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Voice-coil technology for the E-ELT M4 Adaptive Unit

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Abstract. We present our design of the E-ELT M4 Adaptive Unit based on voice-coil driven deformable mirror technology. This technology was developed by INAF-Arcetri, Microgate and ADS team in the past 15 years and it has been adopted by a number of large ground based telescopes as the MMT, LBT, Magellan and lastly the VLT in the frame of the Adaptive Telescope Facility project. Our design is based on contactless force actuators made by permanent magnets glued on the back of the deformable mirror and coils mounted on a stiff reference structure. We use capacitive sensors to close a position loop co-located with each actuator. Dedicated high performance parallel processors are used to implement the local de-centralized control at actuator level and a centralized feed-forward computation of all the actuators forces. This allowed achieving in our previous systems dynamic performances well in line with the requirements of the M4 Adaptive Unit (M4AU) case. The actuator density of our design is in the order of 30-mm spacing for a figure of about 6000 actuators on the M4AU and it allows fulfilling the fitting error and corrections requirements of the E-ELT high order DM. Moreover, our contact-less technology makes the Deformable Mirror tolerant to up 5% actuators failures without spoiling system capability to reach its specified performances, besides allowing large mechanical tolerances between the reference structure and the deformable mirror. Finally, we present the Demonstration Prototype we are building in the frame of the M4AU Phase B study to measure the optical dynamical performances predicted by our design. Such a prototype will be fully representative of the M4AU features, in particular it will address the controllability of two adjacent segments of the 2-mm thick mirror and implement the actuators ”brick” modular concept that has been adopted to dramatically improve the maintainability of the final unit.

1 Introduction

In year 2002 the upgraded Multi Mirror Telescope (MMT) run by Steward Observatory at Mt. Hopkins (AZ) successfully started the operation on sky of the first adaptive secondary mirror build with voice coil motor technology [1]. After this 640mm diameter mirror, four more units are currently being built, namely two adaptive secondary for the Large Binocular Telescope (LBT) [2], one for the Magellan telescope and one for the VLT-UT4 in the frame of the Adaptive Optics Facility (AOF) programme [3]. All these units shares the same technology which is based on a free-floating Zerodur thin mirror, typically from 1.6mm to 2mm thick, having a pattern of permanent magnets glued on its back surface. These magnets face voice coils actuators mounted on the mirror cell structure, which provides both the stiffness and the cooling functions. The shape of the thin mirror is measured in real time by a set of capacitive sensors co-located with the actuators, which are referred to a stiff backplate to give a fixed reference surface to the floppy mirror shell. A fully decentralized feedback loop is closed at each individual actuator-sensor pair through a dedicated real time controller, which provides centralized functionalities, e.g. the feedforward, as well. Both the control electronics aboard the adaptive secondary unit and the voice coil actuators themselves are actively cooled by fluid to remove order of 1.2 W/act altogether. The four units built so far by our team ranges from 336 actuator of the MMT to the 1170 actuators of the VLTDeformable Secondary Mirror (DSM), sharing the same basic design of both the electromechanical and the electronics subsystems. They have been conceived as a truly parallel design, thus very much suited to be scaled up to larger Deformable Mirrors as the one required by the E-ELT. Beside this built-in scalability, we found that the Voice Coil technology itself provides valuable features for the E-ELT large DM application, as hereafter summarized. We rely on a truly contactless design, in fact an air gap of the order of 0.1mm is left between each actuator coil head and the permanent magnets. The mirror shell is restrained to the rigid reference body by flexures only, which limit its in-plane motion only, while leaving totally free its deformation. This means that our system can tolerate faulty actuators without imposing any fixed position or additional stiffness to the mirror. We have demonstrated by analysis a tolerance up to 5% of actuators failures, still achieving the required wavefront (WF) correction budget. Such a feature is deemed to be a strong benefit as the DM size and number of actuators scale up from order of 1000 as in the present units up to 6-7000 foreseen for the E-ELT M4. Another useful feature of the contactless design is that it makes the mirror figure not sensitive to the differential thermal deformation of the mirror itself and the mounting structure. In general, this relaxes a lot the mounting tolerance between actuators and thin mirror, which affects (lightly) just the actuators efficiency, instead of imposing a position lateral constraint to the mirror. Again, such feature becomes important for the M4 case, where construction tolerances of 3m diameter mirror structure are challenging. Two more advantages of the contactless design are worth to the mentioned. First, the Voice Coil Motor (VCM) actuators are hysteresis free, which makes them as stable as the position reading of the embedded capacitive sensors. These have proved to stay within 10 nm/hour over the full range of working conditions specified for the E-ELT. Finally, the VCM actuators and their capacitive sensors allow reaching operational strokes as large as 150 m, which becomes a strong plus for the M4 case in which important field stabilization requirements adds on the AO correction ones.

