On the way to build the M4 Unit for the E-ELT

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ABSTRACT

While the Deformable Secondary Mirror for the VLT is tested with the GRAAL adaptive system, the M4 adaptive mirror design is approaching detailed design. Although the two designs use the voice coil technology developed by Microgate and ADS, the M4 Unit requirements are more stringent. The M4 unit aims to provide adaptive correction and to cancel part of telescope wind shaking and static aberrations. The final specifications have been settled and the key performances will be demonstrated shortly on a one meter prototype. We present the main design drivers and associated requirements. We discuss what the challenges are in terms of stability and performance of the associated key technologies. We additionally describe the selected design, the current status of the project and the required schedule and work plan to manufacture the E-ELT quaternary mirror.

Keywords: adaptive secondary mirror, voice coil technology, hexapod, E-ELT, thin shell mirror, adaptive telescope

1. INTRODUCTION

Adaptive mirror primary objective is to correct for the atmospheric turbulence and to deliver in consequence a corrected image to the instruments. Adaptive mirrors are usually mounted on a hexapod to allow pupil registration and offload large stroke slow changes of the first rigid modes. With the increasing need of stroke at fast response, the design of adaptive mirrors has been changing since the first units ([1], [6]), the objective being always to get a reliable, stable and fast mirror providing large stroke, while limiting the power consumption.

We present here the main design changes implemented on the M4 design [4] with respect to the deformable Secondary mirror for the VLT [2] and we explain the main driver for the design changes. We describe the key requirements for both the Deformable Secondary Mirror and M4 in Sect. 2 and we present the main difference between the two designs in Sect.3. Sect. 4 is dedicated to the design status, schedule and workplan to manufacture the final M4 unit.

2. KEY SPECIFICATIONS FOR AN ADAPTIVE MIRROR

2.1 The VLT Deformable Secondary Mirror

Mirror Stroke requirements

The VLT Deformable Secondary Mirror (VLT DSM) has been designed to provide field stabilization capability, chopping and adaptive optics correction. The field stabilization is performed by tilting the mirror shell. The maximum amplitude required is 12 arcsecond mechanical which corresponds to a 60 micron stroke; larger stroke up to 105µm is achieved during chopping, with 20 arcsecond amplitude. Field stabilization is the main driver for gap size. The selection of the gap between the shell and the reference body has always been a trade-off between achieving the required stroke (which would tend to increase the gap) and making the best use of the air damping effect (which pushes towards limiting the gap distance to get an efficient air damping effect). The Deformable Secondary Mirror shell is therefore levitating with a 65 micron gap in the standard conditions. To provide more stroke capability for chopping, the piston is moved away from the reference body by 15 additional microns during the on-sky position when the adaptive optics is not working.

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The mirror correction capability is 80nm RMS WFE residual at 0.8 arcsec seeing, and a maximum 150 nm RMS WFE residual at 1.5 arcsec seeing. The standalone system performance verification has demonstrated that the mirror can correct for such seeing applying field stabilization at the same time.

Hexapod Stroke requirements

The hexapod is requires ± 6 arcmin centering stroke for pupil registration and offloading during observation. In addition the hexapod allows feeding both Cassegrain and Nasmyth foci. A range of ± 8 mm around both foci is available for fine adjustments and offloading of the VLT DSM during observation.

Stability requirements

Good DSM passive stability is required under gravity changes: the VLT DSM shall not move by more than 40 micron laterally, 60 micron in focus and 8 arcsec in tip-tilt. This performance requires Look-Up Tables correction on the as-built system.

2.2 The M4 Adaptive Mirror

Mirror Stroke Requirements

Compared to the VLT DSM, the M4 shall withstand 2.5 arcsec seeing conditions, still delivering an image with 0.5 arcsec Full Width Half-Maximum and correcting for quasi static alignment errors and field stabilization. The system shall withstand burst of turbulence and wind while maintaining full telescope wavefront sensing performance, i.e. maintaining the guide stars in the wavefront sensors and keeping telescope acquisition and guiding close loop control.

