Building the ESO ELT M4 adaptive unit

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ABSTRACT

The M4 Unit manufacturing phase has started since more than one year and while the procurement of large components is on-going, several sub-systems are currently being integrated. This article presents the status of the integration and testing. A section details the expected performances for each sub-system. We further compare the M4 mirror performance analysis with test results from a full segment prototype and from a prototype hexapod leg. Finally, we provide an overview of the next steps.

Keywords: deformable mirror, adaptive secondary, voice coil actuators, ELT

1. INTRODUCTION

The ELT M4 adaptive unit is a ten tons system including 2.5 meter adaptive mirror and a positioner for the ELT telescope. Early design concept studies started in 2006 and were concluded with the selection of the technology used for adaptive secondary mirrors with voice coil motor [1]. A huge effort has been put on early prototype to remove major risks and validate new designs with respect to existing adaptive secondary mirrors. The final design was completed in December 2017 and since then the manufacturing of all components has been launched. This article presents the main characteristics of the unit and its expected performance as obtained at the final design. The second part is focused on the manufacturing status of various parts and we present as well some the sub-systems tests already performed. The schedule for integration and tests is presented in the last section.

2. THE M4 UNIT DESIGN

The M4 unit (Figure 1) is a 4 meter structure located at the center of the telescope in the Adaptive relay unit, below M2 and above M1, M3 and M5 units. This unit includes an adaptive mirror, a hexapod and a Nasmyth switcher to feed the two Nasmyth foci. The unit is expected to be stable to 250 micron in plane, 2.5 arcsec in tip-tilt and 2 mrad in clocking considering all thermal and gravity change conditions. This will be reached using look up tables.

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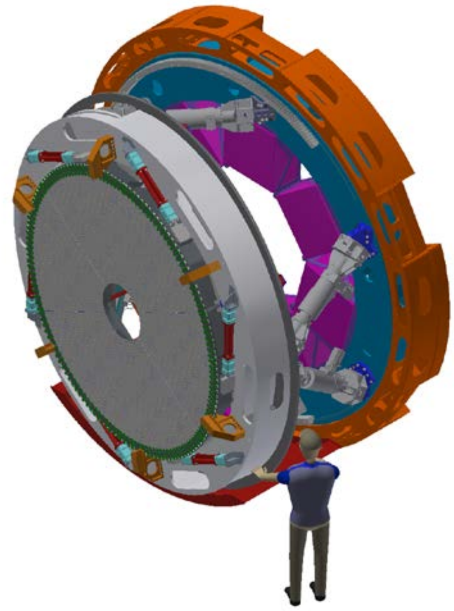


Figure 1: M4 Unit: the orange and blue structure is the Nasmyth Switcher. It includes as well the electronics cabinets in purple. The Adaptive mirror in dark grey (left part of the sketch) is attached to its cell (in light grey) by the lateral and axial supports. The mirror and the cell are attached to the Nasmyth switcher with the hexapod.

2.1 The M4 adaptive mirror

The adaptive mirror includes 5352 voice coil actuators with co-located capacitive sensors. Contrarily to previous existing adaptive secondaries, the actuators are not directly mounted on a monolithic cold plate but instead they are grouped in bricks. The bricks are mechanical structures including few tenths of actuators (ranging from 28 to 36 depending on the type of brick), associated electronics (driver, capacitive sensor, power and logic boards) and a cold plate to keep the brick in the acceptable temperature range. They are mounted on the pockets of the reference body using three clamping mechanisms per brick to have a good restrain and allow an easy dismounting in case a brick need to be replaced. While only 4866 actuators are in the clear aperture, the additional actuators are controlling the external part of the mirror shells in such a way to reduce the aberrations induced by the lateral membranes. A total of 174 bricks with five different geometries is needed to fill the reference body surface. The bricks need to be cooled to avoid heating the mirror. Considering the large number of connections and the risk associated in case of leaks of coolant, a large effort has been made to use direct gas expansion cooling technology. The system is using the liquid to gas transition of the pressurized gas to cool down the unit. The design has been optimized with R134a gas and allow to remove all the heat produced by the mirror, the kinematic support and the electronic cabinets.

