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# Electronics design of the LOR WFS Module of MAORY

G. Di Rico*[a,f], M. Bonaglia[b], L. Busoni[b], I. Di Antonio[a,f], A. Valentini[a,f], M. Bellazzini[c], P. Ciliegi[c], F. Cortecchia[c], E. Diolaiti[c], S. Esposito[b,f], F. Feautrier[e], R. Ragazzoni[d,f], B. Salasnich[d]

[a]INAF – Osservatorio Astronomico d'Abruzzo, Via Maggini snc, 64100 Teramo, Italy;
[b]INAF – Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy;
[c]INAF – Osservatorio di Astrofisica e Scienza dello Spazio, via Gobetti 93/3, 40129 Bologna, Italy;
[d]INAF – Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy;
[e]INSU – IPAG, 414 Rue de la Piscine, BP 53, 38041 Grenoble Cedex 9, France;
[f]ADONI – Adaptive Optics National Laboratory, Italy

## ABSTRACT

The LOR WFS module will provide low and medium order sensing for the MAORY MCAO mode. It is composed of three identical units, hosting two Shack-Hartmann wavefront sensors each: an infrared 2x2 sub-apertures, used for low order modes, and a visible 10x10 sub-apertures for the slow truth sensing needed to correct the LGS WFS measurements. In this paper we show the current design of the NGS WFS control electronics and the interfaces with the MICADO instrument.

**Keywords:** ELT, Adaptive Optics, MCAO, Control Systems, Motion Control, Electronics, PLC

## 1. INTRODUCTION

MAORY[1] (Multi-conjugate Adaptive Optics RelaY) is the first-light MCAO facility of the E-ELT, providing a Strehl ratio >30% in K band (goal 50%) in median seeing conditions (r0 = 0.157 at $\lambda$ = 0.5 µm) and a uniform PSF over the 53'' x 53" square FoV of MICADO[2], with a sky coverage of 50% at any Galactic latitude. The MCAO mode of MAORY is based on the simultaneous use of 6 LGS and 3 NGS wavefront sensors, at least 1 internal DM and the telescope's adaptive and tip-tilt mirrors M4 and M5 respectively. MAORY will also provide a SCAO[3] mode to achieve diffraction limited performance on a limited FoV, measuring distortions by a further NGS WFS and correcting them though M4 and M5.

From the opto-mechanical point of view, MAORY consists of an optical relay, which re-images the telescope focal plane for the science instruments. The relay is supported by an optical bench (see Figure 1), which is mounted on the telescope Nasmyth platform in gravity invariant configuration. The main bench[4] hosts most of the Post-focal Relay Optics[5] (PFRO) and several calibration units (two belonging to MAORY and one to MICADO), while the LGS module[6] is just below it. The PFRO consists of six mirrors and a dichroic beam-splitter, which separate the science light from the LGS light. The six LGSs, launched from the edge of the telescope aperture, provide an asterism with a radius of 45 arcsecs. The LGS images are then acquired by 6 Shack-Hartmann based WFSs with 80x80 subapertures each.

The NGS module is placed on a vertical structure with octopod legs, next to the MAORY bench, between the last mirror of the PFRO (on the top) and the MICADO cryostat (see Figure 2). The allocated volume for this module is a torus with 2.6 m diameter and 1.0 m height, called Green Doughnut (GD). It is shared by the SCAO (on top) and the Low-Order and Reference[7] (LOR) subsystems. The ladder (LOR module) implements the NGS sensing functionalities needed by MAORY in MCAO mode. It consists of 3 identical units to sense aberrations from 3 NGS in a technical field of annular shape, ranging between 40 and 90 arcsecs off-axis. They are disposed around the MICADO FoV, to pickoff one NGS each, within a portion of the technical patrol field, to increase the number of available NGSs and hence the sky-coverage. In this paper we describe the current status of the preliminary design of the LOR control system, focusing to its electronics. The description of the opto-mechanics and the performances analysis of the LOR Module are given in [7]. The project is currently in its phase B, that will end with the Preliminary Design Review in 2019.