The M4 mirror needs as well to provide less than 120 nm RMS WFE correction residuals at 0.5 arcsec seeing, less than 145 nm RMS WFE correction residuals at 0.85 arcsec and 180 nm RMS WFE correction residuals at 1.1 arcsec seeing. The M4 shall limit on-sky tip errors below 0.3 milliarsec RMS and on-sky tilt error below 1.3 milliarsec RMS at 1000Hz.

Hexapod Stroke Requirements

The M4 hexapod requirements have been defined to provide means for pupil alignment during telescope integration and for pupil registration during the telescope loops closure. While the centering stroke of ±20 mm will only be used for AIV in the telescope, the ±2 arcmin tip-tilt stroke is needed for the bootstrap of the telescope to off-load misalignment.

Stability requirements

The M4 Unit has stringent stability requirements as the M4 position shall be known under any telescope position and environmental conditions. The M4 in plane position stability (x,y) shall be better than 500 micron PV, better than 0.5 mm PV out of plane (z) and better than 1 arcsec in tip-tilt.

Due to the segmentation of the E-ELT Primary Mirror, the local curvatures of the M4 optical surface shall have a radius larger than 20km on spatial scales 80mm or larger, under any telescope position and environmental conditions over a 15 days period. That requirement constrains the creation of scalloping errors in the pupil.

These requirements have strongly constrained the selection of the material for the reference body as it is further discussed in Section 3.3.

3. DESIGN DIFFERENCES

3.1 Shell design

All adaptive secondary units manufactured before M4 are using a single thin shell. The segmentation was proposed during M4 conceptual design phase to reduce risk of breakage, to limit manufacturing costs, and to ease maintenance of the system. The M4 Demonstration Prototype was tested with a segmented shell during Phase B in 2010. Adoptica, a consortium between Microgate and ADS, successfully demonstrated that petals cophasing and flattening requirements were met. Nevertheless no optical closed loop test was done (out of scope of Phase B).

Having a segmented shell instead of a continuous one is not changing the design of the mirror mechanics and electronics. A different type of membranes has been designed for M4 to fulfill the need for lateral restraint without using the central hole. VLT and LBT adaptive mirrors had already different membranes design as one being convex and the other concave.

Compared to a single shell design, the segmented shells are increasing the complexity of the adaptive optics control with the need of implementing a specific filtering to avoid differential pistons across the segmented M4. This is further discussed hereafter.

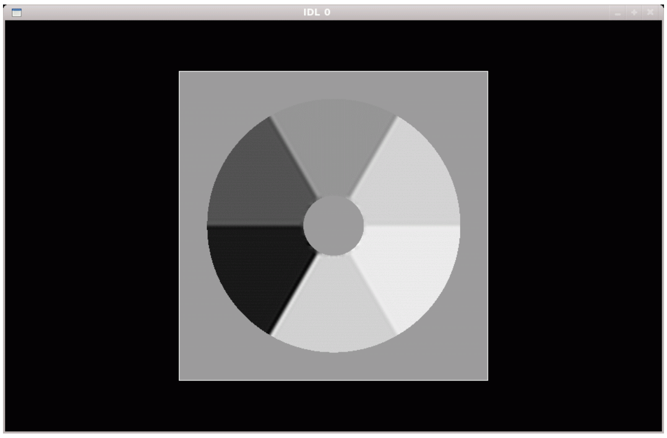

Figure 1. Schematic representation of an island mode on the deformable mirror with segmented shells.

3.2 Modal Filtering

Reducing the island effect with standard modal adaptive optics reconstructor like Maximum a Posteriori (MAP) techniques does not allow improving the correction. The MAP reconstructor allows filtering or damping the control modes depending on their signal to noise ratio, which in effect smoothes the output wavefront, to filter out noise and/or undesired modes. But with piston effect on each segment, a large phase jump is observed at the level of two adjacent segments. Optimizing the reconstructor reduces the final correction but reduces as well the jump between two segments.

An alternative method has been analyzed constraining each pair of actuators along the gaps between the segments to carry out the same command. This is done by creating a “macro-actuator”, i.e. forcing an actuator one side of the shell to execute the same displacement as the actuator on the other side. This reduces the number of degrees of freedom on the DM but prevents the formation of island modes. This method improves the correction and will be further optimized.

