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ABSTRACT

The Multi Conjugate Adaptive Optics RelaY (MAORY) for the ESO Extremely Large Telescope (ELT) is an Adaptive Optics module offering Multi-Conjugate (MCAO) and Single-Conjugate (SCAO) compensation modes. In MCAO, it relies on the use of a constellation of Laser Guide Stars (LGS) and up to three Natural Guide Stars (NGS) for atmospheric turbulence sensing, and multiple deformable mirrors for correction, providing uniform, high Strehl and high sky coverage. MAORY will be installed at the Nasmyth focus of the E-ELT and will feed the MICADO first-light diffraction limited imager and a future second instrument. MAORY is being built by a Consortium composed by INAF in Italy, IPAG in France and the School of Physics at the National University of Ireland Galway. In this paper we report about the status of the design of the MAORY Real Time Computer, which is the component in charge of implementing the main AO control loops, as well as of auxiliary computations to keep the loops operating optimally, and of telemetry data collection for post-processing, monitoring, testing and troubleshooting. We will start by discussing the evolution of requirements towards MAORY RTC, with an emphasis on the main driving ones. Then, we will describe how the analysis of requirements has led to the derivation of the main design parameters. Finally, we will illustrate possible RTC designs satisfying user requirements, while also complying with standards set forth by ESO.

Keywords: Multi-Conjugate Adaptive Optics, Extremely Large Telescopes, MAORY, Real Time Computer

1. INTRODUCTION

MAORY[1] [2] is a post-focal adaptive optics module for the E-ELT. MAORY offers at least two adaptive optics modes to support the MICADO[12] near-infrared camera: Multi-Conjugate Adaptive Optics (MCAO) and Single-Conjugate Adaptive Optics (SCAO).

In the MCAO mode, MAORY uses the adaptive mirror M4 and tip-tilt mirror M5 in the telescope and up to two post-focal adaptive mirrors (PFDM1 and PFDM2) to achieve high performance with excellent uniformity of the PSF across the scientific FoV of about 1 arcmin diameter. In order to ensure high sky coverage, wavefront sensing is based on a constellation of up to eight LGS projected from the telescope side at 45 arcsec off-axis and three NGS positioned over a technical FoV of 3 arcmin outer diameter. LGSs are used for high-order wavefront sensing; NGSs are necessary for low-order wavefront sensing to measure the modes which cannot be accurately sensed by the LGSs.

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In the SCAO mode, MAORY uses only the telescope's M4 and M5 and a single NGS SCAO wavefront sensor to achieve excellent performance on a narrow FoV around the NGS itself. The MAORY SCAO mode development is made jointly by the MAORY and MICADO consortia. In both modes wavefront sensing is performed in closed-loop with optical feedback from the sensors to the deformable mirrors. The status of MICADO MAORY SCAO module is described in a separate paper[4].

In this text we will describe the status of the design of the Real-Time Controller for the MCAO mode, which is expected to undergo its Preliminary Design Review in the first quarter of next year. The structure of this paper is as follows: in Section 2 we give an overview of the AO control scheme employed in MAORY, in Section 3 we briefly describe the characteristics of the sensors and actuator which have an impact on RTC dimensioning, in Section 4 we illustrate the real-time control strategy, then, in Section 5, we discuss the soft real-time tasks of the RTC. In Section 6 we describe the preliminary design of MAORY RTC, including possible alternatives for the HRTC implementation. Finally, in Section 7, we give our concluding remarks.

2. AO CONTROL OVERVIEW

An overview of the Adaptive Optics control scheme employed in MAORY has been given in a previous paper[3], to which the reader is referred for more details, here we give a cursory overview useful for the rest of the discussion.

