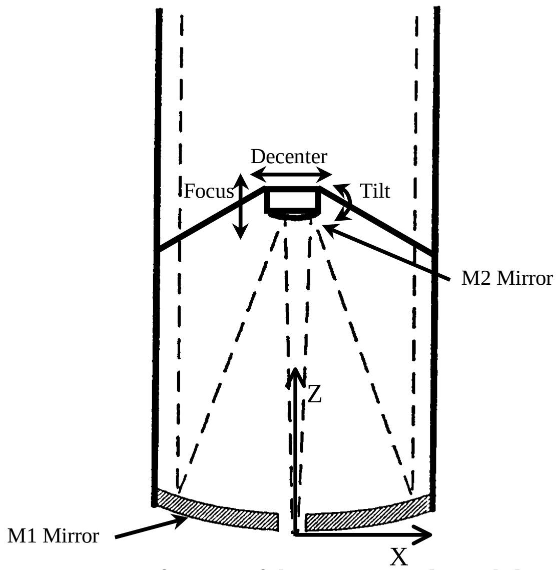


Figure 1 : Definition of the geometrical instabilities

2. OBJECTIVES

The need for the opticians is first to carry out corrections according to 3DOF (refocusing and 2 tilts). But the fact that this mechanism is intended for a secondary mirror of standard Cassegrain telescope is constraining. That imposes the obstruction of the mechanism does not occult the field of view of the telescope, or in other words it must be included in a cylinder of diameter equal to the mirror’s one and placed behind this one. So kinematics will be completely off-set compared to the optical centre around whose the movements must be done. Thus, a

3DOF mechanism will involve rejections in transverse which will be necessary to compensate. It is seen that the control of 2 additional DOF is necessary to compensate the rejections in translation X and Y of such a kinematics.
To withstand launch vibration levels, structural modes have to be higher than 100 Hz. Moreover, for operation in orbit, it will be necessary to be insensitive to the microvibratory disturbances. This criterion results in an absence of mode below 150Hz.
The ground tests impose to be able to maintain the telescope in a centred position with the mirror axis in the horizontal direction (compensation of gravity).
The lifespan is fixed at 1 million movements.
The thermal conditions are not constraining since optics is located in a stable thermal environment (20°C+/-5°C).
To increase the reliability and to decrease the complexity of the mechanism, it was imposed not to use a locking device. All the efforts of the launch will thus be seen by the actuators. This is a very significant criterion for MCM dimensioning.
Finally the most significant specifications relate to the characteristics of the mirror to be supported and the strokes to be carried out :
- The mirror to be controlled and its fixture weight 3 kg and the overall dimensions fit in a 280 mm diameter for a 100 mm height
- The specified strokes amplitudes are of 70 µm in refocusing (Z), +/- 50 µm in transverse (x, y) and +/- 100 µrad in tilt (θx and θy).

3. CONCEPT
The concept selected is based on 3 vertical actuators which produce the focusing and tilts movements, and three horizontal actuators which produce the transverse movements. The system is controlled in closed loop.

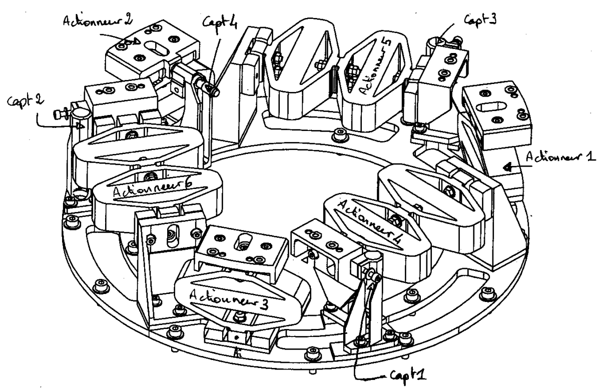
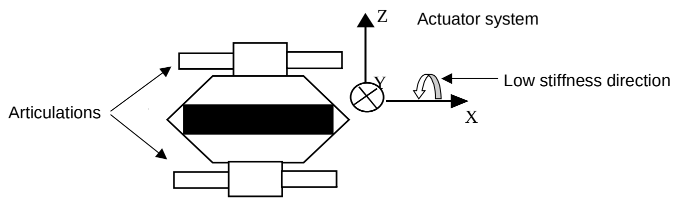


Figure 2 : View of the MCM

The mechanism motorization is ensured by piezoelectric actuators integrating a mechanical amplification.
The control of the mirror position is done by 5 capacitive position sensors.