The reference body is the optical reference of the adaptive mirror and it is the support of the mirror shells. It is made of six silicon carbide segments brazed together (Figure 2 right). The manufacturing of the part was challenging due to the requested accuracy for the holes and ribs position. The reference body is also supporting one side of the capacitive sensor armatures. Due to the relatively low resistivity of the Silicon carbide material, the capacitive sensor armature is coated on borofloat hexagon tiles which are glued on the reference body surface. This solution allows also an optimal design of the snap-in insert that picks up the capacitive sensor signal. The reference body is supported by twelve axial and six lateral supports attached to a cell to obtain a low deformation with gravity change (Figure 2 left).

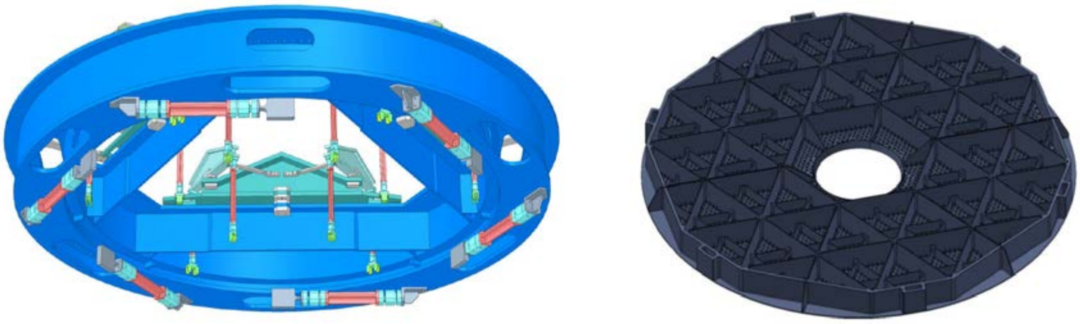
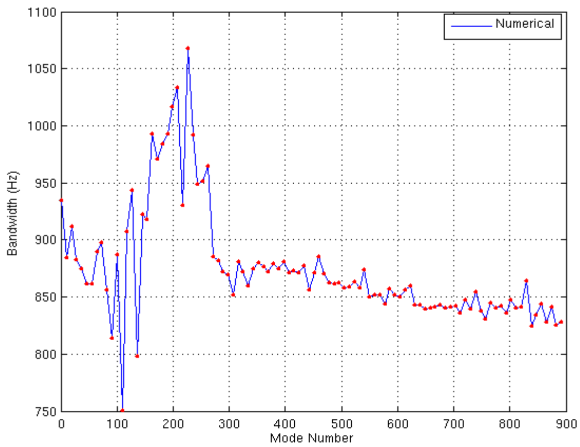


Figure 2: The M4 mirror Cell – shown on the left picture- is a three meters diameter aluminum structure with axial and lateral supports to handle the Silicon carbide reference body – shown on the right picture - as a standard optical mirror.

The optical surface reflecting the light and deforming in real-time is composed of six 1.95mm thin mirror shell petals made of Zerodur. The back surface of the mirror shell is coated to create the second part of the capacitive sensor armature. Each mirror shell is also equipped with 892 permanent magnets, located at the same position as the actuators. During observation, these flat mirrors petals are sustained by magnetic force at a median gap of 90 micron away from the reference body surface. To avoid any lateral movement, the mirrors are equipped with 36 membranes on their external radius. (Figure 5 right).

The final design of the mirror has included a detailed analysis of the mirror mechanical and optical performance in a large range of operational to survival load cases. Bandwidth of the system has been simulated in deep to determine the close loop transfer function and the maximum phase lag for each modal command (Figure 3), as well as the modal settling time (Figure 4 right).



