Last progress concerning the design of the piezo-stack M4 adaptive unit of the E-ELT

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ABSTRACT

CILAS proposes a M4 adaptive mirror (M4AM) that corrects the atmospheric turbulence at high frequencies and residual tip-tilt and defocus due to telescope vibrations by using piezostack actuators. The design presents a matrix of 7217 actuators (triangular geometry, spacing equal to 29 mm) leading to a fitting error reaching the goal. The mirror is held by a positioning system which ensures all movements of the mirror at low frequency and selects the focus (Nasmyth A or B) using a hexapod concept. This subsystem is fixed rigidly to the mounting system and permits mirror displacements. The M4 control system (M4CS) ensures the connection between the telescope control/monitoring system and the M4 unit - positioning system (M4PS) and piezostack actuators of the M4AM in particular. This subsystem is composed of electronic boards, mechanical support fixed to the mounting structure and the thermal hardware. With piezostack actuators, most of the thermal load is minimized and dissipated in the electronic boards and not in the adaptive mirror. The mounting structure (M4MS) is the mechanical interface with the telescope (and the ARU in particular) and ensures the integrity and stability of M4 unit subsystems. M4 positioning system and mounting structure are subcontracted to AMOS company.

Keywords: Adaptive optic, Adaptive unit, E-ELT, hexapod, mirror, PZT actuator

1. INTRODUCTION

ESO has initiated in October 2007 a preliminary study [1] (part of phase B) to demonstrate the feasibility of the M4AU, adaptive unit with an adaptive mirror ϕ2,7 m, for the European extremely large telescope (E-ELT). This telescope has a novel 5 mirror design [2] [3] including the adaptive mirror in the telescope, explaining its exceptional size.
CILAS has proposed, in partnership with AMOS, BOOSTEC, ONERA, Observatoire de Paris Meudon a concept based on piezostack technology [4] that fulfills all the requirements (no show stopper identified). Breadboards and demonstration prototype [5] are manufactured and tested to validate our assumptions and to mitigate the risks.

2. ANALYSIS OF THE MAIN REQUIREMENTS

The M4AU is designed in collaboration between CILAS (Orléans in France) and AMOS (Liège in Belgium). It consists of four main units: The M4AM (adaptive mirror), the M4CS (control system) designed by CILAS, and the M4PS (positioning system) and M4MS (mounting structure) designed by AMOS.
The main function of the M4 adaptive unit is to correct the aberrations of the wave front due to the following perturbations:

- Atmospheric turbulences

- Telescope vibrations and deformations
- Wind

The M4AM corrects the atmospheric turbulences at high frequencies by using piezo electric actuators. This subsystem is fixed to the M4PS.

The M4PS ensures all movements of the M4AM at low frequency and select the focus (Nasmyth A or B). It corrects essentially the telescope deformations (gravity and thermal load). This subsystem is fixed rigidly to the M4MS and permits M4AM displacements. The different kinds of displacements are:

- Translation movements
- Tip/tilt movements
- Rotation to address the Nasmyth foci

The M4CS ensures the connection between the telescope control / monitoring system and the rest of the M4AU (the adaptive mirror and the positioning system in particular). This subsystem is composed of electronic boards, mechanical support fixed to the M4MS and the thermal hardware. With piezo actuators, most of the thermal load is minimized and dissipated in the electronic boards, not in the adaptive mirror. The thermal architecture is simplified.

The M4MS is the mechanical interface with the telescope (and the ARU in particular) and ensures the integrity and stability of M4AU subsystems.

We not intend here to summarize all the requirements but to explicit those that impact the overall architecture:

- Mirror outer diameter is 2,7 m and inner diameter is 0,7 m, slightly elliptical (2 %). Regarding the slight ellipticity, the mirror will be circular and will be the largest adaptive mirror ever built.
- The fitting error shall be less than 145 nm leading to a very high quantity of actuators. The analysis performed by ONERA showed that around 7217 actuators are necessary in a triangular meshing to reach the fitting error goal of 110nm.
- Correction capability of the mirror (see analysis in next paragraph). The desired stroke is proportional to the length of the actuators and directly linked to the thickness of the mirror.
- First eigen frequency shall be higher than 20 Hz. As a consequence, the structure shall be very stiff.
- Mass shall be lower than 10 tons involving the use of lightweight parts such as the mirror base plate made of silicon carbide.
- Local flatness shall be less than 15 nm. No print through are admitted. The interface between the actuator and the optical plate shall be designed carefully. Nevertheless, the type of performances was achieved with previous design made by CILAS.
- Global flatness shall be lower than 250 nm. In open loop, this requirement is easily reached by the stroke correction provided by the PZT actuators. In open loop, we shall minimize the impact of the creep and the hysteresis of the PZT actuators. A breadboard is dedicated to the demonstration of these performances.
- The temperature of all external surfaces of the M4AU including the surface of the mirror itself, in the absence of wind shall not differ from that of the ambient air by more than ± 1 ºC. Our thermal architecture is based on the following assumptions: Passive thermal control of the external covers (low inertia, thermally decoupling with the housing structures), exchanges with the sky limited (-50 °C), no internal dissipation in the M4AM, cooling fluid reserved to M4CS dissipation since no internal dissipation in the M4AM.
- Cross coupling of the positioning system shall be less than 0,25 arcsec and less than 0,025 arcsec during any time period of 0,2 s. This requirement is challenging for the hexapod and greatly impacts the quality of the mechanical pieces of the hexapod but also the strategy of command of this sub system.
- MTBF better than 3 years, lifetime 30 years leads to use reliable technologies and to develop specific maintenance concepts (including preventive ones)
- Power consumption shall be lower than 8 kW.

3. OVERVIEW OF THE PROPOSED DESIGN

The M4 adaptive unit is part of the Adaptive Relay Unit (ARU) tower of the E-ELT (see Figure 2). The optical beam coming from the M2 crosses the mirror in its centre and is reflected by the M3, located bellow the M4. The M4AU shall then reflect the optical beam from M3 to M5, the tip/tilt mirror. The M4AU is attached to the ARU tower in 6 points. A dedicated tool (figure 1) is designed in order to store and transport the unit to the load area close to the telescope, to support and interface the unit with the crane integrated in the telescope and to be compatible with the integration procedure of the unit in the tower.