4. ARCHITECTURE
The selected architecture for this mechanism is described below:
The focusing and tilts movements (movements according to Z, θx and θy) are produced by three vertical actuators APA120ML-PP placed at 120° on a 120-mm radius circle.
The transverse movements (movements according to X, Y and θz) are produced by three horizontal actuators made of APA120ML-PP pairs mounted in series and constituting the sides of an equilateral triangle set inside a 91 mm radius circle.
Other architectures have been studied, but the layout of horizontal actuators in this configuration ensure a best mechanism stiffness around the z axis, compared to a layout in star at 120°.
The architecture analysis gets to use articulations at ends of each actuator so that to decrease constraints in the actuators and parasitic stiffness which reduce the strokes.
As the standard articulations were not enough stiff meet the minimum eigen frequencies requirement, a specific development was necessary.
This induced to analyse a specific articulation, with a high axial stiffness (axial direction of articulation), so as to reduce the actuators stiffness requirement.
The designed articulation is a simple pivot made of a one-piece part in APX4 stainless steel material and with a low rotational stiffness around one axis. This joint allows articulating the actuator at each end according to the highest transverse actuator stiffness (around the horizontal axis of the actuator plan, see fig below).



The mechanism's rotation plan is located 40 mm under the mirror inferior plan.
The overall dimensions fit in a diameter of 280-mm and a height of 77-mm.

The mechanism uses piezoelectric actuators APA120ML-PP specially designed to meet its requirement.

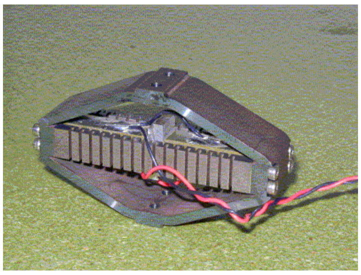


Figure 3 : The piezoelectric actuator APA120ML-PP

The displacement of piezoceramics is limited to some tens of µm. To overcome this limitation, the actuators integrate an elastic mechanical amplifier [1]. The solution consists of using a longitudinal piezoelectric actuator and an elliptic shell. In our case, the amplification is only of 2 in order to keep a good stiffness. The characteristics are synthetyzed in the table 4.

Displacement	µm	120
Blocked force	N	1400
Stiffness	N/µm	12
Voltage range	V	-20/+180
Dimensions	mm	H45/L79/W20
Mass	gr	185

Table 4 : Characteristics of the APA120ML-PP

The APA120ML-PP actuator is a more robust version of the APA120ML actuator. Therefore, thanks to an added pre-load of piezo ceramic by elastic spring and thanks to the change of frame material, the mechanical strength of the actuator has almost been doubled. It can withstand up to 1800N on the actuation axis.

The mirror positioning measurement is performed using 5 capacitive position sensors (FOGALE): 3 vertical sensors MCC10 type with a measuring range of 1 mm and 2 horizontal sensors MCC5 type with a measuring range of 0.5 mm.

Vertical sensors are set at 120° at tops of an equilateral triangle set inside a circle of 131 mm radius and aims directly at the rear side of the mirror interface. Z, Rx and Ry are the degrees of freedom measured by the 3 vertical sensors.

One of the horizontal sensors is oriented following –X in the axis of the mirror centre and has the mirror interface of a vertical actuator as the target : X and Ry are the degrees of freedom measured by this horizontal sensor.

The other horizontal sensor is oriented following –Y, with an offset of 93 mm from the mirror centre and has mirror interface of a horizontal actuator as the target : Y, Rx and Rz are the degrees of freedom measured by this horizontal sensor. The torsion movement of the mechanism is dissociated from this sensor reading by taking into account the supposed known value Rz (given rotation around Z axis of the mechanism done during the initialisation phase to put the horizontal actuators at their middle stroke).

The mechanism structure in aluminium material is composed of the mechanism's interface plates, the added brackets of the 3 horizontal actuators, the added brackets of the 5 position sensors and the mirror interfaces.