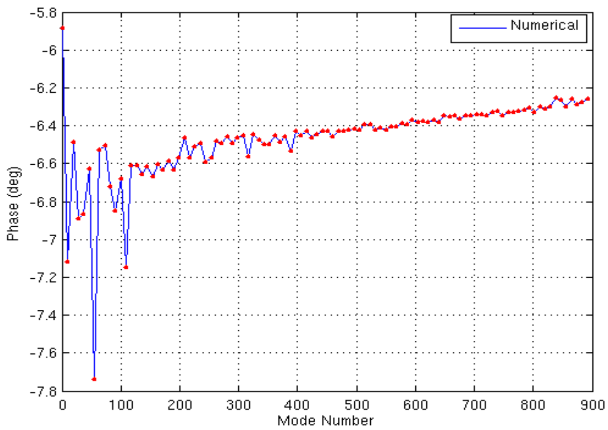
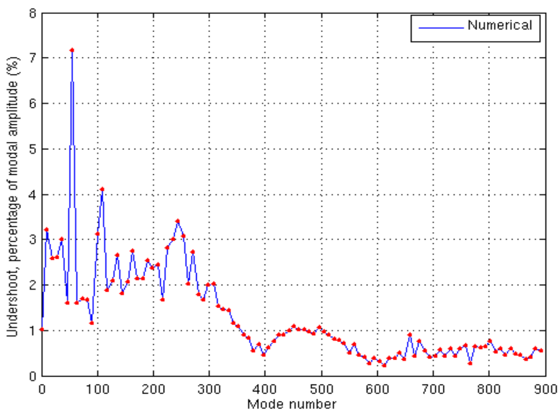


Figure 3: Left: M4 mirror bandwidth versus modal shape command; closed loop transfer function identified on M4 model. Right: M4 mirror maximum phase lag within the bandwidth [0 - 40] Hz for each modal command



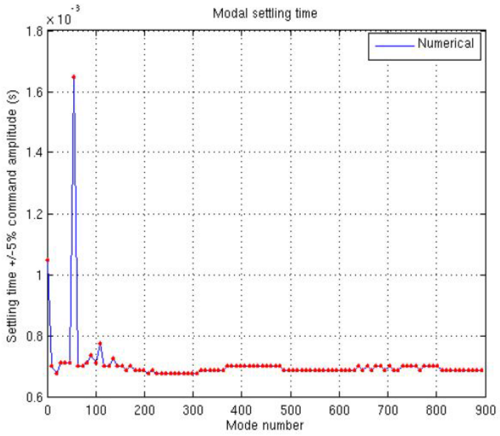


Figure 4: Left: undershoot versus modal command. Right: M4 mirror modal step response settling time. Mode 60 shows a longer settling time because the first cycle of the damped oscillation exceeds the 5% range.

The mirror is well in specification in term of closed loop bandwidth and phase lag for each modal command. The settling time requirement is also fulfilled with a large margin for almost all the modes. Only the mode 60 is in specification with no margin.
The actuators and magnets have been optimized to provide enough stroke to work at a gap larger than previous systems. The M4 mirror will have an operational gap of 90 micron to cope with the correction of quasi static low order modes and at the same time to correct for atmosphere disturbances. The mirror has been designed to provide enough stroke for worst conditions. The newly developed actuators have the capability to deliver 1.83 Newton. With the increased gap and strongest bias magnets implemented to restrain passively the shell even in case of wind, the amount of force required to have a mirror with a flat operational shape is larger than for previous systems and is estimated to 0.36N.

The capability of the mirror to provide the required fitting error in various seeing conditions has been computed in detail considering at the same time the low order telescope errors. As shown in Table 1, the mirror meets the requirements in term of fitting error under all seeing conditions with some margin.

Table 1: Fitting error performance of the M4 mirror under various seeing conditions

ITEM	Fitting error performance				UNIT
	Good Seeing (0.50")	Median Seeing (0.85")	Bad seeing (1.10")	Worst seeing (2.50")	
atmospheric fitting error. Piston and tip-tilt removed.	82	128	158	314	nm RMS
High order	19	19	19	19	nm RMS
cophasing error	36	36	36	36	nm RMS
telescope focus disturbance (fitting)	10.8	10.8	10.8	10.8	nm RMS
telescope astigmatism disturbance (fitting)	5.5	5.5	5.5	5.5	nm RMS
telescope coma disturbance (fitting)	6.6	6.6	6.6	6.6	nm RMS
quasi-static Zernike (fitting)	2.6	2.6	2.6	2.6	nm RMS
deformation of the M4 Adaptive Subunit	8.4	8.4	8.4	8.4	nm RMS
good seeing	**93**				**nm RMS**
median seeing		**135**			**nm RMS**
bad seeing			**164**		**nm RMS**
worst seeing				**317**	**nm RMS**
M4 requirement	**120**	**145**	**180**		**nm RMS**

The influence functions have been obtained from the FEA detailed model, including the membranes effects (see Figure 5).