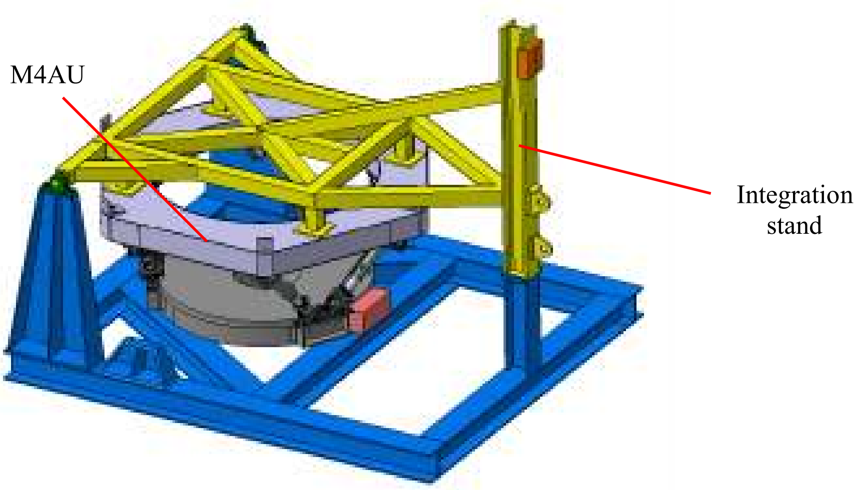


figure 1: The M4 adaptive unit installed in the integration stand

The preliminary design of the M4AU is presented in Figure 3. The next paragraphs give a brief description of the four sub systems of the M4AU.

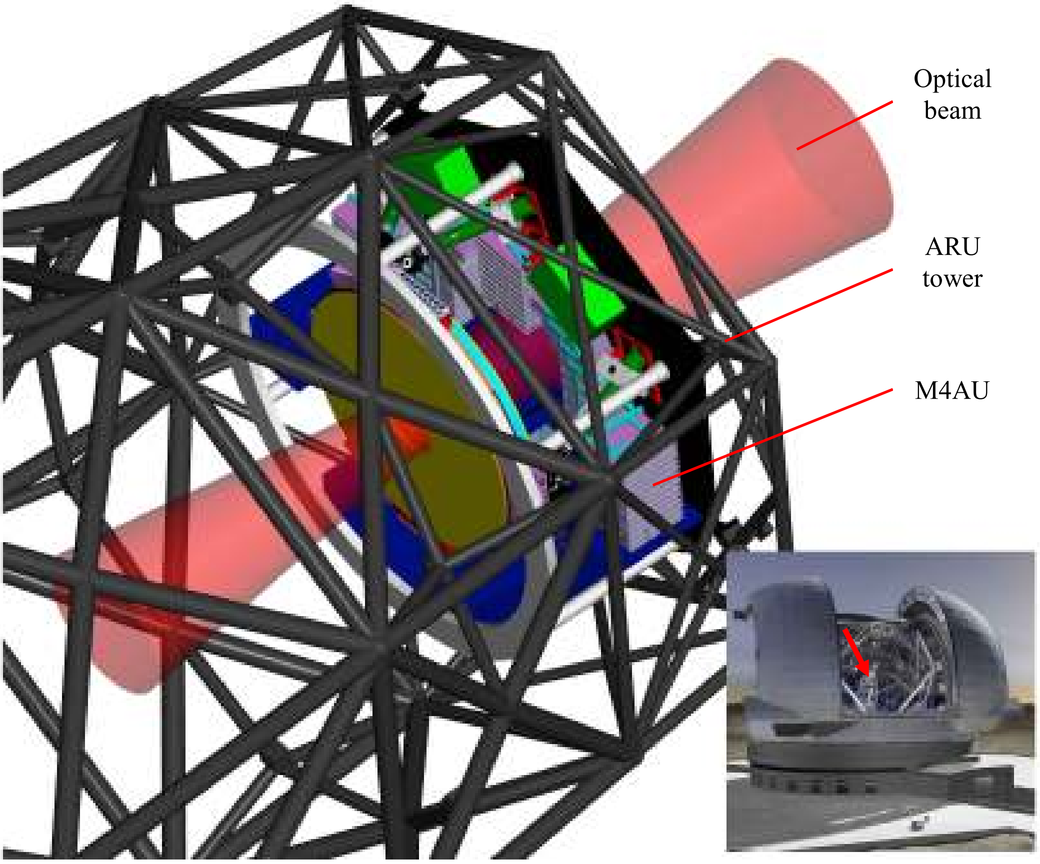


Figure 2: The M4 adaptive unit fixed on the Adaptive Relay Unit (ARU) tower of the E-ELT