The M4 segmentation will not increase the fitting error significantly but more investigation is required to analyze if the island modes are only differential positioning or if combination of tilt create also these modes. We will in particular study in the next months if any analysis of the Shack-Hartmann spots could help is the improvement of the correction.

3.3 Mechanical Design

With the large size increase of M4 with respect to previous adaptive mirrors (91 cm for the LBT, 1.15 m for the VLT DSM, 2.4 m for the E-ELT M4) and the need for stringent stability, a major redesign of the reference body was needed. This was done since 2010 in several steps: a detailed analysis of the various options in term of material for the reference structure was done including Zerodur, ULE, Silicone Carbide, Aluminum and CFRP solutions. Stability requirements lead to discard some of these materials. Only two alternatives materials (Zerodur and Silicon Carbide) were selected and deeper analyzed in terms of stability, mass, manufacturing risk and cost.

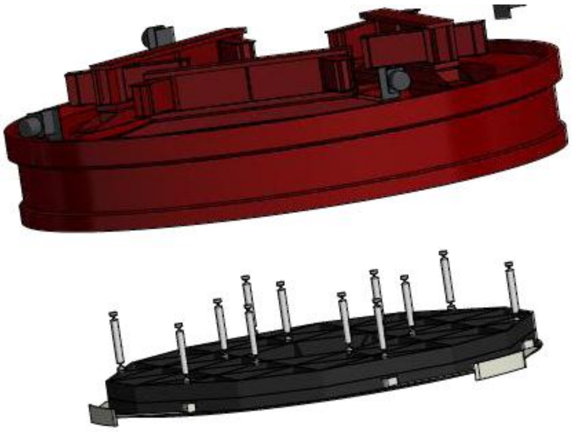

Figure 2. Exploded view of the reference body and its support system is shown here. The lower part is the lightweight reference body while the higher part and light grey parts in the lower parts are the support structure and whiffletree support.

The analyses performed during M4 preliminary design phase concluded that two Silicon Carbide and Zerodur designs would match the stiffness requirements. After final analysis, the Silicon carbide has been chosen as a baseline solution, while the Zerodur has been selected as an alternative one. In both solutions, the Reference body is supported as a common large size mirror, i.e. using an axial whiffletree support and tangential lateral support that limit the reference body deformations within a few microns PTV under gravity and thermal loads. As Silicon Carbide was never used as reference body material and as some new design elements have been introduced to have working capacitive sensor with such material, the two solutions are kept and tested in parallel. For the Silicon Carbide option, glass tiles are bonded on the Reference body surface (Figure 3) to hold the capacitive armatures. The conductivity of Silicon Carbide does not allow making those armatures by direct coating on the reference body surface.

Figure 3. Silicon Carbide prototype with glass tiles bonded on it. One side of the capacitive sensor armatures is coated on each tile.

3.4 Control aspects

Control requirements have evolved between the VLT DSM and the EELT M4.

Indeed the VLT DSM is requested to monitor any command received and skipping non acceptable commands in terms of force stroke. The focus and coma commands are offloaded to the hexapod every minute while the higher modes are offloaded to the VLT M1 every minute.

For E-ELT M4, the stroke limitation is performed at hardware low level, for each shape actuator. The strategy of command skipping or clipping is managed by the Telescope Control System (clipping is obtained by reducing temporarily the controlled modes). During the design phase, detailed analyses showed that clipping was recommended for an optimized power and force management. However further developments are still needed to determine the best control strategy as a function of the observing conditions. In any case, the M4 Control System shall provide full freedom to the telescope to select the appropriate skipping or clipping strategy. The M4 Control System is designed to fulfill the latency requirements whatever strategy is selected.

The force capability of the actuators has been increased in order to minimize the conditions in which the skipping/clipping conditions occurs; this required a redesign of the electromagnetic equipment, which allowed also a significant increase of its thermal efficiency, thus reducing the power consumption.