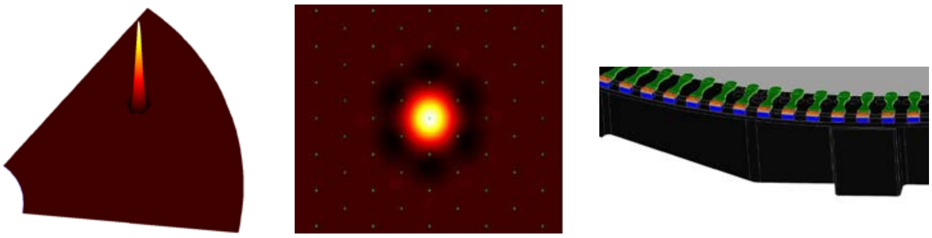


Figure 5: Left and central image: Influence function obtained from the FEA model including the membranes restraining the shells laterally; right image: membranes design

2.2 The M4 kinematic support

The M4 kinematic support provides structural support within the unit and kinematics for rigid body motion of the optical surface and for switching between the Nasmyth foci of the telescope. It contains as well all the cabling and piping required from the M4 Adaptive Subunit to the M4 Service Connection Point. The hexapod is providing a lateral and tip-tilt fine movement to keep aligned the vertex of the M4 mirror. The Nasmyth switcher is allowing to select between the Nasmyth A and Nasmyth B.

The rotating structure is the fixed flange of the hexapod and it is at the same time the structure support for the Cabinet need for the whole unit. It supports the driving unit of the Nasmyth, a circular rail with carriages, a main gear, motor, pinion and encoder. The system is able to rotate the M4 unit by 180 degree in 2 min with an accuracy of better than 13 arcsec.

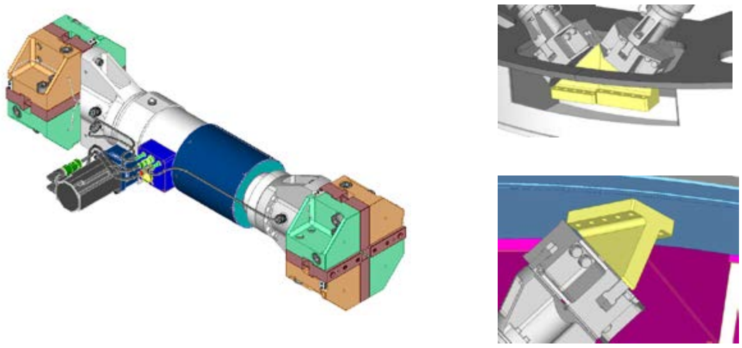


Figure 6: Design of one hexapod actuator and wedges used to fix the actuators to the two opposite structures. The flexible joints are represented by the brown/green structure on the two sides of the actuator, the central part includes the encoder, the gearset, the roller screw and axial bearing

The hexapod actuators design is based on a roller screw driven by a brushless motor through a worm wheel gearbox (Figure 6 left). The roller screw pitch is 2 mm. The nut is preloaded to remove play. The worm wheel gearbox is selected because it is not reversible and thus it assures the actuator will keep its position even when switched off without the need of any specific brake. The selected worm wheel is a special low play version, assuring a virtually backlash free positioning. An absolute, fully digital, rotary encoder is mounted on the roller screw axis. The encoder resolution on the screw shaft corresponds to a linear displacement of 0.059 nm/bit. Two electrical limit switches are used to define the actuator safe stroke, with mechanical safe stops placed beyond them. Actuator body structural parts are made of stainless steel and aluminum where possible and compatible with thermo-elastic effects. Flexible joints are mounted on the actuator body ends. They provide the rotation capability by using flexible elements. The hexapod actuators are mounted on the reference body cell and rotating structure by some wedges (Figure 6 right).