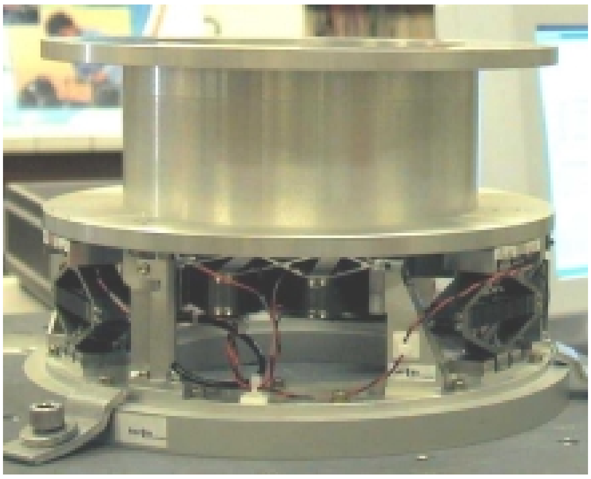


Figure 5 : the MCM and its dummy mass

The mechanism is controlled by a digital computer (PC) that includes an algorithm on LABVIEW ® software (initialisation of the demonstrator, sensors' data treatment, mirror centre position calculation, calculation values of the position difference between order and reading of mirror centre and actuators, command generation via an Integral Proportional type of correcting network) and a control interface under LABVIEW ® software (instructions acquisition and display of different parameters).

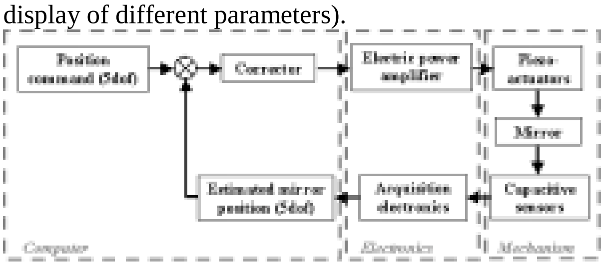


Figure 6 : Closed loop of mechanism control

5. THEORETICAL PREDICTIONS

Assembly stiffness, strength to mechanical constraints :

To predict the mechanism behaviour during launching phase (minimum stiffness for a first mode above 150 Hz, normal modes and mechanical strength characterisation), a finite element model of the mechanism has been developed using NASTRAN ® software.

The main characteristics of the finite element model are the listed below:

- actuator modelled by a beam / springs system allowing to take into account the coupling terms of the actuator stiffness matrix ;

- articulation at each end of the actuator modelled by stiffness introduced on 6 springs elements
- amplification factor hypothesis : Q = 100 for articulations, Q = 50 for actuators

The capability of APA120ML PP actuator to withstand launch constraints corresponding to a 60g acceleration response at mirror level, is demonstrated by the stress calculation in the shell and the piezo from constraints calculated in the actuators with the finite element model of the mechanism.

The articulation strength is validated by applying calculated constraint in spring elements of the mechanism finite element model to a volumic finite element model of the articulation.

The first mechanism mode predicted is a transverse deflection of the mechanism at 238 Hz.

Kinematic domain:

A mechanical model developed on MATLAB ® software allows to simulate the behaviour of the controlled mechanism. The model includes:

- a piezoelectric actuators module with their electrical model ;
- the capacitive position sensors module ;
- a control module including the generating of actuator orders, the correcting networks and the usual defaults of sensors.

The model objectives were:

- to determine the optimum architecture of the mechanism ;
- to analyse and optimise the control ;
- to analyse the dynamic behaviour of the mechanism under the vibration environment.

The analysis with the MATLAB ® software model shows that the mechanism is able to do the specified movements in the specified accuracy in orbit and at ground level.

6. FUNCTIONAL TESTS

The goal of the functional tests was to define the kinematic zone reachable by the mechanism. They were carried out in three steps : functional test with vertical optical axis, test with horizontal optical axis, test after vibrations with vertical optical axis.

The mechanism was piloted by a computer and a test electronics. The control/command software integrates a proportional / integrator corrector. According to this, for a step command, the system is stable and responds in 500ms without overlap. The slow device dynamics was chosen in purpose. Indeed, the goal of this application is to compensate the long and medium term drifts due to thermoelasticity.

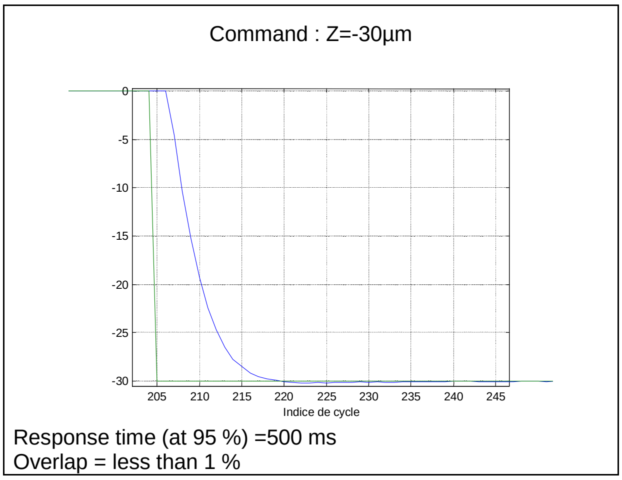


Fig 7 : Step response

The kinematic domain described in the specification is respected in its very broad part. Only two extremities of this zone remain inaccessible despite the theoretical predictions. They are the cases where the vertical actuators are supplied in negative voltage. Indeed, they are quickly limited by the voltage available (-20V). The critical points correspond to the configurations where the system is at its maximum position in Z and when we want to realize a tilt displacement combined on the two transverse axes : either Ry max and Rx max, or Ry min and Rx min. All the remainder of the kinematics domain is respected, with a large part over the specification.