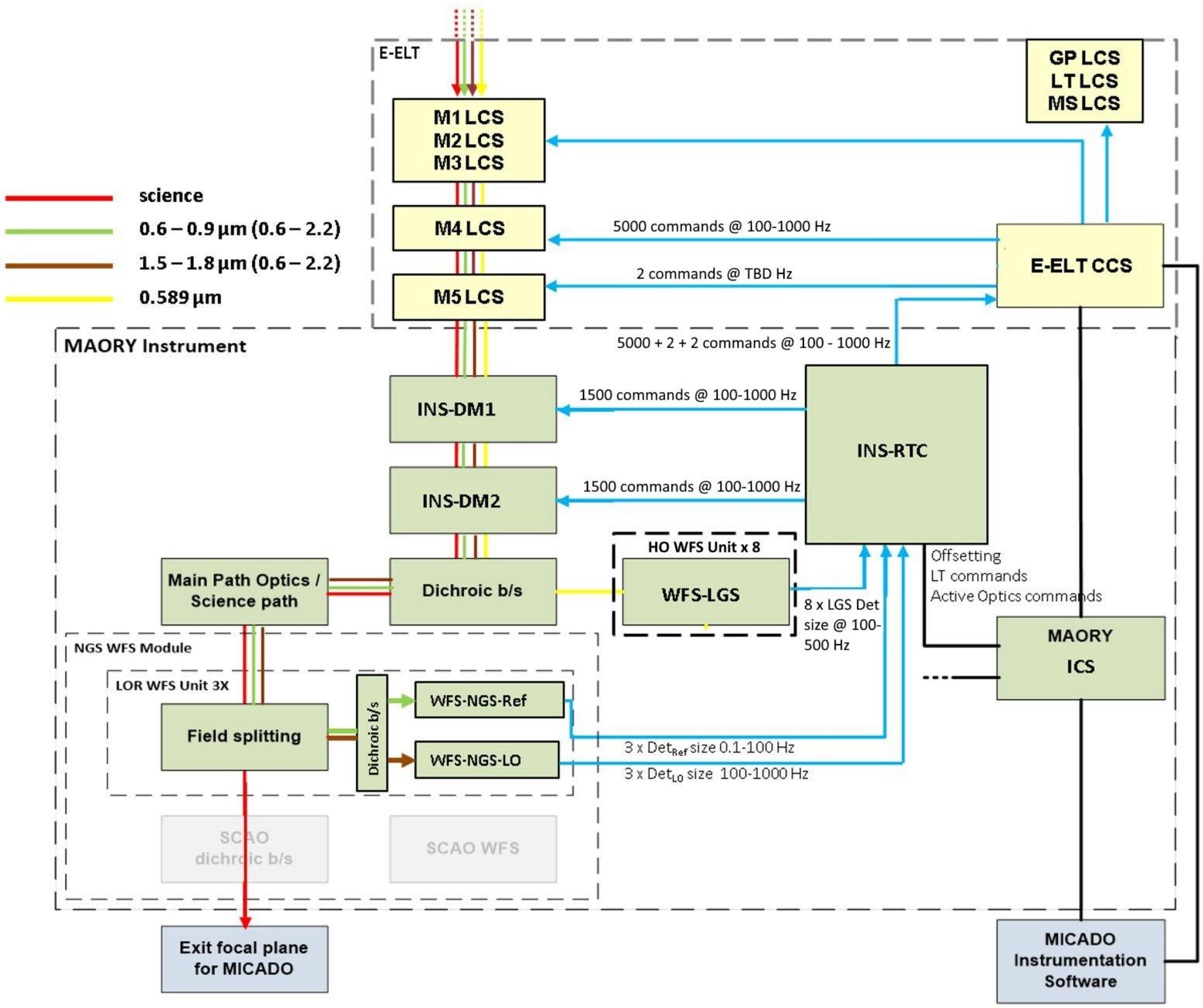

Figure 1. General view of MAORY AO control in MCAO mode. As indicated in the legend, red lines mark the science path, green lines the NGS visible light path, brown lines the NGS infrared light path, and yellow lines the LGS light path.