3. M4 UNIT MANUFACTURING STATUS

The final design was concluded early 2018 and since then the manufacturing of all components has well advanced. A detailed status is presented in the sections 3.1, 3.2 and 3.3.

3.1 Manufacturing status of the M4 mirror components

The mirror is the subsystem with the highest number of components and the procurement has been initiated quickly in 2018 to reduce any risk of delay. It has been very successful as today most of the components are already in house and the integration is already well advanced. The status of bricks integration is well in schedule: 30 bricks over the 174 needed are already fully integrated, all voice coil motors are ready to be integrated, 60% of the permanent magnets and 40% of tiles are received (Figure 7). All the power and logic boards are in house and the calibration is ongoing. Most of the driver boards are already in house going through the calibration (Figure 8) and most of the capacitive sensor boards have been also manufactured and are ready for final integration on the bricks.

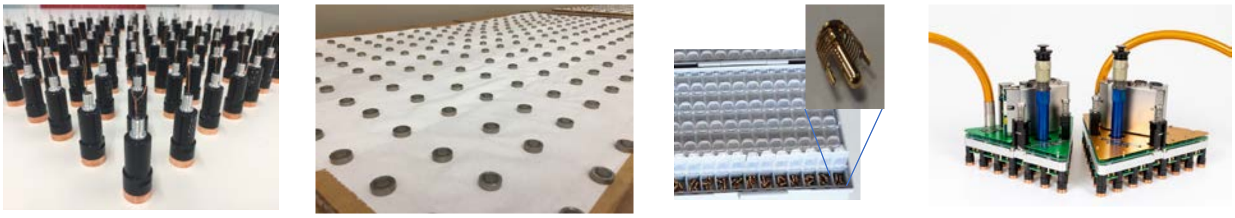


Figure 7: From left to right: voice coil motors ready to be integrated into the bricks, permanent magnets with their Zerodur puck ready to be bonded on the mirror shells, capacitive sensor contacts 60% ready for integration and two bricks integrated and functionally tested.

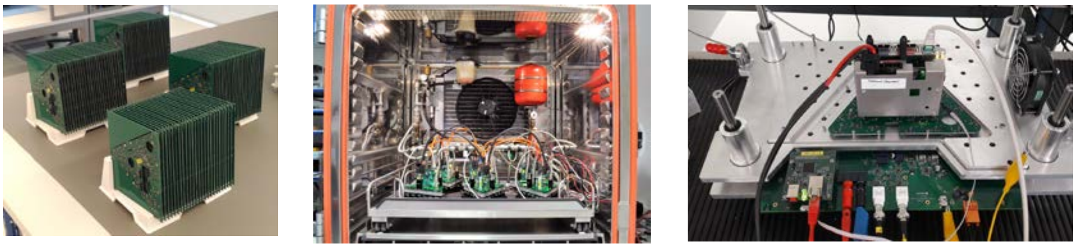


Figure 8: on the left, the driver boards for bricks of type A and B. In the center, the setup for the burn-in tests and on the right the calibration of the driver boards

The procurement of reference body - which started in 2017 – is progressing. The 6 segments have been brazed and the grinding of the front surface is expected to start end of October. The reference body cell is manufactured and already in house as well as its lateral and axial supports.
The manufacturing of the thin shells also started in 2017. Four thin shells are already ready for integration (Figure 9) [2]. The first task will be to create the capacitive sensor armature on the shells by coating the back face with specific coating pattern. Then the permanent magnets will be bonded.

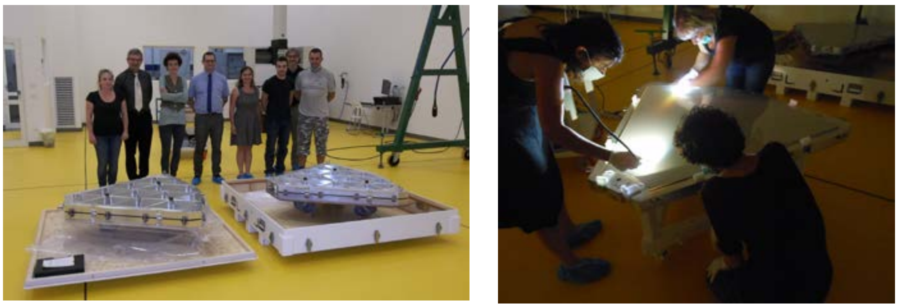


Figure 9: on the left, the two first shells delivered in 2018. Two additional have been delivered in 2019. On the right, final optical inspection after delivery at Adoptica.