*gianluca.dirico@inaf.it; phone 0039 0861 439705; fax 0039 0861 439711; www.inaf.it

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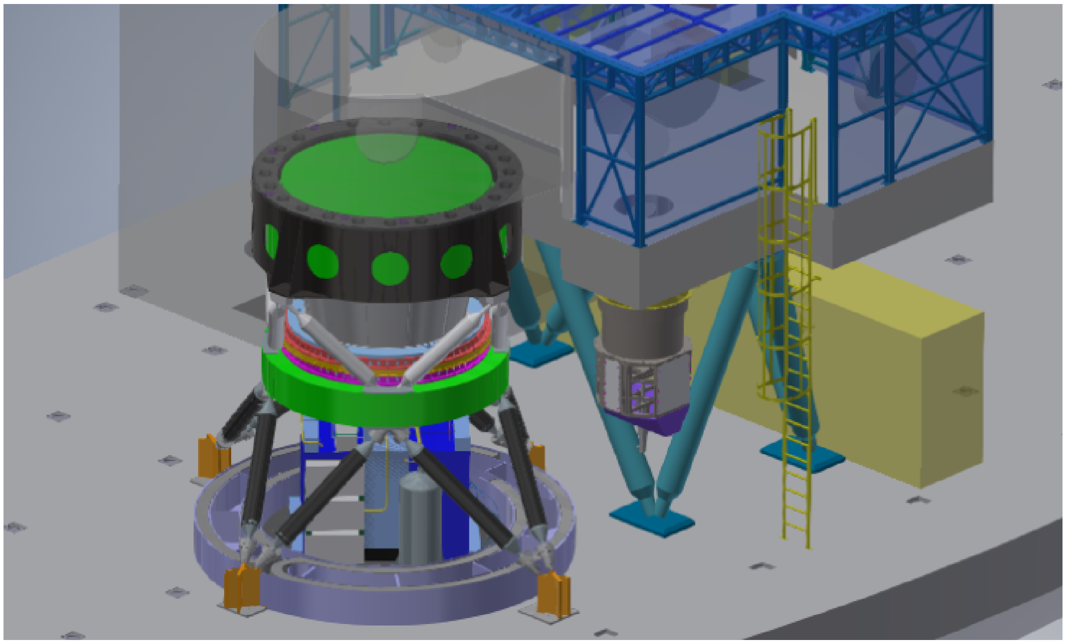

Figure 1. MAORY and MICADO instrumentation on the ELT Nasmyth platform. The bench with blue legs is the main MAORY bench, hosting the Post-focal Relay Optics (PFRO), three calibration units and the LGS module (the grey structure mounted on the bottom surface of the bench). The NGS Module is hosted in the green cylinder (called Green Doughnut, GD) on top of the vertical structure with octopod legs, close to the MAORY bench. The MICADO cryostat (not visible here) is below the GD, centered on the optical axis, that goes vertically, downstream of the last mirror of the MAORY PFRO (visible on top of the GD volume).

## 2. THE LOR WFS SUBSYSTEM

The GD volume is used by the NGS WFS module. It is connected to the MICADO cryostat, in order to minimise non-common path aberrations with the science instrument. The GD is divided vertically in 2 parts: on the top 400 mm height it hosts the SCAO module (holding a NGS wavefront sensor and other tools for the SCAO mode), while on the 600 mm below, it hosts the Low-Order and Reference module, holding three wavefront sensors for the MCAO mode. They cover an annular patrol field of 180 arcsecs diameter (except the MICADO scientific field of 53''x53''centered on the optical axis). Each probe is fed by its 45° pick-off mirror that folds the NGS beam in a plane orthogonal to the optical axis and parallel to the MICADO rotator plane, to cover approximately 1/3 of the patrol field (with some overlap) and increase the sky coverage, allowing to select up to three NGSs for the MCAO. They are needed to measure the low-order modes (tip-tilt, but also focus and astigmatism), which are not reliably measured by the LGS wavefront sensors, due to the tilt indetermination problem[8], and to de-trend the LGS measurements from the slow spatial and temporal drifts due to the atmospheric Sodium layer, together with instrumental effects such as spot truncation.

The 3 LOR WFS units, arranged in a 120° geometry, are identical subsystems, supported by a single honeycomb steel plate, rigidly connected to the MICADO rotator through a support structure. Each LOR unit is composed of an optical bench, mounted on a custom high precision gravity-variant stage, (660x330mm travel, with required accuracy of 1μm). On top of each acquisition stage (see Figure 3), an optical bench will host the LOR opto-mechanics, that is composed of:

- a set of reflective fore-optics needed to compensate the differential focus between the 3 LOR WFS, to correct for atmospheric dispersion and to center the pupil on the SH sensors;
- a fast Low-Order (LO) channel to sense at high frequency (up to 1kHz, depending on the NGS brightness) the atmospheric tip-tilt, focus and astigmatisms. It implements a 2×2 SHS, using an ALICE camera, based on Teledyne e2v CCD220 (provided by ESO[9],[10]), with a FoV of ~2 arcsec and working in the 1.5-1.8 μm wavelength range, to maximize the WFS sensitivity needed by the sky-coverage requirements (limiting magnitude $m_R = 24$).
- a Reference (R) channel, hosting a 10×10 SHS, using a FREDA camera, based on a SAPHIRA eAPD array detector (provided by ESO[9],[10]), with a FoV of ~1 arcsec and working in the 0.6-1.0 μm wavelength range. It is used as a

low frequency "truth sensing" at a frequency between 0:1÷10 Hz, to de-trend the LGS measurements, disentangling the distribution in height of the LGS non-common path aberrations (NCPA) and to properly offset the reference slopes of the 6 LGS WFSs.

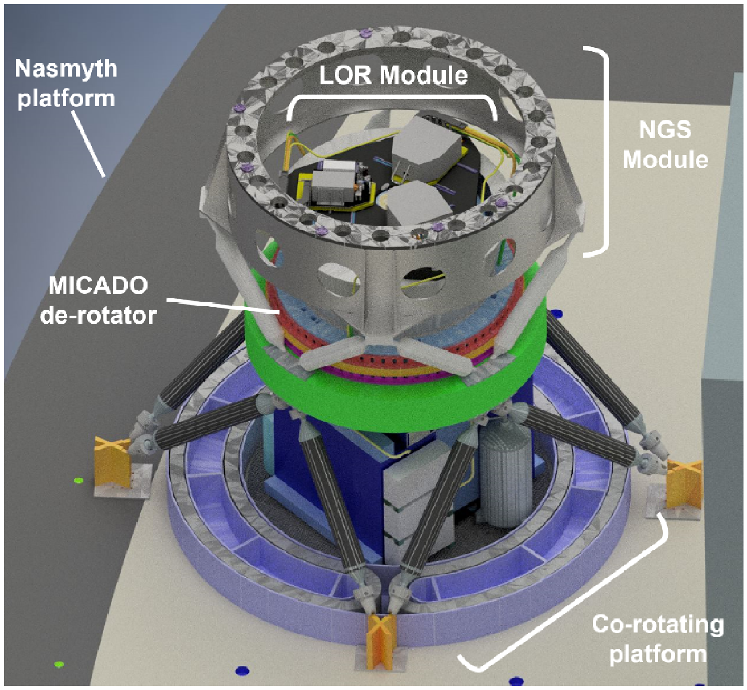


Figure 2. The MAORY-MICADO vertical structure close to the MAORY bench (the grey volume on the right) on the Nasmyth platform. The LOR module is visible on top of the structure (the SCAO module located in the upper part of the NGS Module has been removed here). The MICADO cryostat and the NGS module are de-rotated to keep the field alignment. The platform on the bottom, hosting the nitrogen dewar and all the control electronics, follows the rotation of the subsystems above, within a range of ± 1°.

In the current design, the fore-optics is composed of the following active devices:

- a reflective trombone needed to compensate the differential focus among the 3 LOR WFS units. The selected motorized axis is a Micronix PPS-28SM linear stage ensuring a travel range of ±10 mm with an accuracy of 10 µm;
- a visible technical camera with 10" FoV, an Allied Vision Prosilica GE 2040 CCD with GigE output, mounted on a moving stage (the same linear axis used for the reflective trombone), to be inserted in the optical beam during tests and maintenance operations;
- a tip-tilt mirror on a Physik Instrumente S335 piezo-actuated stage, to adjust the pupil position on the LO and R WFSs, with an accuracy equivalent to 0.6 µas on-sky, when controlled by an auxiliary loop[11];
- an infrared ADC (for the LO channel only) to compensate the atmospheric chromatic dispersion in the H band and restore the PSF quality on the WFS detector. The ADC design has been adapted from the ERIS project. It is composed of two prisms counter-rotated by two Standa 8MPR16-1 rotary stages, coupled with two RLS ASKIM SSI absolute encoders.