Real time command paths are marked with light blue lines, non-real time ones are in black. Devices belonging to MAORY are colored in green, while ELT devices are represented by yellow boxes. The greyed-out SCAO boxes are not in use in MCAO mode. Finally, the two grey boxes at the bottom represent MICADO subsystems.

With reference to Figure 1, light collected by the telescope enters MAORY Common Path Optics, which include the two Post-Focal Deformable Mirrors (INS-DM1/2 in the Figure). At this point, light is split by a dichroic: light of wavelength shorter than 600 nm goes to the LGS Wavefront Sensors, while light of longer wavelength goes in the direction of the science path. The light required for the NGS (Low-Order and Reference, LOR) Wavefront Sensors is picked up outside the science field of view ("Field splitting" in the Figure) and is split by a dichroic: visible wavelengths are directed to the Reference WFS, while infrared ones to the Low-Order WFS.

Pixel data collected by LGS and LOR Wavefront sensors are sent to the RTC, which drives in closed loop the MAORY (Post-Focal DMs) and Telescope real-time actuators. The latter include the adaptive quaternary mirror M4, tip-tilt mirror M5 (both seen as one single unit by the RTC) and the Laser Launch Telescopes Jitter Mirror.

3. REAL TIME SENSORS AND ACTUATORS

As described in the previous section, wavefront sensing in MAORY is performed using both Laser and Natural Guide Stars. While the number of NGSs required for MAORY operations has been fixed since a long time, the number of LGSs has been subject to a trade-off study during the course of the Phase B (Preliminary Design). Similarly, for the LGS WFS detector, two alternatives were considered during preliminary design. Further, possible designs for the WFSs, depending on the previous choices, could lead to higher number of actuators in the post-focal DMs in order to be fully exploited. So, in order to deal with design uncertainties and be able to develop a preliminary design for the MAORY RTC, we decided to maintain two sets of requirements for the LGS WFS and the number of PFDM actuators: a "baseline", comprising the most "conservative" requirements, and a "goal", comprising the more demanding requirements. The MAORY LGS WFS parameters are reported in Table 1. In consideration of the much lower number of sub-apertures, the NGS WFSs are not considered critical in the dimensioning of the RTC. It was then natural to develop the preliminary design of MAORY RTC targeting the goal requirements, under the assumption that, if a design for the goal requirements can be realized, then converting to the "baseline" would be a matter of "down-sizing". Parameters for the NGS WFS are basically unaltered and can be found in the previous paper[3].

Table 1. MAORY LGS Wavefront Sensor parameters.

	Baseline	Goal
Number	6	8
Wavelength	589 nm	589 nm
Type	Shack-Hartmann	Shack-Hartmann
Geometry	72 × 72	80 × 80
Detector Type	CMOS	CMOS
Format	800 × 800	1600 × 1100
Frame Rate	500 Hz	500 Hz
Readout Mode	Rolling Shutter	Global Shutter

The number of commands of ELT M4 has been taken to be 5000, while for the post-focal DMs two numbers have been considered: a baseline of 700 and a goal of 1500 actuators.

4. REAL TIME CONTROL STRATEGY

Figure 2 illustrates the main control loops and tasks for the MCAO configuration. Pixel data from the WFS cameras will be processed to produce slopes. Pixels will be reordered as needed (depending on readout scheme for each camera), calibrated and centroids will be computed for each sub-aperture. The actual centroid algorithm will likely differ for each WGS, in particular, since the LGS WFS spots will be elongated, the LGS spot centroid will be computed by means of a weighting map.

The baseline control strategy is based on Pseudo Open-Loop Control (POLC) algorithm[7]. Three POLC loops are foreseen: High Order (LO) and Low Order (LO), that compute the split tomography and the real time correction of the wavefront distortion, and the Reference (REF) loop that measures and corrects slower wavefront distortion of low to medium order poorly sensed and/or corrected by the other loop.