3.5 Reliability and maintenance aspects

Reliability and maintainability issues are quite difficult to manage for such complex systems.

The accessibility to the components of the VLT DSM has been optimized although some maintenance aspects remain a bit difficult, the hub dimensions and the fact that everything is included in the hub volume is limiting an easy access to only a few components. Accessing and maintaining the electronic boards for instance require the mirror to be removed from the hub.

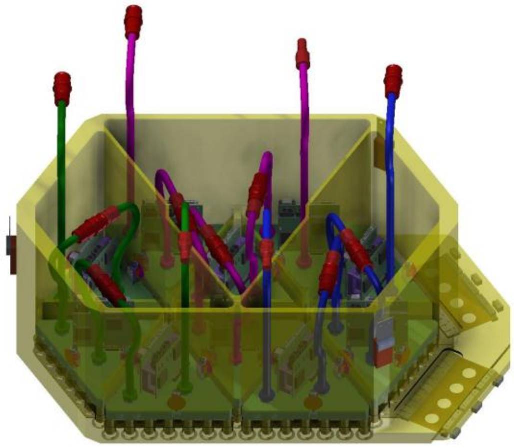

Figure 4. Demonstration Prototype design. The bricks are inserted in each cell, each actuator going through on hole of the reference body.

The EELT M4 will have almost 4 times the VLT DSM actuators number (4356 master actuators) and accessibility is one of the key factor taken into account in the initial M4 design phases. A brick concept was introduced to ease actuator replacement while the unit is installed inside the telescope. Bricks containing up to 36 actuators are Line Replaceable Units that are placed into the reference body lightweight pattern cells (Figure 4). In addition a special effort has been made during the design optimization of the reference body and cell, the spinning flange and the mounting structure to allow access for maintenance.

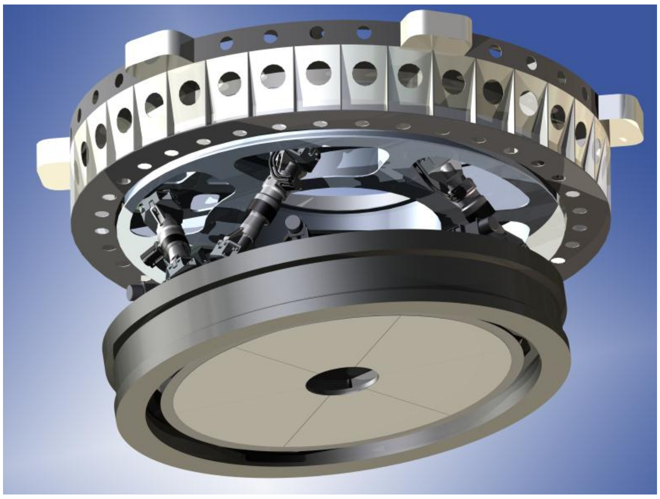

Figure 5: M4 Design at Preliminary Design. The unit has been optimized for a total mass of 9.4 tons.

4. M4 DESIGN STATUS AND NEXT STEPS

4.1 M4 Design status

The design (Figure 5) has been optimized in the last year to fulfill the requirements in terms of stroke, stability, mass and volume. The reference body interface has now a 12 points whiffletree axial support and six laterals supports. Those are attached to a reference structure that provides interface to the hexapod. The reference body is made of Silicon Carbide while the reference structure is in the Carbon Fiber Reinforced Polymer. The mounting structure is the interface between the M4 and the telescope: it contains the attachment points and the spinning flange, the cables pipes and electronic crates.

The total mass for the unit is a bit more than 9 tons.

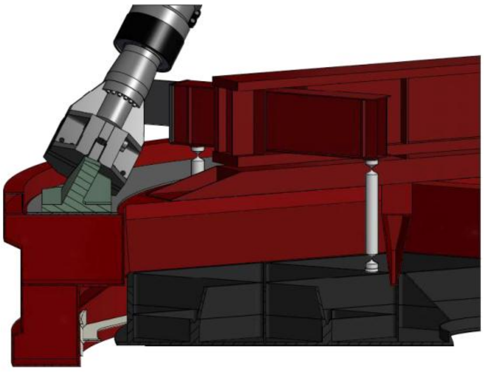

Figure 6. Interface reference body-hexapod leg on the left picture. Angles of the legs have been optimized to have a compact design.