The graph Fig8 shows the specified and real displacements amplitudes on the critical zone.

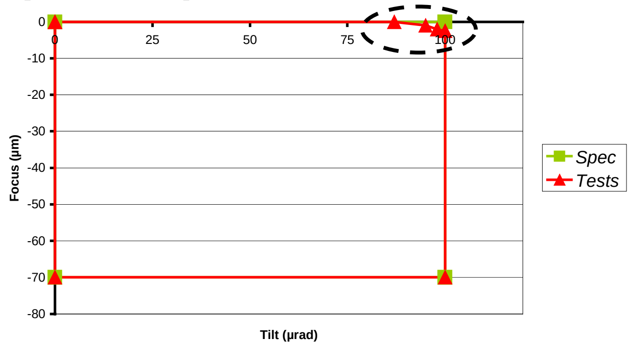


Fig 8 : Displacements domain (specification and tests)

The variations between theory and tests can be explained by the fact that the stiffness of the articulations were not taken into account in the kinematic model under MATLAB ® software. These stiffnesses exert a resistant effort, limiting the elongation amplitude of the actuators.

7. VIBRATIONS TEST

For the vibrations test, the demonstrator was equiped with a dummy mass representative (with respect to mass and inertia) of the mirror and its fixture. The instrumentation was composed of 3 tri-axes accelerometers laid out above each vertical actuator.

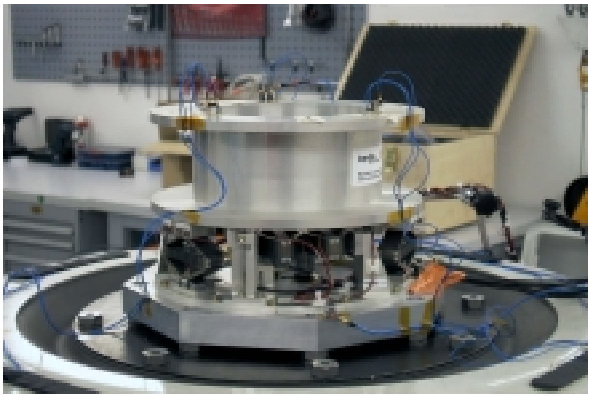


Figure 9 : MCM during the Z vibrations test

The piezoelectric actuators were connected in short-circuit. Indeed, the electromechanical coupling can lead to the ceramics destruction (by electric breakdown), due to the generation by the actuators of a too high voltage. Wiring in short-circuit also allows to avoid a nonlinear behaviour of piezoactuators (their apparent stiffness varies according to the voltage applied).
The principal natural frequencies identified during the test are as follow :
- 155Hz : Rx and Ry flexion mode
- 234Hz : Rz torsion mode
- 330Hz : Z axis mode

These results are below the values computed by finite elements. These variations between model and test can be explained by the use of brackets to support the horizontal actuators which were not taken into account in the FE model.
The MCM demonstrator underwent mechanical tests at qualification level, according to the ECSS standard
sine (5-100Hz) : up to 30g peak-to-peak for each axis
random (25-2000Hz) : maximum of 0.1g²/Hz between 100 and 500Hz for each axis, but with notchings on the 330Hz mode for the Z axis and on the 234Hz mode for the X and Y axes(which results in 10.5grms).
During the tests along the axes perpendicular to the optical axis, the sine solicitation highlighted the strong influence of the first mode (bending mode at 155Hz) in its range of excitation where the output reach 60g at 100Hz. For random excitation, it was noted the presence of a second significant mode at 310Hz which has required the addition of notching.
No modification of the structural characteristics of the system was observed, nor deterioration of the piezoactuators performances.
The measurement of the electric current generated by the electromechanical coupling shows that the sine vibrations are more dimensioning in term of effective power, while the random vibrations lead to higher peaks of power. The highest electric output is produced by the horizontal actuators during the transverse vibrations. These actuators are mechanically in series and electrically in parallel. Thus, during the sine test on the Y axis, a horizontal actuator has generated $0{,}37A_{RMS}$ at 100Hz.
One shall not neglect the effect of the electromechanical coupling of piezoelectric ceramics (which here was cancelled by a wiring in short-circuit) for a complete system mechanism / electronics. In a first approach, one can say that a flight configuration would be mechanically more favourable and electrically less favourable than the test configuration. It will be then important during the design of the command electronics, to think about voltage protections such as Zener or Transil diodes, which will also dissipate a part of the electric power produced.