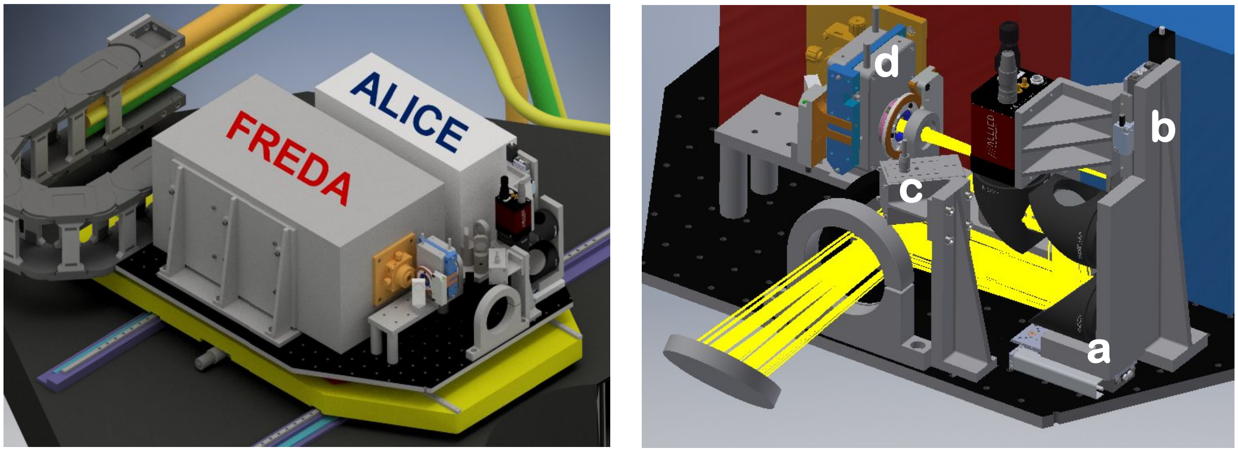


Figure 3. (Left) a single LOR unit. The acquisition stage (yellow) below the optical bench (black) is used to patrol the NGS technical field. The volumes of the ALICE and FREDA cameras, used for the 2 WFS channels, are represented by grey boxes. (Right) main active components of the fore-optics: a) the trombone stage; b) the technical camera assembly; c) the tip-tilt mirror; d) the IR ADC assembly.

Table 1 List of the main components for each LOR WFS unit.

| Unit Acronym | Description | Model/type Reference | Manufacturer |
|---|---|---|---|
| SBO | Support Board (XY dual axes) | Customized / brushless motors with dual feedback control loop | n/a |
| TRO | Reflective Trombone linear stage | PPS-28M (piezo) | Micronix |
| PSM | Pupil steering mirror | S-335 (piezo actuator) | PI |
| ADC | Atmospheric Dispersion Corrector Assembly (rotary stage + encoder) | 2x 8MPR16-1 (stepper motor)<br>2x AKSIM- MHA7SSH16BT10F00 | Standa<br>RLS |
| ACA | Acquisition Camera | Prosilica GE-2040 | AVT |
| ACS | Acquisition Camera Stage | PPS-28M (piezo) | Micronix |
| VCA | 240x240 px Visible Camera | ALICE / on-board Peltier controlller | ESO |
| ICA | 320x256 px Infrared Camera | FREDA / on-board Peltier controlller | ESO |
| TMP | Temperature sensors | PT1000 | n/a |
| RHU | Relative Humidity Sensor | HMP110 | Vaisala |

# 3. CONTROL ELECTRONICS DESIGN

Despite their compact volume, each LOR unit hosts several active devices to be controlled, as shown in **Error! Reference source not found.**Table 1.

Critical points due to the tight volume, are the arrangement of subsystem components and the routing of several cooling pipes, cables and fibers from the moving units to the corresponding control systems. Taking care of all these constraints, the current design allowed to identify suitable solutions also to ensure easy procedures for maintenance. Moreover, it is currently under investigation the possibility to provide each LOR WFS with a DM in the IR path (Dual AO configuration, see 3.5), while keeping untouched the visible channel.

## 3.1 Electronics Cabinets

The LOR module Instrument Control Electronics (ICE) is distributed inside 2 customized cabinets on the co-rotating platform (CPF, see Figure 4), below the MICADO support structure. They host the ICE of the three LOR WFS units, the power supplies required by the visible and infrared cameras, and several subsystem auxiliary devices.