In order to reduce the required computing power, the coordinate system of the modal bases that describe the reconstructed atmospheric layers, the pupil and metapupils wavefronts as well as the DMs commands is kept fixed with respect to the nominal telescope pupil, i.e. all the planes are kept at constant distance, orientation and center. The spread of the turbulence strength among the reconstructed layers will thus depend on telescope elevation other than the atmospheric properties. The post focal DMs surfaces will thus rotate with respect to the coordinates system as consequence of the telescope elevation. Also, the NGS WFSs, both Low-Order and Reference, will rotate with respect to the coordinates system as consequence of sky rotation.

Three primary loops will be implemented in hard real-time in MAORY RTC: High-Order (HO) and Low-Order (LO) loops will compute the real time commands on the basis of the LGS WFS and NGS LO WFS measurements, while the Reference (REF) loop, based on NGS REF WFS measurements, corrects slower wavefront distortion of low to medium order. As a baseline the HO and LO tomography and commands are computed in a split way so that the eventual commands are the simple concatenation of the results of the two loops. Deformable mirrors commands are numerically shifted and rotated before being applied, to correct for mis-registration and for rotation of the DMs with respect to the coordinate system. Feedback from the DMs, reporting the commands actually applied, is then used to compute the pseudo open-loop slopes.

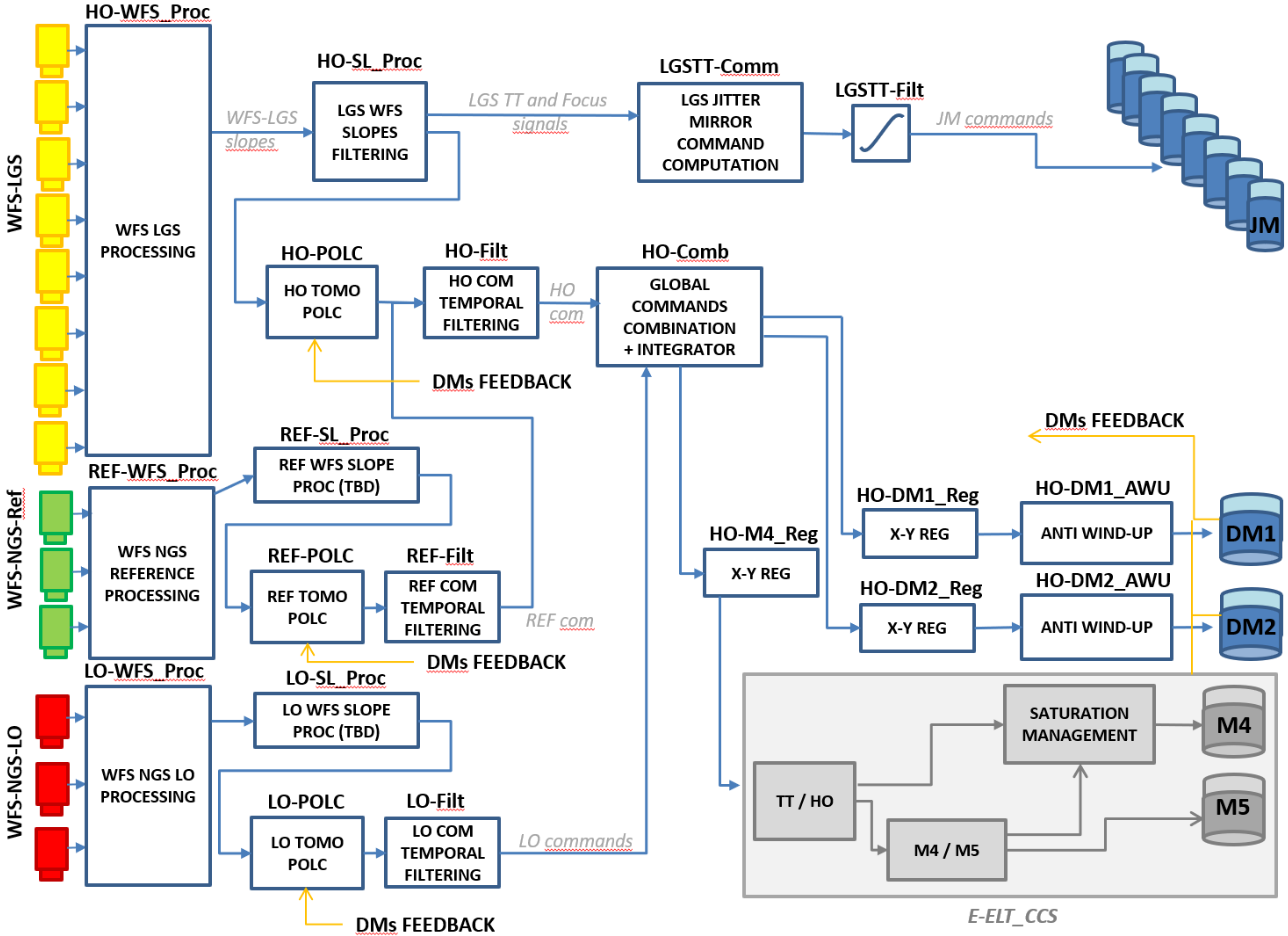

Figure 2. MAORY control loops and tasks for the MCAO configuration.

5. AUXILIARY TASKS

Besides the hard real-time loops, the MAORY RTC must implement a number of auxiliary tasks which run in "soft real-time", i.e. which must not meet strict deadlines for completion but are required for optimal AO correction or for other purposes, e.g. monitoring and housekeeping.

The first set of soft real-time tasks concerns the computation of optimal values for certain loop configuration parameters, which can be in the form of matrices, maps or scalar values. Among these there are the tasks which take large chunks of telemetry data as input (pixels, slopes, commands, …) and produce updated maps like, e.g., WFS background maps, LGS WFS centroid weighting maps, Turbulence and Noise covariance matrices, Post-Focal DM registration matrices, etc. The most computationally demanding task in this group is the computation of the control matrix for the high-order loop, which involves the inversion of a large matrix.