8. MICROVIBRATIONS TEST
The aim of the microvibrations test was to measure on one hand the disturbances generated permanently by the mechanism in stand-by (controlled in closed loop), and on the other hand the transitory disturbances generated during a movement.

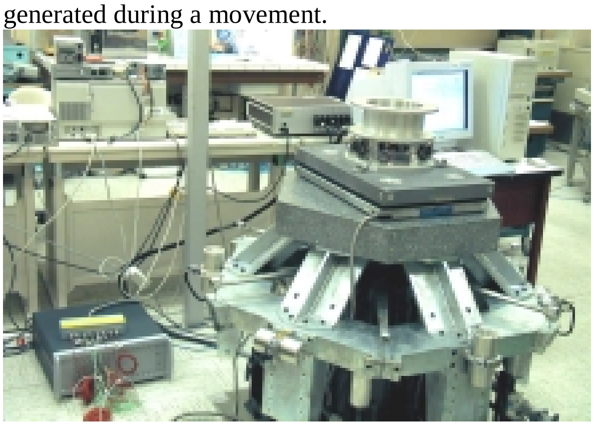


Figure 10 : the lay out for the microvibrations tests

The frequencies of the identified disturbances are those of the MCM structure. Their amplitudes depend on electronics and the control mode (the slowest is the response of the system, the most quiet it is).
The internal electric noise of the control loop, due in particular to the capacitive sensors, is changed into mechanical noise by the actuators. The measured amplitudes are however low (some hundredth of Newton and some thousandth of Newtonmeter). Their lowest frequency is the first eigen frequency of the structure (155Hz).
The transitory forces created at the satellite interface during a displacement were evaluated for each of the 5 active DOF. The slow response time of the command makes it possible to limit the amplitude of these transients.

9. ENDURANCE TEST
This test was intended to validate the behaviour of the mechanism and in particular the stability of the positioning for a constant command over a long period. The endurance test thus consisted in positioning the MCM on a given coordinate using the 5 controllable axes. In order to simulate repositioning movements that

would be ordered to the MCM in orbit, the command permuted between two distinct instructions on each axis. The period of these permutations was about 4h.
The endurance test has evaluated the stability of the mechanism during more than 350h. The MCM lifespan is in fact only dependent on the actuator's one. The APA piezoactuators were previously qualified to 10^{10} cycles of displacement (full stroke). This concept is compatible with this application, knowing that for a typical mission of 5 years, the number of actuations can be estimated to 10^6.
The control noise remained stable during the test : 0.015µm in focus, 0.05µm in transverse and 0.15µrad in tilt. Complementary tests are in progress to determine the absolute positioning error of the system. For this, a 5 axes optical test bench will be laid down.
It was observed that the closed loop control allows to mainly compensate the internal thermal expansions in the MCM, as well as the intrinsic hysteresis of piezoceramics.
Finally, the electric power consumed by the MCM in stand-by mode was evaluated to 120mW. Which is negligible compared to a classical electronics electric power.

10. CONCLUSION

A Mirror Control Mechanism, intended for a M2 mirror of Cassegrain telescope, has been designed, manufactured and tested. This mechanism is able to control any type of axisymmetric mirror within 5 degrees of freedom. It presents the main following characteristics :

- 5 DOF of actuation : about 100µm stroke in translations and 200µrad stoke in tilts
- high positioning accuracy (some tenth of µm and some µrad) thanks to the use of piezoelectric actuators
- High stiffness and resistance to launch load without locking device (for a 3kg mirror)
- overall dimensions : ∅280mm / H77mm
- mass : 3.5kg (without electronics)
- power in hold mode : about 120mW

The most important lesson learned from this study is the high influence of the electronics on the mechanical behaviour of the MCM. The control electronics will define the amplitude of the microvibratory disturbances and can be use to dissipate a part of the launch load energy.
This concept can be adapted to smaller versions of mirror requiring an active control, and in a more general way to equipments for which the pointing precision is a key requirement.

11. REFERENCES

[1] R. Le Letty, F. Claeyssen, G. Thomin : « A new amplified piezoelectric actuator for precise positioning and semi-passive damping », 2nd space microdynamics and accurate control symposium, 13-16 May 1997, Toulouse

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