2 M4AU system overview

Our feasibility design of the E-ELT M4AU is shown in Figure 1, divided into the four subsystems identified by ESO: the adaptive mirror itself (M4AM), the positioning system (M4PS) to control position and attitude of the M4AM, the mounting structure (M4MS), which makes the interface to the telescope Adaptive Relay Unit (ARU). Within the control system, we can distinguish three main subsystems, namely:

- the M4AM Adaptive Mirror control system, placed directly on the adaptive unit and performing all co-located control tasks;
- the M4PS power and control unit, that is again installed aboard the M4AU;
- the remote Control System (M4CS), performing the global control tasks and providing the power conversion from the main power distribution.

We briefly describe hereafter the main features of each M4AU subsystems.

2.1 M4AM

The proposed design is based on a structural reference body made of CeSiC, which provides two functions: its front face has glass inserts which are metal coated to make the capacitive sensors armatures for each actuator; moreover, the reference body open back honeycomb design allows mounting into each cell the so called "actuators brick", thus providing the actuators mounting structure. We have 5 different bricks types to fit the reference plate geometry, typical one having 36 actuators, making a regular triangular pattern on a 31.5mm pitch. Altogether we have 6306 actuators (5928 on the optical area). We have chosen the brick approach to make the power, signal and cooling lines simpler and credibly manageable on such a large number of actuators. Each brick is interlaced to the nearby ones in a daisy chain layout comprehending just three simple interfaces, namely power, high speed data

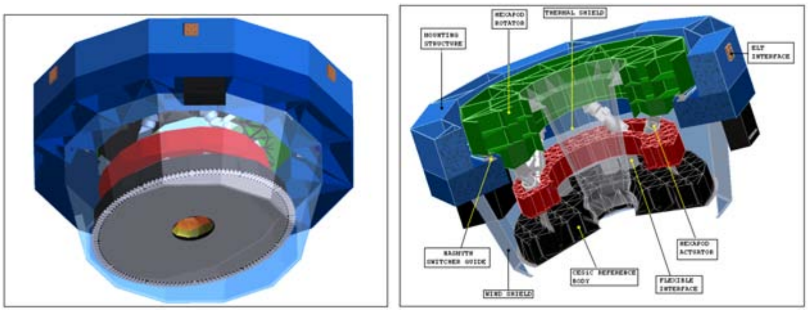

Fig. 1. Feasibility design of the Voice Coil actuated E-ELT M4AU.The main subsystems are listed in the exploded view on the right.

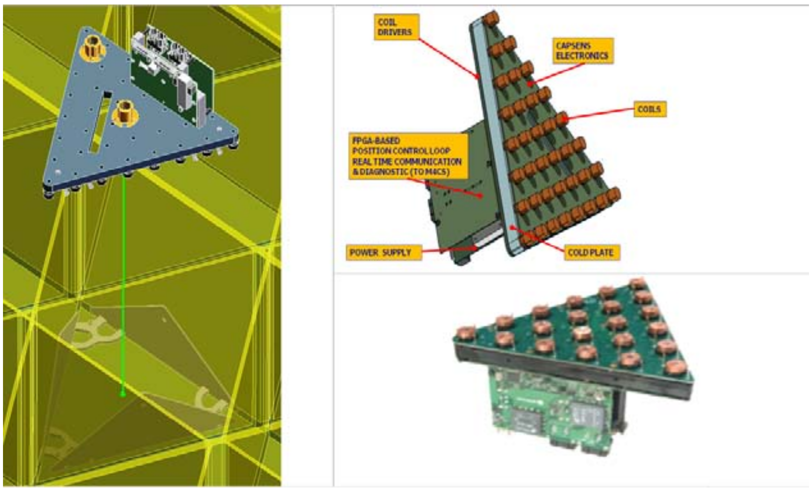

Fig. 2. Actuators brick layout (top right) and its mounting concept into the reference body (left). Brick prototype pictured (bottom right).