Spinning flange and hexapod

The spinning flange is supporting the railways, brakes and motor on its top and the hexapod legs on the bottom. Nasmyth selection is made using two circular concentric rails to rotate the unit by 180 degree.

The hexapod leg design has been kept unchanged in the last year, while new flexure joints have been designed to connect the hexapod legs to the structural elements. Prototype flexure joints have been manufactured and tested. Each leg has a mass of 180kg.

Reference body structure and bricks

The reference body is an open back lightweight structure with triangular cells. The reference body front face holds the capacitive sensor armatures surrounding the 4356 actuator holes. The armatures are either directly coated on the front face

(Zerodur case) or held on coated borosilicate tiles (SiC case). The triangular cells on the back surface hold the ‘actuator bricks’.

Each brick (Figure 7) hoists 28 or 36 actuators, and four electronics boards: the capacitive sensor board, the voice coil driver board, the brick power supply board and the brick control board.

The brick power supply board generates the supply rails needed by all boards comprehended in the brick from the single 48Vdc bus. It collects as well diagnostics data.

The FPGA-based Brick control board is the brain of the system at the brick level. In addition to managing interconnection between the high speed and CAN links, it receives commands and pass them to the actuator control loop, performs the actuator control loop, acquires in parallel all the ADCs for capacitive sensor readings and update in parallel all the DACs to drive coil currents. Finally, the board does some system monitoring and stores the real time actuator data.

The voice coil driver board is including a high efficiency switching H-bridge with integrated current control loop for driving the voice coils motors. The capacitive sensor board acquires the local gap value and provides the signal conditioning for the capacitive sensor elements build from the thin shell and the reference body.

Figure 7. Standard brick of 28 actuators. The capacitive sensor board is located at the bottom of the brick; the voice coil driver board is on the upper face of the brick while the control and power supply boards are located on each side of the vertical heat sink.

A new concept of capacitive sensor signal pick-up has been developed to improve the connection between the capacitive boards and the capacitive sensor armatures. The electrical contact between the brick and each of its capacitive armatures is made using flexible 2 points magnetic connectors. That allows quick and easy mounting and dismounting of a brick for maintenance. The design of the flexible magnetic connector is not yet frozen, different design options are being tested at the time of writing, they show very promising results.

Each brick is mounted into a reference body triangular cell using three flexures. The mounting is kinematic and does not require adjustment in case of brick replacement; it introduces very low stress into the reference body.

Each brick is cooled using liquefied gas, quick cooling pipe connectors allow easy brick mounting and dismounting. Using a liquefied gas as a cooling medium avoids leakage issues, both at the level of the M4 and the other optics.