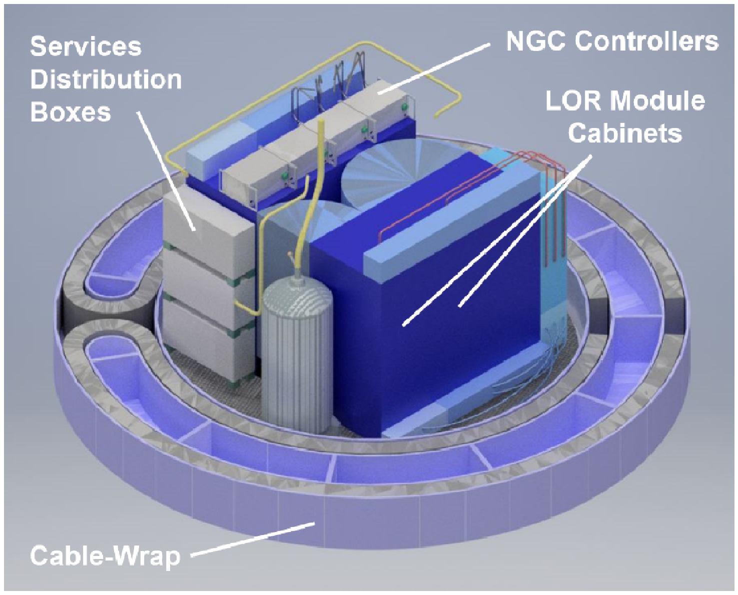


Figure 4. The Co-rotating platform (CPF) below the MICADO support structure. Six cabinets host the control electronics of the NGS Module (SCAO and LOR subsystems). Scientific detector controllers, distribution boxes connecting main SCPs and a Nitrogen dewar for the MICADO cryogenic system are also shown. The whole platform is surrounded by backward-bending cable-wrap around the CPF that is used to route all connections to the Service Connection Point (SCP) on the Nasmyth platform.

The selected cabinets are customized Shroff Varistar LXH3, with dimension 600x800x1600 mm and air/water heat exchanger in the plinth. The max cooling capacity is 3kW.
The cabinets temperature will be managed by ESO Thermal Control Unit (TCU) or by a PLC based system. It will be connected to the pressure sensors and to the valves, in order to control the cooling flow rate and to provide the required thermal dissipation, while monitoring the possible coolant fluid leakage. Despite all precautions, the occurrence of condensation cannot be completely ruled out, therefore all cabinets will have a condensation drain.

### 3.2 The LOR Instrument Control Electronics (ICE)

The LOR WFS Instrument Control Electronics is based on EtherCAT fieldbus, according to ESO standards. The core part of the ICE is the embedded PC from Beckhoff. All EtherCAT terminals and auxiliary devices will be housed in several 19" sub-rack from Pentair-Schroff. To simplify integration tests and maintenance operations, the architecture has been designed to be as much modular as possible. For this reason, a main sub-rack will host the Common ICE Electronics, while every WFS unit will have a separate ICE module accommodated in smaller 19-inch sub-racks. The architecture has been designed as the best trade off among the instrument hardware complexity, standards compliance and volume constraints. Despite the compact and modular design, components arrangement allows easy access for maintenance operations.
All time-critical processes will be synchronized through the Time-Synchronization Terminal EL6688 with Ethernet interface. It will receive the IEEE1588 Precision-Time-Protocol (PTP) signal provided by E-ELT SCP.
Analog I/O terminals (ES4102, ES3162, ES3204) placed in each LOR sub-rack are used to control the PI S-335 tip-tilt steering mirror required to stabilize the pupil on the WFS field (through three E-727 amplifiers), and to monitor temperature and humidity values. Digital I/0 (ES2004 and ES1004) are used to switch ON/OFF piezo amplifiers, secondary power supplies, third-parties controllers and as input for limit and reference switches and failures detection. Communication though the EtherCAT fieldbus will be ensured using EtherCAT coupler (EK1110) and Extension terminals (EK1100, EK1122) to connect each LOR sub-rack according to a star topology.
To meet requirements, all mechanisms have been selected with position feedback for open loop or (when required) closed loop operation. For this reason, Beckhoff terminals for stepper and DC motors will be used whenever possible, combined with encoder terminals for 1Vpp or RS-422 differential feedbacks. Since LOR acquisition stages require

powerful brushless motors, they will be controlled by GOLD DC Whistle EtherCAT servo-drives from ELMO They have been already successfully used at VLT, where they demonstrated to be very reliable and easy configurable devices.
Moreover, low emission power supplies (PSU) from KNIEL will provide the required power, in a redundant n+1 configuration, to provide sufficient power to keep all the system working in case of a single PSU failure.
All camera Local Control Units (LCU) instead, will be housed in a 19'' rack system in the Telescope Control Room.