communication and cooling. In this way, the actuators brick becomes a Line Replaceable Unit (LRU) in the ESO concept, which is a subsystem which can be replaced directly on the telescope from the back side of the M4AM, without the need to remove the mirror shell. This is made possible by the relatively relaxed installation tolerances allowed by the contactless concept. Each brick carries aboard the local power and control electronics, thus making the communication with the rest of the bricks and the M4CS fully digital. Even if the control architecture has remained unaltered with respect to the current adaptive mirrors, the actual implementation of the brick modular concept demanded several improvements and modifications. Both communication and digital control functions are now fully implemented in hardware (FPGA). This allowed power consumption, space and performance optimization, while still maintaining the complete remote configurability of all FPGAs. The power distribution has been tailored on the brick concept by distributing just a single power line and generating locally all power rails needed by the brick control system. The capacitive sensors electronic and electrostatic designs have been improved to enhance noise immunity, stability and range of operation. Similarly, also the coil and the coil drives design has been optimized with the aim of improving power efficiency. An independent diagnostic system and a fail-safe communication concept allow system operation even in the unlikely case of complete failure of one brick. The total mass of the M4AM including actuators is about 1 ton. The M4AM is mounted on the M4PS by means of six flexures sets, providing stiff mount as well as radial compliance for the differential thermal expansion of the reference body and the M4PS structure.

2.2 M4AM - Mirror Shell

Our DM works with a 2mm thick Zerodur mirror. We conceived the M4AM design to be applicable to either a monolithic 2mm thick, 2740mm diameter Zerodur mirror shell as well as to a segmented mirror made by a set of six segments having the same stiffness. In both cases the mirror shell is mounted on the reference body by a set of flexures attached to its outer diameter. The reference body is the same for both solutions. The control bricks layout and interconnection is also fully identical for both the monolithic and the segmented case. Our approach to study both segmented and monolithic shell design during Phase B is aimed to maximize the risk mitigation against mirror production, operation and maintenance potential accidents. In this perspective we adopted a design and a prototype strategy to prove during Phase B both the feasibility of the single shell and also the functionality of the segmented design. Our Demonstration Prototype mounts two segments to prove their control and co-phasing. Moreover, a dedicated breadboard has been made to investigate the reliability and feasibility of the segmented mirror external restraint. The test proved that such restraint can withstand loads four times higher than what was calculated by the FEA. The same restraint design applies to the monolithic shell case too. A monolithic shell prototype 2mm thick is now under manufacturing at SAGEM. The prototype will be done in standard glass to prove the feasibility of the thinning process as well as assessing the handling issues expected for such a big shell. All the tools and procedure that will be used are fully representative of the final ones. If the feasibility of such a shell will be confirmed, the actual segmented solution could be easily switch to a monolithic one without any impact on the actual M4AM design.

2.3 M4AM - Demonstration Prototype

Our Demonstration Prototype (DP) has been designed and built to be fully representative of the M4AM: the DP is actually a 'cut' of the final M4AM unit taken along one of the radius separating two segments. The CeSiC reference body has been made with a comparable thickness of the final M4AM one, by using manufacturing process that can be applied to the large case too. We tested the capacitive sensors inserts manufacturing and installation as well, to make the DP sensors electrostatic and mechanics response as the M4AM one. The actuators bricks are fully representative of the final ones, both for the electromechanical part and the electronics mounted aboard. The same applies to the power and communication lines and to the cooling one. The two mirror shells are mounted on the DP to make the radial edge in between them as the one of two petals of the final M4AM. In particular we can test the edge effect on the fitting error, the control issues related to the edge actuators and the co-phasing of two adjacent shells. To this purpose a Piston Sensing Unit is mounted on the DP to measure the relative piston of the two segments; six of these sensors will equip the M4AM to phase one segment relative to its neighbor. The test and characterization phase planned for the DP follows the main stream planned also for the final M4AM unit. First, the dynamic performances of the DP will be measured offline the optical bench, by using its embedded metrology made by the capacitive sensors. In this frame we will also characterize the thermal dissipation and power consumption of the unit by means of the on-board housekeeping metrology. In a later stage, the DP optical test will include the measure of the power demanded to flatten the mirror shells under a full interferometric measure, the characterization of actuators influence functions, the optical measure of the radial edge effect and long term mirror position and figure stability as functions of capacitive sensor one.

2.4 M4PS & M4MS

We have decoupled the two functions specified to the M4PS, namely the control of M4AM lateral displacements and tilts which are provided by a hexapod and the switching between the two Nasmyth focal stations which is made by a rotator stage. The reason of such choice is to limit the hexapod stroke, in particular the rotation of the end joints of the actuators; we designed them to be made by flexures instead of universal joints to achieve higher stiffness and hysteresis free motion at the same time. We have proven that the positioning and stiffness requirements posed to the hexapod actuators by the M4AU specifications are achievable by our Hexapod (HP) actuators, by testing a prototype fully featured for the M4PS application. Our design of the M4MS is made of a welded steel structure of the order of 2.3 tons and the M4PS rotator unit is also a welded steel construction of about 2.5 tons. We have studied an alternative design to make both these structures out of Carbon Fibre Reinforced Plastic (CFRP) to save altogether about 2 tons of weight.