The integration of the reference body is the critical point in the schedule due to the number of steps and as the reference body delivery is now delayed with respect to the initial schedule. All the sub-systems to be integrated will be ready by the time the reference body is delivered.

3.2 Manufacturing status of the M4 kinematics support

To reduce risks of procurement of the hexapod, one actuator was produced and extensively tested during the final design phase (Figure 10). The prototype actuator performance was validated mid-2018 and immediately the procurement of the components for six additional actuators was launched. All the six legs have been manufactured and integrated with the objective to have the fully calibrated and verified hexapod by mid-2020.

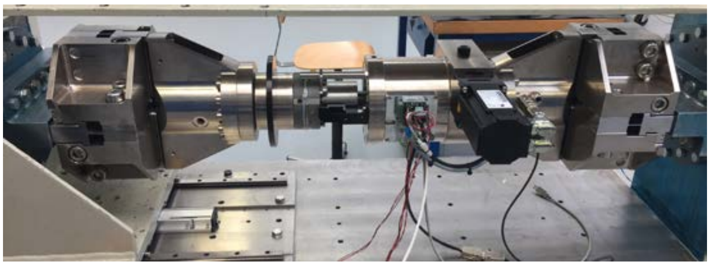


Figure 10: hexapod leg prototype on the test bench

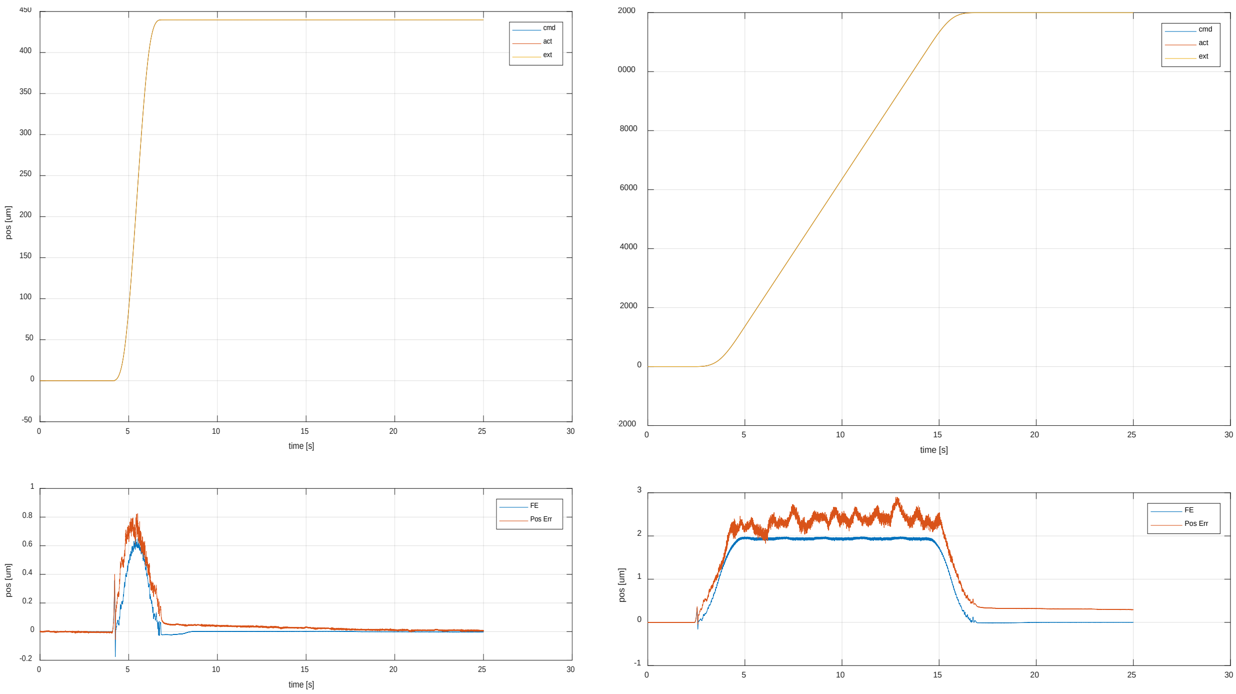


Figure 11: Performance of the actuators for two different steps sizes: on the left for a step of 0.44mm and on the right for a step size of 2 mm. In both case the accuracy obtained is ten times better than the requirements

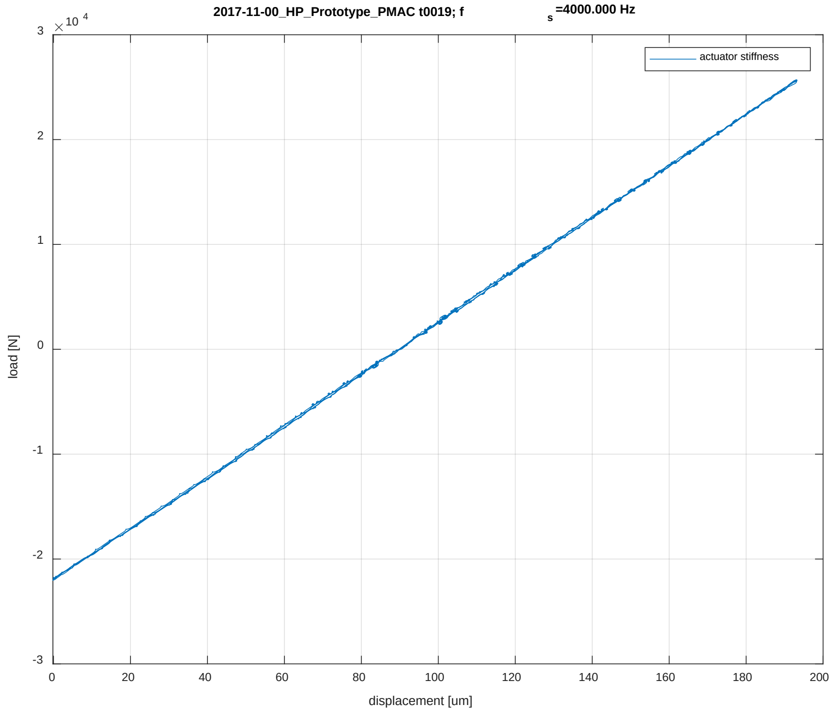


Figure 12: The stiffness of the prototype has been verified experimentally. The stiffness is 246.9 N/micron and the hysteresis is lower than 1 micron.

The hexapod actuator is able to perform a repositioning command within specification for both small and large steps (Figure 11). The irreversibility of the actuator has been demonstrated by testing it in open loop and demonstrating that the trajectory is as expected. The stiffness of the prototype has been verified experimentally. The stiffness is 246.9 N/micron with an hysteresis lower than 1 micron (Figure 12).

The mechanical parts of the M4 kinematic support are currently manufactured. The Nasmyth switcher is expected to be ready early 2020.

The software is also well advanced. Already from the early implementation phase, the ‘final’ configuration and architecture has been used for all internal testing phases, both for the low-level firmware and the middleware, so to allow a continuous improvement and robustification of the code. Moreover, self-testing capabilities have been integrated in the code, using well proven tools already adopted by ESO (Jenkins, WAF). A full interface test has also been done early 2019 between a one full segment prototype and the telescope control network, verifying the time network, deterministic network and control Network (Figure 13 left).