A second set of tasks concerns the estimation of atmospheric and system parameters, in most cases telemetry data from the hard real-time loops are required. Among these tasks we have: estimation of C_n^2 profile, atmospheric parameters (r_0, τ_0, wind speed, …), sodium profile, MCAO performance parameters.

Finally, a third set of soft real-time tasks concerns measurements of various system quantities, some of which may be used for offloading of corrections through high-level software. These include: computation of LGS WFS mean tip-tilt and focus, average WFS pixel frame, average WFS slope measurement, sub-aperture illumination measurement, etc.

Calibration procedures also pose requirements on soft real-time tasks. Calibration of actuators-sensors Interaction Matrices (IM) requires application of patterns on actuators, recording of the WFS signal and subsequent correlation of the data. Synthetic IM computation tasks usually operate on configuration parameters only and implement complex algorithms (involving the modelling of actuator-WFS relationships) to produce the corresponding IM. Other calibrations (e.g. of Non-Common Path Aberrations, NCPA) foresee the injection of disturbance and recording/processing of data with the science detector.

Another soft real-time task involves the collection and monitoring of real-time telemetry for the detection of anomalies and communication to high-level software. In this category are comprised alarms arising, e.g., because of number of non-illuminated sub-apertures or saturated actuators is too high, etc.

Intensive data recording for offline analysis is required during system AIT and commissioning phases, usually involving high data volume. The main purpose of this functionality is the detailed numerical verification of individual system features and possibly aiding specific interventions in the bench and/or component calibrations.

For analysis purposes, telemetry data from the RTC control loops needs to be complemented with the applicable loop configuration parameter updates, system parameter estimations, major system state changes -e.g. loop closure, etc. occurring during the recording. In addition, a means of time-correlating all these data to each other is required.