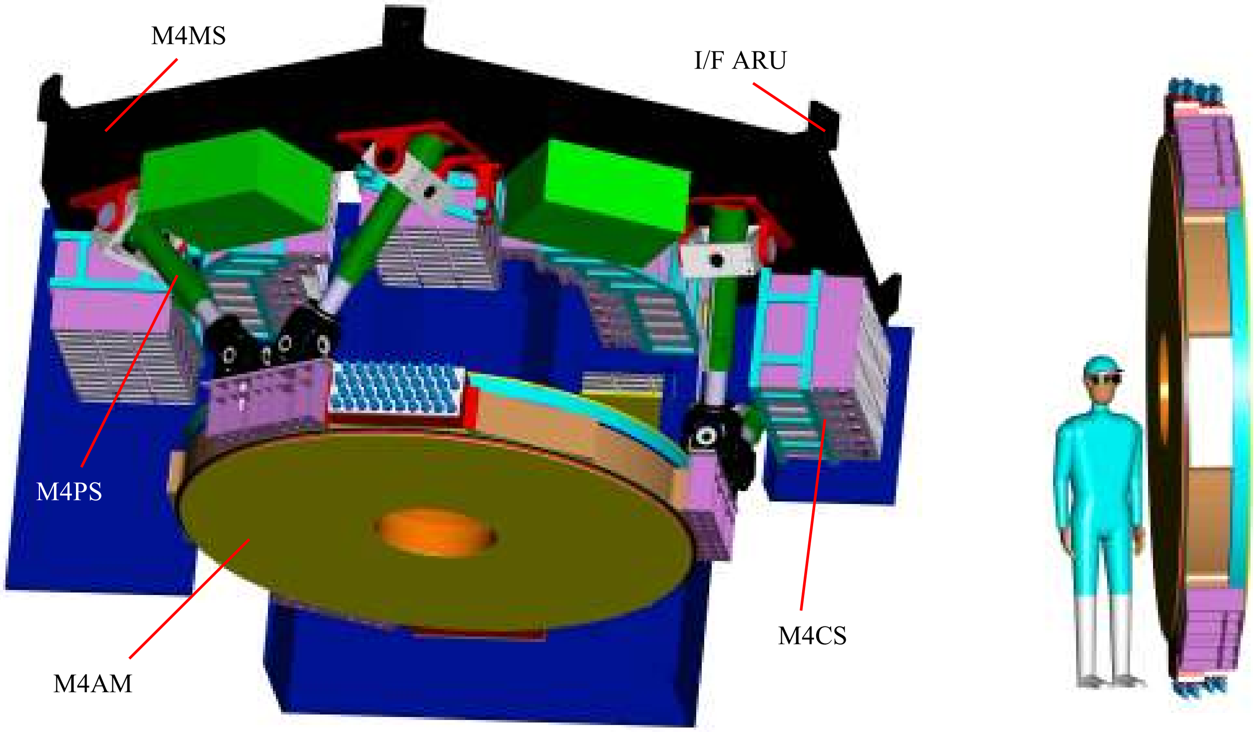


Figure 3: Preliminary design of the M4 adaptive unit of the E-ELT (left, the whole M4AU/right, the relative size of the M4AM)

The deformable mirror (M4AM) is mainly composed of the following assemblies:

- The optical plate, made in Zerodur®, has a specific shape with tips and is rigidly mounted on the PZT actuators. In front of the actuators, the thickness is 15 mm, while between tips of 6 mm. This specific shape has been design to minimize the print through effect. The Zerodur® has been chosen because of its exceptional return of experience in large size and CTE close to the silicon carbide one.
- The actuators are arranged in a triangular geometry with an inter actuator spacing of 29 mm. The actuator is an assembly of several pieces: The optical plate interfaces, the head actuator, the piezo-stacks and the rear part (Figure 4). The optical plate interface has a specific shape to reduce the stress induced into the optical plate during deformation. The piezo-stack is a multilayer assembly made of hard piezo electric material and is the key part of the actuators. The stroke is proportional to the quantity of PZT layers (current design set to 400 plates of 0,5 mm). The rear part (made of ceramic) allows the insertion of the electric contact and the adjustment on the fixing base plate.

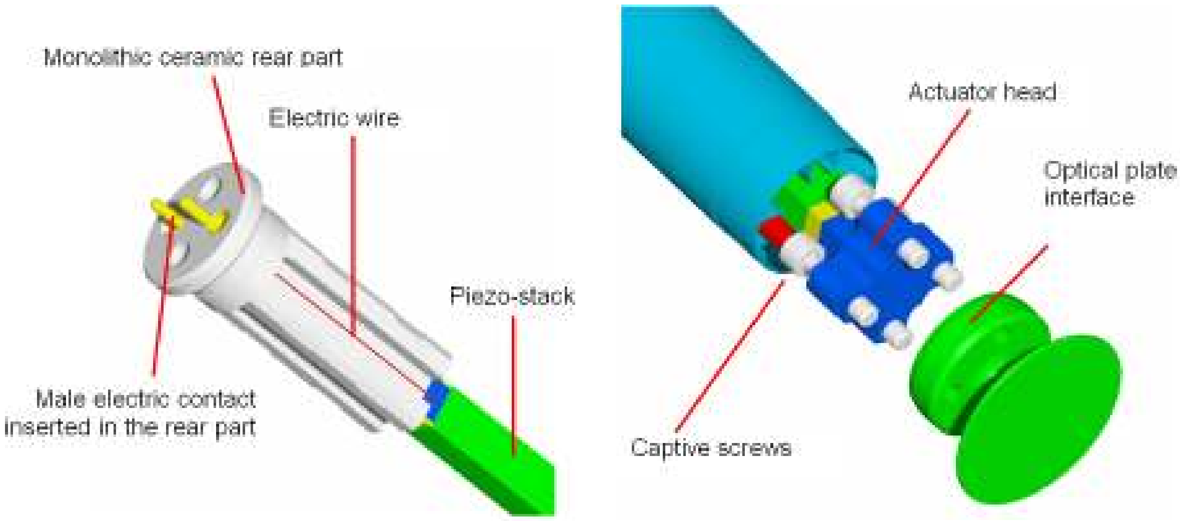


Figure 4: Preliminary design of the PZT actuators (Left: Rear part, Right: Optical plate interfaces)

- The base plate is made of the structural base plate and the fixing base plate. The structural base plate is made of silicon carbide and has a thickness of 250 mm. The main function of this base plate is to provide stiffness to the mirror. Due to the large size of the mirror, this plate is not made in one piece but composed of 6 petals brazed together. The piece shall be drilled of so many holes as the actuators. Finally, mass constraints involve its lightweighting leading to a detailed Finite Element Model analysis. BOOSTEC has been chosen for the manufacturing of this critical part and was associated throughout the design. The fixing base plate made in Invar is attached to the structural base plate and permits the accurate fixing of the actuators at the back side of the mirror (see Figure 5). The invar exhibits a low CTE and limits the bi metallic effect to a minimum value.
- High voltage distribution PCBs close to the actuators simplify the electrical connection and provide access to the actuators if exchange is required.
- High voltage electric mixing boxes are surrounding the mirror and permit to choose spatial distribution of each 96 actuators of a high voltage driver. They are located along the Nasmyth rotation axis to avoid stress in the cables during each focus selection.
- Covers (central, front and rear) protect the mirror from dust and humidity.