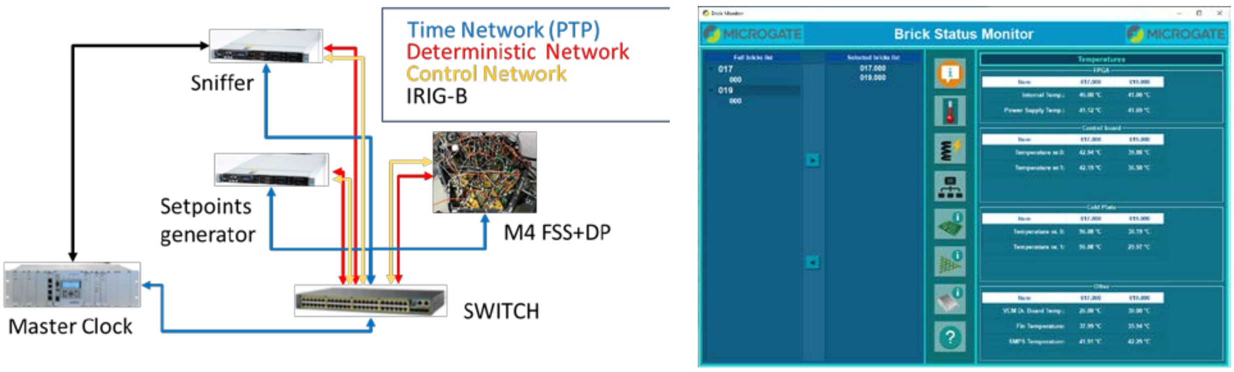


Figure 13: On the left, diagram explaining the interface test done between the full segment prototype and the telescope control network has allowed to verify the time network, the deterministic network and the control network. On the right, the GUI of the brick status monitoring

Some effort has been put in the development of the software graphical interface to be able to use it as well during the testing of the sub-system. It is for example the case for the brick (Figure 13 right) for which the graphical interface is already completed and daily used to test the bricks.

3.3 Manufacturing status of the auxiliary tools

Several auxiliary tools are required for integration and testing of the M4 unit: two stands and the optical test tower [5] for the final optical calibration plus a series of integration tools for sub-systems and calibrations tools. The procurement of the tools for sub-system integration and calibration has been finalized already some time ago and these tools are now daily used to integrate and calibrate electronic boards, bricks.

The manufacturing of the shell transport, cleaning and coating boxes is also finished and the two tools are ready to start the coating of the shells.

The M4 mirror stand foreseen or the integration and testing of the M4 mirror is already in house. The unit stand is expected to be ready early 2020 while the optical test tower various components will be ready for integration early 2020. It includes the two mirrors currently polished at AMOS and the structure which will be delivered by end 2019. Part of the devices equipping the test tower have been individually integrated and tested [6] in 2018-19, including the lens system to relay the laser interferometer beam, the tool for its optical calibration and the phasing sensors. A detailed description of the latter, including the results of the performance test, is given in [4].

The test tower will be used to flatten and calibrate the adaptive mirror as described in detail in [3][7].

4. SCHEDULE FOR THE M4 UNIT

Few key steps are planned in the next years. First of all, the gas cooling design needs to be finalized. A prototype has been built and tested for extended time. It has allowed to verify the performances as well as the reliability of the components. The final design is expected to be finished by end 2019 and the manufacturing will start immediately afterwards. A large effort has been put on the reliability and safety of the system due to the use of R134a gas.
The integration of the reference body is expected to start end 2020 and the unit will be ready for optical test end 2021.
While the M4 unit will be integrated and electromechanically tested, the optical test tower will be aligned, tested with a reference mirror, calibrated and validated. The stability requirements for the tower are demanding and will require some time to be demonstrated.
The optical tests are expected to last 1.5 year and the system is planned to be ship to Chile by mid 2024.

5. CONCLUSIONS

The M4 unit is expected to be ready in Chile by mid-2024. The manufacturing is proceeding as expected and the final integration of the mirror will start by end of next year. There are still few challenging tasks before shipping the system to Chile. The final integration is the first challenge since it is a delicate task with many integration steps: populating the reference body with all the borofloat tiles, mounting all the interfaces to the bricks, positioning all the bricks, fixing the system to its support. Once this step is finished the integration and electro-mechanical calibration of the 6 shells will also take time. The shape of the mirror is quite different from the previous adaptive units and it may induce some additional time to properly control the mirror in the initial calibration phase. The optical calibration and phasing of the mirror will also require time and may strongly dependent all the stability reached with the optical test tower.

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