### 3.3 Routing cables, pipes and fibers

The CPF is surrounded by backward-bending cable-wrap. It is needed to route all connections from the MAORY and MICADO subsystems to the Service Connection Points (SCP) on the Nasmyth platform. Moreover, all cables, fibers and cooling pipes between the NGS module and the CPF are routed through holes in the MICADO de-rotator. Three main bundles have been identified from the CPF to the LOR units. They will be split in different groups of feedthroughs on the de-rotator flange, to separate power cables, feedback signals, fibers and cooling lines.

Main connections between the CPF and the LOR module are:

- 2 Cooling liquid lines (inlet/outlet pair)
- 3 Ethernet links for Technical Cameras
- 6 power cables for LOR acquisition stage motor
- 12 acquisition stages encoder signals cables
- 6 servo cables (used for miscellaneous motors and feedback signals)
- 15 piezo voltages and sensors cables for pupil steering mirrors
- 3 signal cables for environmental probes and sensors;
- 18 Optical fiber pairs from cameras to LCUs and RTC[12], and for the IEEE 1588 Precision Time Protocol (PTP).

### 3.4 Interlock System and Alarms

To ensure safe operations and to prevent human injury and instrument damage, interlock systems are mandatory. They are ensured by potential-free contacts. Moreover, interlocks are software independent, but their status will be continuously monitored by the Instrument Control System[13] (ICS).
An interlock system will be also used to avoid collisions between the three LOR WFS units and the SCAO dichroic during operations. The goal of this safety system is to verify that during SCAO operations, LOR boards will hold a steady (parking) position, allowing the free and safe motion of the SCAO dichroic mount. On the other hand, during MCAO operations, the dichroic mount shall keep its parking position, to prevent collisions with the NGS units. This interlock system will be based on 24VDC mechanical switches and independent hardware to control the two subsystems operation.

A Central Alarm System (CAS) will be used to monitor possible risks for the subsystems, in particular:

- Overheating of the electronic cabinets;
- Coolant liquid leakage;
- Power loss from UPS or normal power;
- Failures of cameras power supplies;
- Motor overheating, humidity and condensing;
- LORs safety alarms, interlocks failures, malfunctions.

In case one or more of these events occur, they will raise an alarm in the ICS and trigger visible and acoustic signals for local operators. This will also help to decrease the downtime of the instrument in case of malfunctions.

### 3.5 Dual AO Option

Preliminary end-to-end simulations of the complete MCAO system[14],[15] have shown that it could be necessary to add a dedicated Deformable Mirror (DM) in the optical path of each LOR to achieve the required performance within the technical FoV, enhancing the AO correction in the direction of each NGS, in a sort of Dual Adaptive Optics (DAO) scheme. It would be possible controlling the DM in open loop, relying on the tomographic measurement of the atmosphere obtained through the LGS WFSs. This solution would require to re-arrange the LO WFS optical design to make room for an additional deformable mirror, while keeping untouched the R WFS and fore-optics layout. Among the

main changes that would be necessary for the new configuration, from the control system point of view, the new design would include 3 DMs and 3 variable spatial filters (iris diaphragms).
For the current design of this option has been selected a MEMS 492-3.5 from Boston Micromachines, having 24 actuators on a 9.2 mm diameter aperture, with a stroke of 3.5 µm. Its drive electronics can be interfaced through a fiber link. The high voltage connections between the DMs and the drivers will probably require some customization, since the length that should be covered from the LOR units to the electronic cabinets on the CPF. A possible solution could also be to place a further small cabinet (hosting the DMs control electronics) close to the LOR WFSs.
The adjustable field stop for the LO WFS internal focal plane in the DAO option should be a commercial unit as the SID-5714 motorized iris diaphragm from SmarAct.

## 4. CONCLUSIONS

The design of the LOR Module is moving towards the PDR, that is foreseen in 2019. Despite the heterogeneity of the whole MAORY system and the large number of interfaces between MAORY and MICADO, in particular in the support structure where the LOR Module will be installed, after several efforts from the two instruments teams, the design of all subsystems and their control electronics has found several suitable solutions. These will allow to deal with limited volumes, different subsystems need, and routing difficulties, mainly due to the rotation of the hosting structure.
The modular architecture of the LOR control electronics has been designed according to ESO standards and specifications. It will make use of custom and commercial devices controlled by an EtherCAT based system, while interlocks will avoid damages and possible risks, combined with the continuous monitoring of devices and environmental conditions.
Finally, a possible option for a new LOR opto-mechanical design has been investigated, considering also the implications that would lead to a more complex electronic design.

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