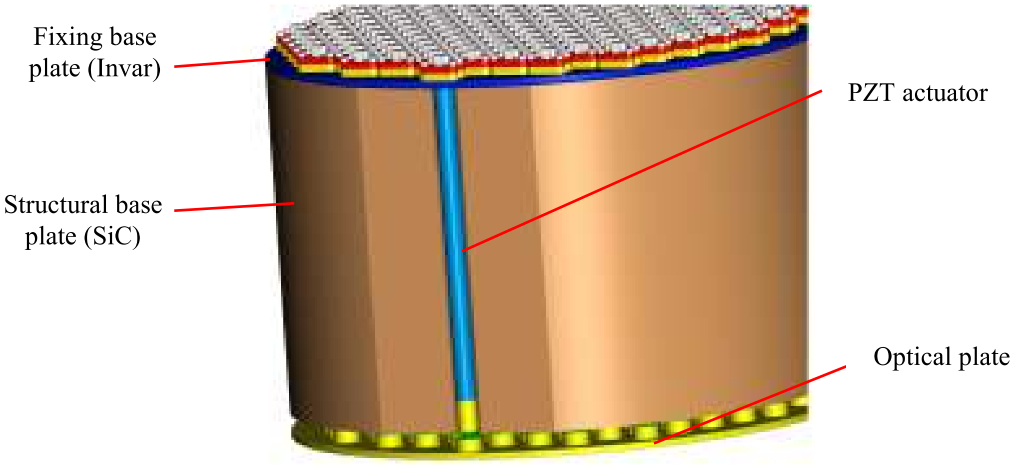


Figure 5: Cut view of the M4 adaptive mirror showing the integration of a PZT actuator in the mirror

The positioning system (M4PS) is a hexapod. The six feet, holding the mirror, are fixed on the mounting structure (see Figure 3). The hexapod allows the M4 positioning and switching between focal stations. A foot is composed of one actuator and two cardans. By actuator we mean: One servomotor, one reduction gear and one linear actuator. An encoder is placed in parallel with each actuator.

- The actuator chosen use satellite roller screw technology to reach highest possible stiffness. The stroke is of 400 mm and the stiffness of actuators is announced to be higher than 200 N/µm. The mass of the linear actuator would be 170 kg. Each actuator is equipped with two limit switches (one at each extremity) and with a linear encoder. This one is positioned along the actuator and the I/F between actuator rod and encoder is made in Invar (to avoid thermal lengthening).
- Support cardans are composed of a structure and preloaded bearings to avoid backlash. The radial run-out of the bearing is estimated to be about 10 µm max (on 360° rotation)
- Mirror cardans use the same bearings and a dedicated structure. Centring pin is foreseen in the face in contact with the M4AM. This stud would have to allow a repositioning of about 25 µm.
- Decoupling bearings: A bearing should take back the rotation induced on the actuator by the different possible configurations of the hexapod.
- Linear encoder: The actual encoder is manufactured by Heidenhain. It's made of Diadur® and Zerodur®. The accuracy of this system is about +/-0.5 µm. The reading head will me mounted on two mini-carriages whose rail is connected onto the supporting plate with the actuator. The encoder scale is also connected on this interface.

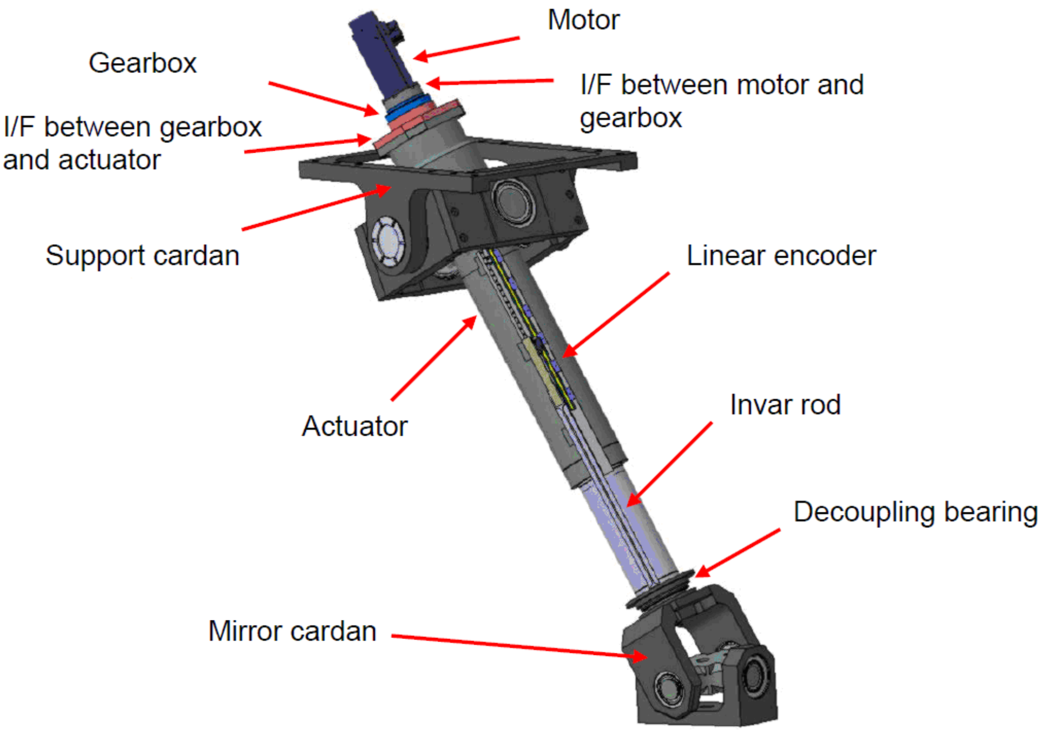


Figure 6: CAD view of a hexapod foot

The M4MS is made of shell elements and consists in a frame box with triangular outer shape and vertical stiffeners. All shells present a thickness of 6 mm. The M4MS is made of steel (Fe 510C) and for a total mass of about 1.5 tons.

The M4CS (control system) is the electronic part of the M4AU. This electronic drives the M4PS and the M4AM piezo actuators with high voltages (in the +/- 400 V range). All the actions made by the M4CS in order to drive the M4AM and the M4PS are due to external orders received from the TCS (telescope control system) and the RTC (real time controller). The M4CS is also in charge of the housekeeping of the M4AU. The Figure 7 shows the functional architecture of the M4CS. The main equipments of the M4CS are the AM Drivers, the M4CS Control Units, the I/O Control Unit and the PS Driver cabinets.