Data must also be collected to allow for PSF Reconstruction (PSF-R). This requires collecting slopes and commands at loop rate, but not pixels, during the execution of an exposure/observation by the client instrument. Besides telemetry from Hard Real-Time Loops, all relevant matrices employed in the control loops must be stored too. The collected data is sent by the MAORY RTC directly to the Observatory Archive, thus, in order to allow associating science data with PSF-R data, a "tag" is sent by the client instrument to the RTC and stored in the PSF-R FITS header.

6. PRELIMINARY DESIGN

The MAORY RTC preliminary design must take into account the requirements coming from the main AO control loops, the interfaces with the Wavefront Sensors and the actuators (ELT M45, LGS Launch Telescope jitter mirror, Post-Focal DMs), and those coming from the auxiliary tasks. An overview of these requirements has been given in the previous section. Besides those, MAORY-specific, requirements, the design must also satisfy the constraints posed by ESO on all RTCs for ELT instruments.

The latter can be summarized (with some loss of information) as follows:

- The AO RTC is in control of the main AO loops, those which are in charge of fast-evolving atmospheric distortions;

- The AO RTC is not in charge of configuring or monitoring the WFSs or the actuators: it just receives pixels from the WFS cameras and sends commands to the actuators;
- The high-level Instrument Control System Software (ICSS) is in charge of coordination, monitoring or configuration of functions and sub-system involved in AO correction;
- The AO RTC shall be composed of a Hard Real-Time Core (HRTC), in charge of controlling the main AO loops, a Soft Real-Time Cluster (SRTC), in charge of the high-level supervision and optimization, and a communication infrastructure, interconnecting the HRTC, the SRTC, the sensors and the actuators, and integrating the AO RTC into the ELT Communication Infrastructure.
- There is no specific constraint on the architecture of the HRTC, except for the requirement to support ESO standard interfaces and to prepare an obsolescence plan covering the instrument lifetime. On the other hand, the SRTC shall be based on ESO IT servers and the SW shall be developed using ESO-provided SRTC Toolkit.
- ESO standardizes all the communication interfaces (except HRTC internal ones) both in HW and SW.