2.5 M4 Real Time Control System

The M4 real time control system maintains the same conceptual scheme already adopted in all present adaptive secondary mirrors: besides the co-located local position control of the actuators, a global control concept computed the static feedforward forces to improve the system dynamics. While maintaining the original concept, the implementation has been significantly modified in order to reduce power dissipation at the level of the M4 unit and improve system maintainability. The digital local control, including the capacitive sensor signal conditioning and analog to digital conversion as well as the coil drives and the respective digital to analog conversion are fully implemented on each modular brick. The FPGA-based control system allows a reduction of the computing times and an optimization of power dissipation at the brick level. Additionally, local supply and diagnostic functions make the brick a fully autonomous unit, so that the brick itself becomes one LRU of the system. The global control tasks, differently to all units currently being built, are implemented on a separate unit placed in some control room away from the M4 unit location and communicating with it by means of just seven fiber optic pairs. This unit is based on a cluster of DSP processors. The computational power demand grows with the square of the number of actuators belonging to a mechanically coupled mirror, so it becomes impressively large in the monolithic shell case. Thank to the very accurate simulation model developed in the frame of the project, it was possible to develop and test numerically a simplification algorithm capable of reducing the computational demand significantly. Simulations show also that there is room for updates to the presently adopted feedforward-feedback strategies that could make it possible to further improve the adaptive mirror performances, e.g. in relation to:

- higher command frequencies, thanks to an improved dynamic behavior,
- a better positioning, even in presence of a relatively inaccurate feedforward matrix identification.

Finally, the M4CS real time computer dimensioning is quite comparable for both the segmented and the monolithic case and can be easily hosted in just two standard 19” crates.

3 M4AU performances

Static and dynamic performances of our DM are hereafter reported as a result of the Preliminary design calculations. The Demonstration prototype will allow to test them altogether. The WFE budget is computed for the 0.86” median seeing median case:

$$\mathrm{WFE} = \sqrt{(\sigma^2_{fitting} + \sigma^2_{manufacturing} + \sigma^2_{servo} + \sigma^2_{quilting} + \sigma^2_{pritnt\ through})} = 129 nm\ rms,$$
where $\sigma_{fitting} = 112nm$, $\sigma_{manufacturing} = 25nm$, $\sigma_{servo} = 57nm$, $\sigma_{quilting} = 5nm$, $\sigma_{pritnt\ through} = 4nm$

The WFE for the 1.1” bad seeing case becomes 166nm rms The computed settling time (all modes) results 0.8 ms at a working gap of 80 m. By simulation, this is expected to easily fulfill the system level temporal error requirement. The mirror jitter resulting from capacitive sensors stability is of the order of 2-3 nm rms measured at 26 kHz (bandwidth). The stability over one night considering a worst case thermal gradient of 0.7 C/hour results being below 60 nm PtV.
The stroke budget for our VCM actuators is made of the following contributions.

DM STROKE = 160μm LINEAR SUM of:

69μm dynamic, (active optics, tracking, defocus, turbulence)
12μm reference plate thermal + gravity deformation

$30\mu m$ fabrication errors (segments thickness variation)
$10\mu m$ integration accuracy
$39\mu m$ M4PS [to compensate for axis crosstalk]

Finally, the power budget of the M4AM is 6.5 kW for the median seeing case. For the bad seeing case we will allow the same power dissipation by cutting the corrected modes down to 5400.

3.1 Final remarks

We presented our design of the M4AM based on existing technologies already applied to others voice coil based DMs that we designed and produced in the past. The major evolution of our design that we adopted for the present application is the actuators brick concept, which simplifies the harness layout on such a large DM and it improves dramatically the maintenance aspects. All the new design features are consolidated already during Phase B of this programme by means of breadboards or prototypes. In particular the Demonstration Prototype is fully representative of the final M4AM: actuator geometry, bricks, cooling plant, back-structure design, mirror segments co-phasing are all implemented in our DP. Finally, the proposed M4AM design is independent from the choice of a monolithic or a segmented shell solution. At the end of Phase B we will be able to select the mirror technology based on experimental results, namely the DP tests and the dummy single facesheet mirror manufacturing test.

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