- The AM Driver generates the high voltage applied to the actuators. These high voltages are generated from the commands send by the M4CS Control. The AM Driver checks the good working order of each high voltage amplifier channel. Moreover, it can test each actuator line continuity and actuator capacitor during continuous operation (38 units including 2 AM driver boards driving each 96 actuators).
- The M4CS Control is in charge of the data exchange with the TCS and the RTC and the main internal sub systems, the computation of actuator commands and tilts command, the change of mode and the control of the modes as well as the housekeeping of the M4AU.
- The I/O Control Unit performs the control of the AM Drivers according M4CS Control orders, collect of the signals coming from the sensors and manage the power supplies of the AM Drivers and of the PS Driver.
- The M4PS is controlled by the M4CS PS Control (2 cabinets)

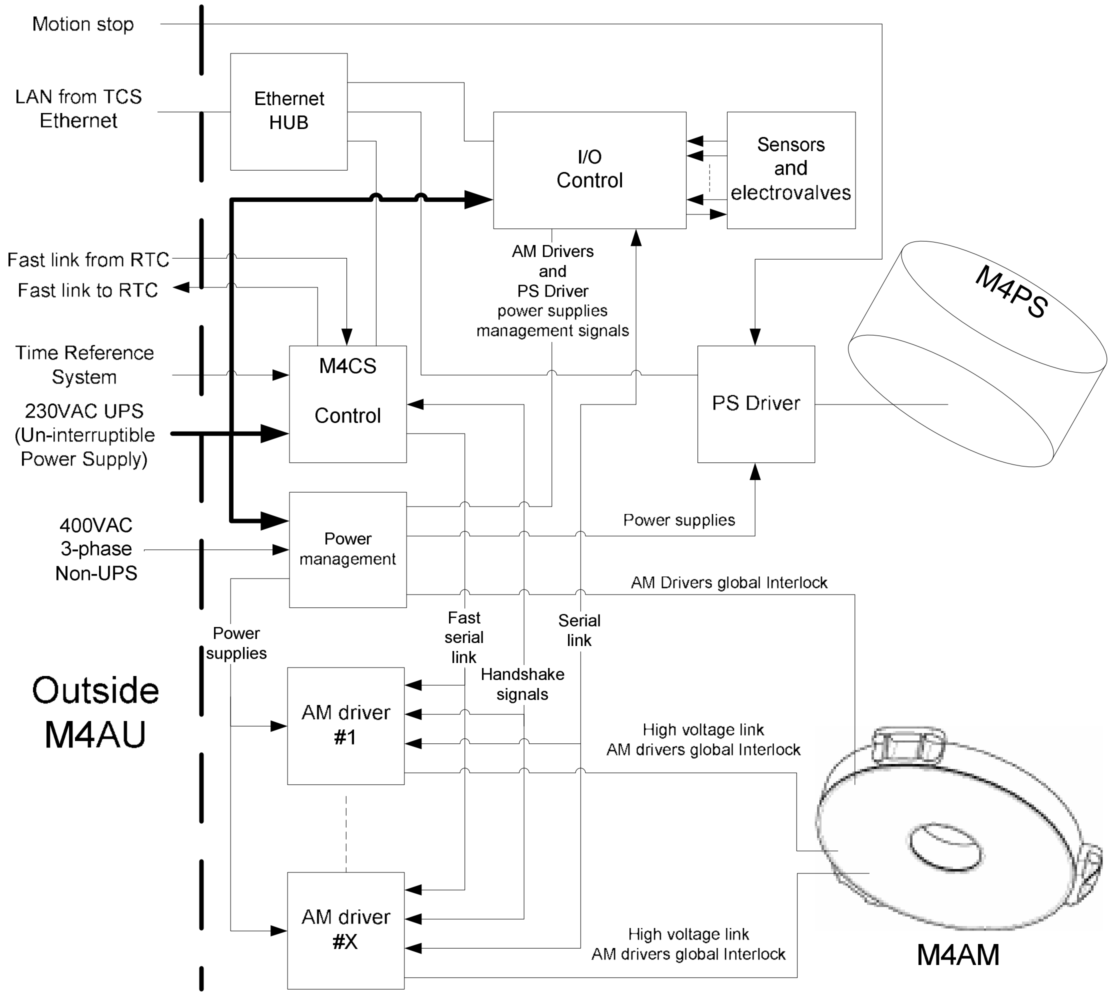


Figure 7: Functional architecture of the M4CS

4. PERFORMANCES ANALYSIS

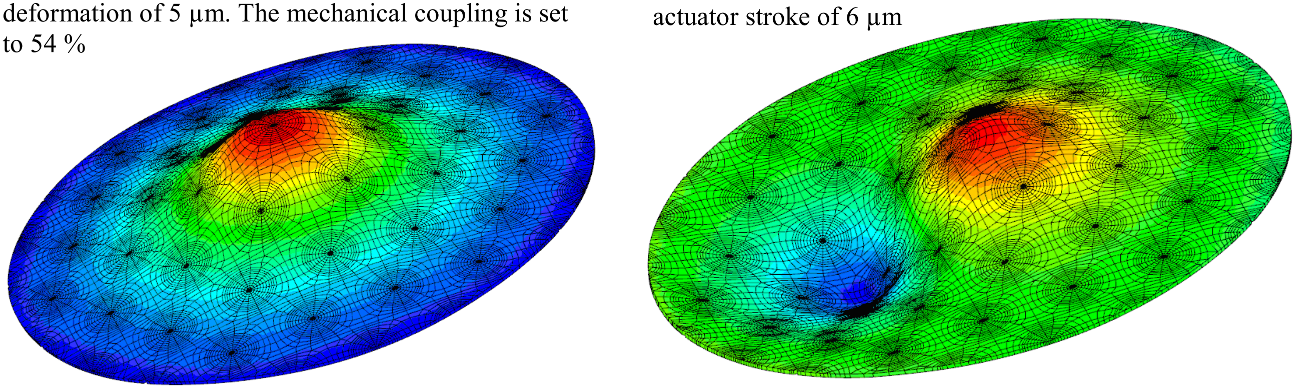
The stroke need for the mirror is decomposed of so-called “static correction” and “dynamical correction”.