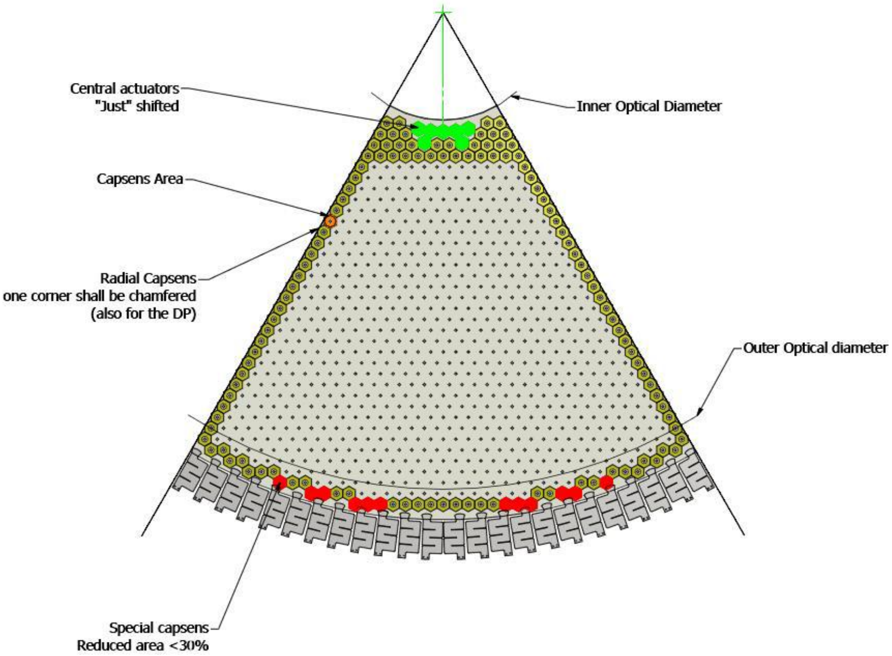

Figure 8: Actuator position in segmented shell. Positions of central actuators have been optimized to reduce the cantilever to the minimum.

Mirror shells

With segmented shells (Figure 8), the magnet pattern is to fill the mirror shells surface and avoid zone with cantilever. With the current design, the largest cantilever is of 43 mm next to the central hole; this cantilever will induce a small reduction of performance at the center of the mirror due to the weight of the glass.

Cooling system

To avoid cooling liquid leaking on M1, M5 and M3 located below M4, M4 is designed to use liquefied gas which evaporates in case of leakage. The complete cooling infrastructure has been manufactured, integrated and tested. The M4 demonstration prototype electromechanical tests and optical flattening will be done using the liquefied gas in order to demonstrate the ability of the system to provide the needed cooling.

4.2 Schedule and workplan

The M4 demonstration prototype is currently integrated and the testbench will be aligned by end July 2014. All the Voice coil actuators have been integrated and tested. The SiC reference structure was received mid May and controlled in performances (Figure **9**). The structure is in specification and ready for integration with bricks (Figure **10**). The bricks are connected via an interface pad which thickness is optimized depending on the reference body rib thickness.

Figure 9. SiC Reference Body of the M4 demonstration Prototype. On the left one can see the back side and the variation of rib thickness due to manufacturing uncertainties. On the right side, the fronts face of the reference body.

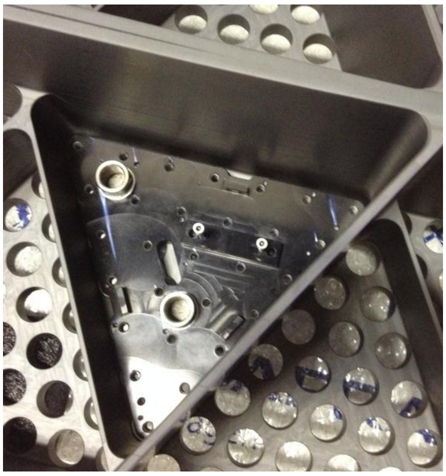

Figure 10. Insertion test of brick coldplate prototype.

During summer 2014, the actuators, boards, mounting interfaces and connectors will be integrated in all bricks. The sub-systems will be ready for integration on the equipped reference body by the end of July and the electro-mechanical test will be done during August. The optical tests will be performed this fall 2014.

The preliminary design review of the full M4 unit will take place in October 2014. The contract should be finished before end of 2014 in order to proceed with final design and manufacturing of the M4 unit and its optical test bench [4] by mid 2015.

5. CONCLUSION

The major improvements made in the M4 Unit design will allow reaching ultimate performance in terms of stability, mass to stiffness ratio, stroke, reliability, ease of access and maintainability. A novel reference body design and its support mechanisms limit its deformations to a few microns under external loads. Embedding the actuators and their electronics into bricks that can be easily installed and removed into and from the reference body well improves the maintainability of the system. Dynamic and stroke performance of the actuators have been improved as well. Novel capacitive sensors armatures and to-brick contacting design have been developed. The overall stiffness-to mass of such a large adaptive mirror is unsurpassed.

The preliminary design of the M4 Unit is almost complete. All the new solutions developed during that phase have overcome potential showstoppers, and the risks have been mitigated at all levels, through extensive breadboarding and tests.

The final design of the M4 Unit will start by mid 2015.

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