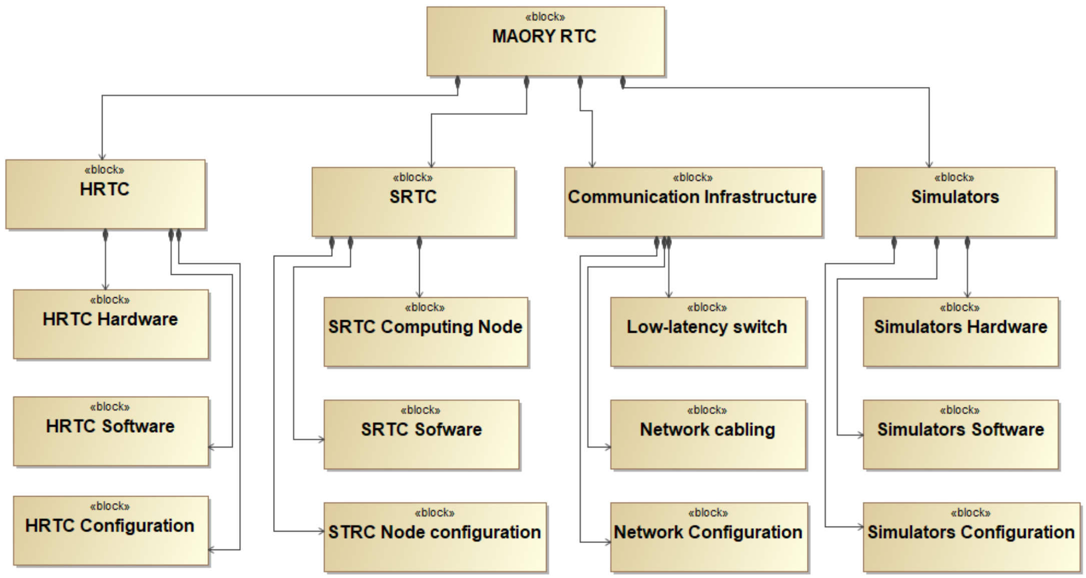

Figure 3. MAORY RTC Product Breakdown Structure

Figure 3 illustrates the Product Breakdown Structure of the MAORY RTC, developed according to ESO constraints. Besides the "mandatory" subdivision in HRTC, SRTC and Communication Infrastructure, a further product is foreseen to support development and testing: the simulators. Simulators will be produced both for WFS cameras and DMs, possibly re-using software developed by ESO for this purpose. They will be used for testing the HRTC without the WFS cameras and DMs, and in particular for numerical verification using simulated data.

6.1 The Hard Real-Time Core

As already mentioned, ESO poses no specific constraints on the internal architecture of the HRTC, in order to allow maximum flexibility in the choice of the solution which can cope with the highly-demanding hard real-time loops. In the MAORY project we decided to procure externally the HRTC and, in the course of the Phase B, we commissioned two studies to verify the feasibility of realizing the HRTC for MAORY using two different technologies.

The first study has been performed by Microgate s.r.l., from Bolzano (Italy), who studied the possibility of realizing MAORY HRTC using the COSMIC platform[6][8]. The HRTC design proposed as result of this study is composed of an off-the-shelf product, the NVIDIA DGX-1 workstation equipped with 8 Tesla VT100 GPUs connected with an ultra-high-speed NVLINK bus which allows direct and dedicated interconnection within the GPU cluster. Another important feature is the High Bandwidth Memory (HBM) directly connected to the GPUs, which is critical in particular for all bandwidth-limited computations, like the MVM. The Real Time Interface is implemented by means of two µXLink FPGA boards by

Microgate. This board, developed in the frame of the GreenFlash project[9], has been specifically designed to act as a "smart interface" allowing, in particular, to transmit the pixels to the GPU cluster and retrieve mirror commands using the GPUdirect protocol, without passing through the CPUs. The proposed design allows to implement all of the hard real-time AO control loops in one single machine.

A second study has been conducted by the research team at the Herzberg Astronomy and Astrophysics Institute of the National Research Council Canada who developed the HEART framework[10] as part of the RTC design for NFIRAOS[11], the TMT first light AO system. The HRTC design, based on HEART, uses commercial-off the shelf (COTS) CPUs running standard Linux distributions (currently CentOS) with the real-time patch and Ethernet communication. HRTC functionalities are partitioned across different server roles. One High-Order Processing (HOP) server is dedicated to each LGS WFS to read and process pixels, and compute the contribution to the DM shape error vector. The HOP servers then send their DM vectors to a single Wavefront Corrector Controller (WCC) server that sums all contributions. The WCC server is also responsible for reading and processing pixels from the low order (LO) and the reference (REF) WFSs, along with final processing of the DM shapes and sending the DM and TT commands. In the "goal" case, in which 8 LGSs are employed, the HRTC is composed by nine machines: eight HOPs and one WCC.