- Static stroke: 37 µm (PV), corresponds to the stroke allocated to the compensation of the optical residual after polishing, the deformation of the mirror in thermo-gravity load and telescope optical error compensation.
- Dynamical stroke: 50 µm (PV), value resulting from the quadratic sum of the following contributors:
  Turbulence without tip-tilt = 32 µm (PV), in worst seeing case, seeing 2.5 arcsec at 0.5 microns: 2.5 arcsec)

Residual tip-tilt after M5 = 38 µm (PV)
Telescope defocus = 7 µm (PV)

Summing these two contributions, we obtain a requirement for the total stroke of 87 µm. Our present design allows a stroke capability of 96 µm.

The following figure shows the typical influence function as well as the inter-actuator stroke capabilities. Figures are extracted from FEM analysis but the stroke values come from experimental values measured on our breadboards.



Single push operation at +400 V leading to a deformation of 5 µm. The mechanical coupling is set to 54 %

Push-pull operation at +/-400 V leading to an inter-actuator stroke of 6 µm

Figure 8: Influence function (left) and inter actuator stroke of the M4 adaptive mirror (right)

On M4, the pitch is 29 mm, the pupil is assumed circular with an inner diameter is 697.6 mm and the outer diameter is 2636 mm. This means that the ellipticity is neglected which is probably a good approximation since the issues addressed here mainly concern the validation of the actuator inner ring implantation and ellipticity hardly affects the geometry at the occultation level. The equivalent pitch in M1 space is 0.462 m. In the triangular geometry the theoretical fitting analytical expression reads:

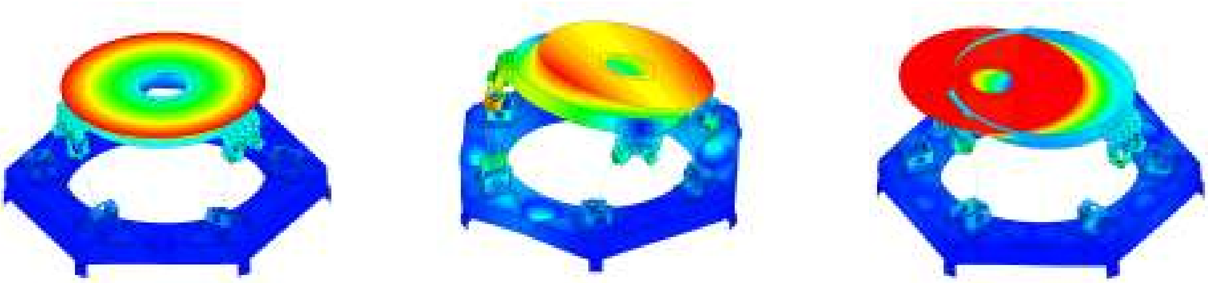
$\sigma^2_{\text{fitting}} = 0.200\ .(\text{pitch}/\text{r0})^{5/3}$. With a total quantity of actuators of 7217, this gives an expected value for the so called fitting error of 108 nm. The numerical calculation are in good agreement with the analytical formulas.

The first mode of the M4AU appears at 27 Hz, which is higher than ESO specifications (>20 Hz).
The following figures present the first modes of the M4AU.

Mode 1 @27 Hz
Hexapod mode with rigid body translation of the M4AM along Y-axis.

Mode 2 @27 Hz
Hexapod mode with rigid body translation of the M4AM along X-axis.

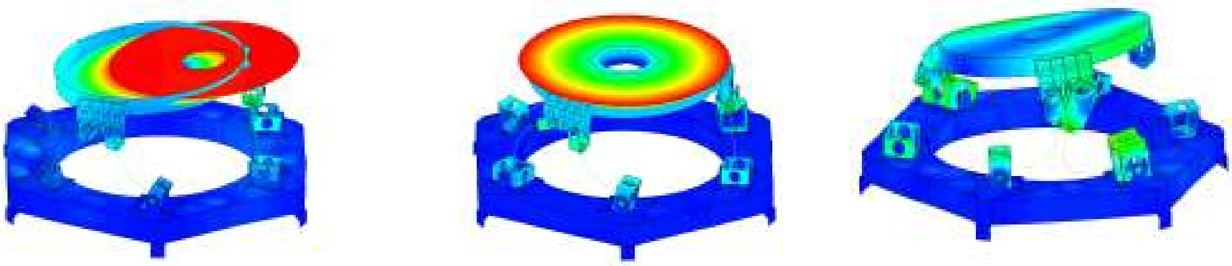
Mode 3 @40 Hz
M4MS local mode ; no influence on the M4AM
(modes 4 to 9 are similar to mode 3)



Mode 10 @45 Hz
Hexapod mode with rotation of the M4AM around Z-axis

Mode 11 @51.4 Hz
Hexapod mode with tilt of the M4AM around X-axis
(mode 12 is similar with a tilt around Y-axis)

Mode 13 @58.1 Hz
M4AM actuators mode with tilt of the M4AM around X-axis and translation of the optical plate along Y-axis



Mode 14 @58.1 Hz
M4AM actuators mode with tilt of the M4AM around Y-axis and translation of the optical plate along X-axis

Mode 15 @58.7 Hz
M4AM actuators mode with rotation of the optical plate around Z-axis

Mode 28 @70.3 Hz
Hexapod mode with tilt of the M4AM around X-axis
(mode 29 is similar with a tilt around Y-axis)

Figure 9: M4AU first modes

Thanks to the return of experience of the tests performed on the demonstration prototype [1], a state space model is built to simulate the transfer function of the whole system. This work is still on going.

The positioning error budget has been analysed by means of a dynamic model developed with MatLab Simulink. M4PS is modelled as an assembly of 6 independent actuators. Each of them is described as a spring-mass model: motor+reducer, screw, mirror mass (see Figure 10).

The stiffnesses are the reducer's one (T1) and an equivalent stiffness (T2 in rotation, F2 in translation) that experiences an eigenfrequency of 27 Hz considering a load of one sixth of the mirror mass.

An external force is introduced to simulate the gravity force (F_{ext} is the axial force seen by the actuators, and varies as a function of elevation angle).

Friction is introduced on each mechanical element. Karnopp model with Stribeck effect is used for this purpose.

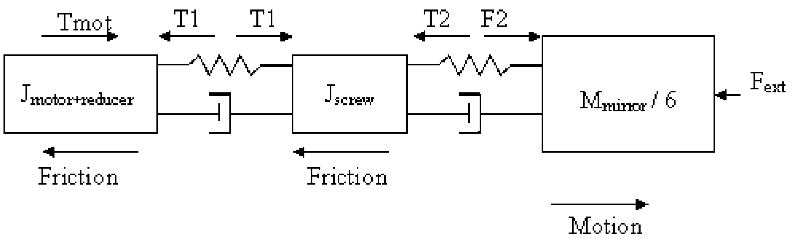


Figure 10: Spring-mass model of one actuator

Simulated trajectories of M4PS are introduced in the model (see Figure 11). Velocities and accelerations are limited for each hexapod axis and converted in position setpoints for each actuator (Inverse kinematics bloc). The actuators are commanded separately and the current M4PS position calculated (Direct Kinematics bloc).

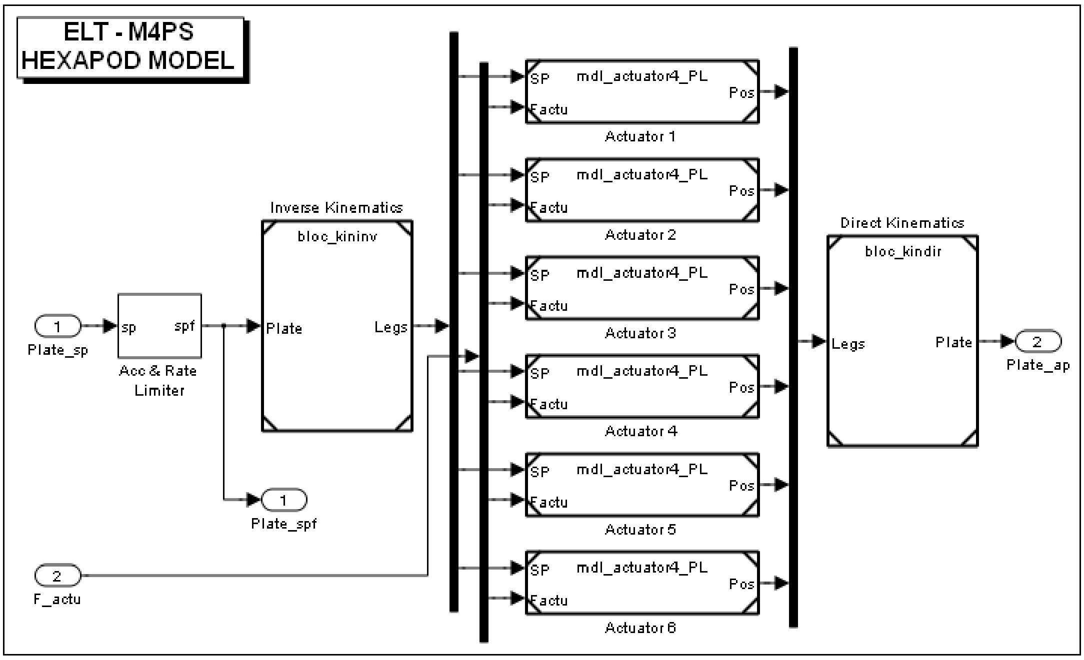


Figure 11: Simulink model of the positioning system

An overview of actuator model is presented on Figure 12. Physics laws of the spring-mass model (including friction) are introduced in the corresponding block. It calculates velocities and positions of each element from motor torque and external force. The motor and amplifier dynamics is also introduced, so that cogging and ripple influence can be studied. The control algorithm is based on a velocity loop closed (PI + notch filter) on the motor resolver and a position loop (PID) closed on a linear encoder.

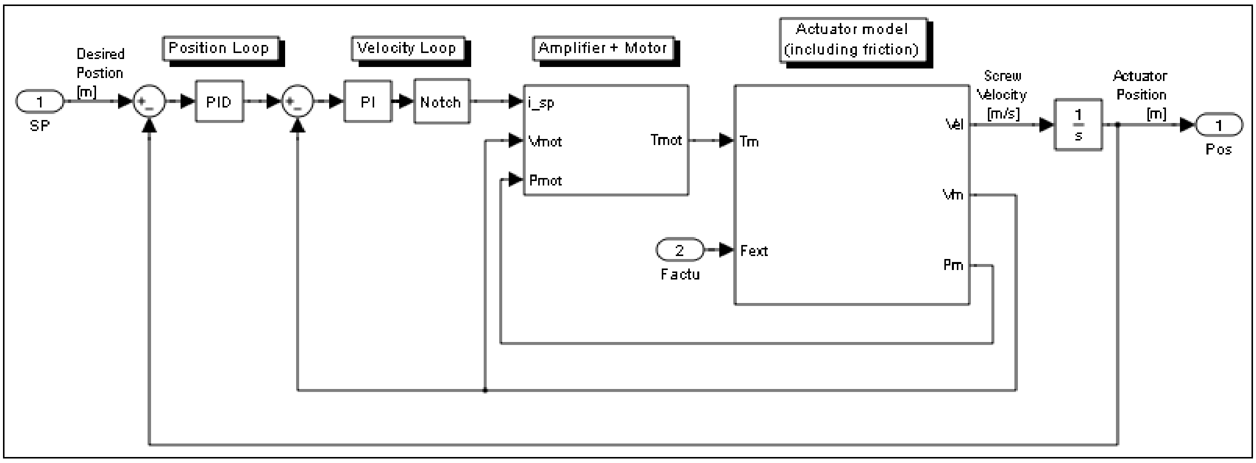


Figure 12: Simulink model of one actuator

Simulink model allows simulating any motion of M4PS. Here is an example of translation along x-axis by means of small steps of 20 µm (a change of direction is considered after 20 seconds of simulation).
Figure 13 shows the positions of each axis of M4PS (TX, TY and TZ above, RX, RY and RZ underneath).