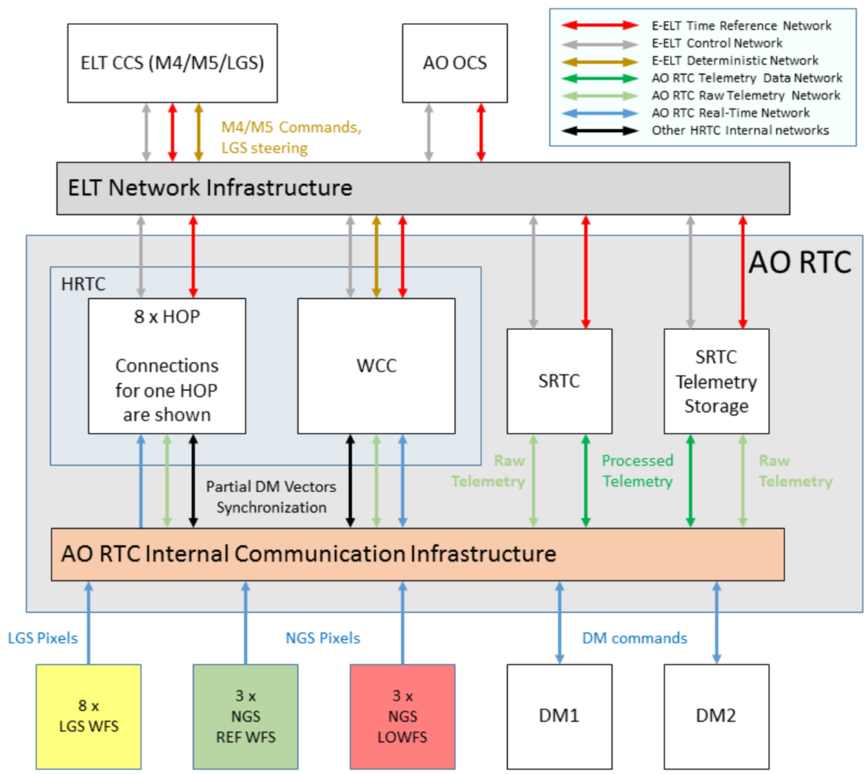

Figure 4. Conceptual view of the MAORY RTC and its interfaces with WFSs, PFDMs, ELT CCS and high-level software in the case of the HRTC being based on the HEART framework.

6.2 The Soft Real-Time Cluster

The Soft Real-Time Cluster is in charge of high-level supervision and optimization of the AO loops. In practice, it must implement all requirements briefly described in Section 5, while satisfying the constraints reported at the beginning of this Section.

The current, preliminary, design of the MAORY SRTC foresees a total of five servers and a switch:

- A first, ESO IT-standard, server acts as a gateway between the HRTC and the rest of the SRTC. Telemetry from the HRTC is transmitted in an unreliable protocol, based on UDP, the gateway collects telemetry data packets and re-transmits data to the rest of the SRTC using a reliable connection, based on OMG DDS. In the other direction, the gateway gets disturbance data from the reliable DDS connection and injects it in the HRTC using UDP packets.

- A second, "number cruncher", server, possibly equipped with accelerators (GPUs), is in charge of the most demanding computations, e.g. periodic calculation of the HO-loop control matrix.
- Two servers are devoted to all other secondary tasks not requiring a high computational load, including task in charge of loops supervision and interface with the high-level AO software.
- A fifth server is devoted to data recording and is therefore configured with high storage capacity. The exact hardware configuration is still to be defined, but in order to support fast collection of all telemetry data at loop rate, this machine might be equipped with a large RAM disk. This node will also run the tasks devoted to PSF Reconstruction data collection and publishing of disturbance data on reliable communication channel.
- Finally, a network switch will provide the necessary connections between the SRTC and the high-level control software as well as between the SRTC and HRTC.

7. CONCLUSIONS

The MAORY Multi-Conjugate Adaptive Optics module for the ELT is approaching Preliminary Design Review. In this paper we have given an update of the requirements on the Real-Time sensors and actuators to which the MAORY RTC must interface and we have reported about the corresponding updates to the AO control strategy. We have then illustrated the RTC conceptual design that satisfies such requirements and the constraints imposed by ESO. As mentioned in the text, we decided to retain in house the responsibility for the Soft Real-Time Cluster, and to outsource the design and construction of the Hard Real-Time Core. The design of the SRTC follows strictly the guidelines provided by ESO and is thus composed by a cluster of IT standard servers and a number of tasks built using ESO-provided SRTC Toolkit. For the HRTC, at least two alternative designs have been studied by external companies and summarized in this text. The final decision concerning the adopted architecture will be taken after PDR, when a provider will be identified following competitive selection procedure.

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