Figure 14 shows the following errors (difference between setpoint and current position) of each axis of M4PS. Values mentioned on the plots are the maximum amplitude of errors.

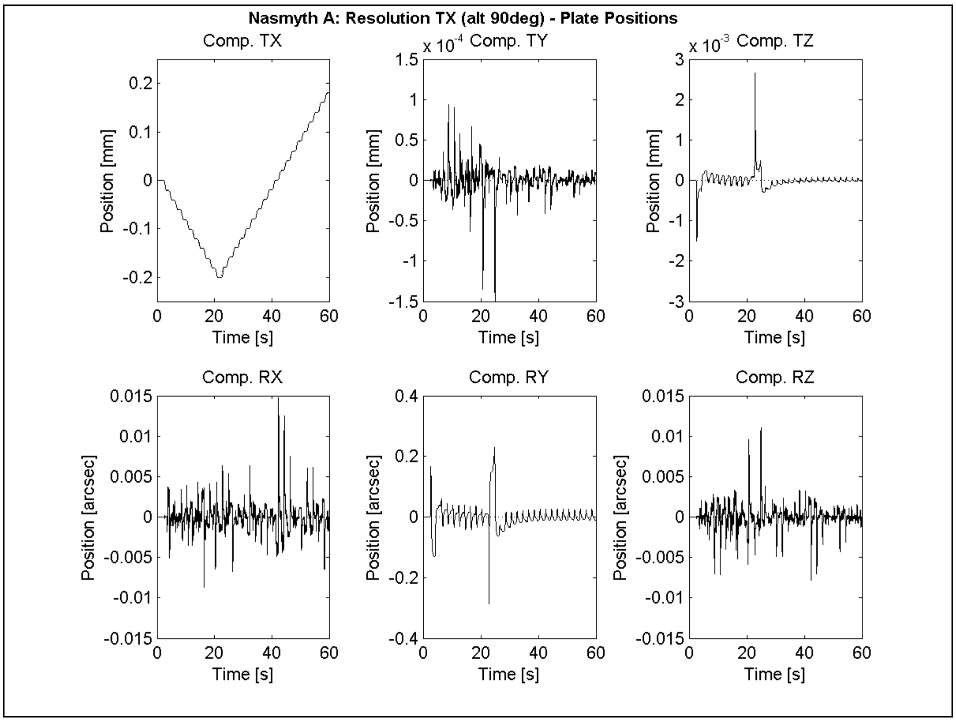


Figure 13: Simulation results: M4PS positions for TX motion

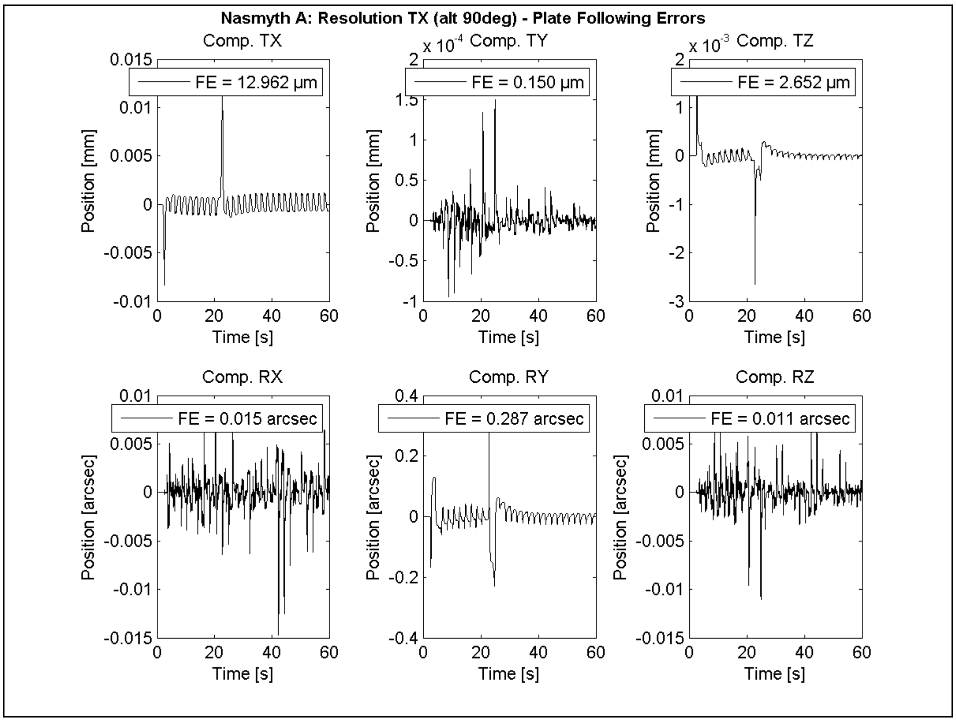


Figure 14: Simulation results: M4PS following errors for TX motion

For the M4PS error budget, other contributors have also been studied, such as:

- Encoder error (graduation and interpolation errors)
- Bearing runout (support cardans, mirror cardans, decoupling bearings)
- Pivot-point position uncertainties
- Modification of geometrical model due to gravity deflections
- Thermal effect

5. CONCLUSIONS

CILAS and its partners are involved in the preliminary design of the M4AU for the E-ELT since end of 2007.
The objective of this first phase is to evaluate the performances of an adaptive mirror with a diameter of 2.7 m based on piezo stack actuators supported by a hexapod.
CILAS proposes a design with 7217 actuators leading to a fitting error value of 110nm (value confirmed by ONERA). The stroke capability is set to 96 µm for a stroke need of 87 µm. Classical architecture of piezo-stack mirror [6] is kept: The optical plate is rigidly mounted on the actuators allowing a polishing of the whole mirror and not of the optical plate alone with the following advantages: The optical defects of the assembly can be removed by polishing, while the polishing of a thin and large optical plate is avoided. There is no thermal load in mirror since dissipated in the electrical units fixed to the mounting structure. Finally, the hexapod proposed by AMOS presents a high stiffness in the mass budget required by ESO.
CILAS and its partners have successfully passed the conceptual design review and the test review of the demonstration prototype. The next milestone corresponds to the preliminary design review (PDR) planned to be held mid July 2010.

ACKNOWLEDGEMENTS

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