MORFEO@ELT: Preliminary Design of the Real-Time Computer

A. Baruffolo*[a], I. Baronchelli[a], S. Savarese[b], S. Lampitelli[a], I. Foppiani[c], G. Capasso[b], P. Schipani[b], A. Petrella[a], D. Selvestrel[a], L. Busoni[d], G. Agapito[d], C. Plantet[d], M. Suárez Valles[e], S. Oberti[e], L. Pettazzi[e], P. Hagenauer[e], R. Biasi[f], M. Manetti[f], D. Gratadour[g], F. Rigaut[g], J.-P. Véran[h], D. Kerley[h], M. Smith[h], J. Dunn[h], A. Balestra[a], E. Giro[a], R. Sordo[a], S. Chinellato[a], P. Ciliegi[c]

[a]INAF - Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, 35122 Padova, Italy;
[b]INAF – Osservatorio Astronomico di Capodimonte, Salita Moiariello, 16, 80131 – Napoli;
[c]INAF - Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, via Gobetti 93/3, 40129 Bologna, Italy;
[d]INAF - Osservatorio Astrofisico di Arcetri, largo E. Fermi 5, 50125 Firenze, Italy;
[e]ESO, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany;
[f]Microgate s.r.l., Via Waltraud Gebert Deeg 3e, 39100 Bolzano, Italy;
[g]Astralis-AITC - Stromlo, RSAA, Australian National University, Cotter Road, Weston, ACT2600, Australia;
[h]NRC - Herzberg Astronomy and Astrophysics, 5711 West Saanich Rd, Victoria, BC, Canada.

ABSTRACT

In this paper we report about the preliminary design of the Real Time Computer (RTC) for the MORFEO@ELT (formerly MAORY@ELT) Multi-Conjugate Adaptive Optics module for the ESO Extremely Large Telescope. The ELT MCAO module MORFEO provides high sky coverage, large field, diffraction limited correction in the near infrared. It relies on the use of a constellation of six Laser Guide Stars (LGS) and up to three Natural Guide Stars (NGS) for tomographic atmospheric turbulence sensing, and multiple mirrors (ELT M4 and up to two post-focal deformable mirrors) for correction. In particular, we will discuss the overall RTC architecture, the main control strategy, including provision for vibrations compensation, auxiliary loops and tasks for optimization of correction. We will also briefly describe our product and quality assurance plans.

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

1. INTRODUCTION

MORFEO@ELT[1] (formerly MAORY@ELT) is the Multi-Conjugate Adaptive Optics module for the ESO Extremely Large Telescope. The ELT MCAO module MORFEO provides high sky coverage, large field (over 1 arcmin), diffraction limited and uniform correction in the near infrared. MORFEO provides two gravity invariant output ports, for MICADO[2] and a future second instrument. It relies on the use of a constellation of six Laser Guide Stars (LGS) and up to three Natural Guide Stars (NGS) for tomographic atmospheric turbulence sensing, and multiple mirrors (ELT M4 and up to two post-focal deformable mirrors) for correction. In this paper, we give an overview of the design of the MORFEO@ELT Real-Time Computer, as presented at the Preliminary Design Review, which took place last year. The structure of this paper is at follows: we first recollect, in Section 2, the main requirements towards the RTC, illustrating also the main AO control loops that it has to implement; we then illustrate, in Section 3, the preliminary architecture developed to satisfy those requirement; finally, in Section 4, we briefly discuss our product and quality assurance plan. This work is a natural continuation of what was presented in a previous paper[3], to which the reader is referred for further information.

*andrea.baruffolo@inaf.it; phone: +39 049 829 3404

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2. MORFEO RTC REQUIREMENTS

2.1 MORFEO RTC Context

A thorough description of the MORFEO AO system is given in a separate paper[4]. In MORFEO, wavefront sensing is performed using both natural and artificial (laser) reference sources.

During the preliminary design phase, two possible choices of the number of Laser Guide Stars (LGSs) and corresponding Wave-Front Sensors (WFSs) were considered: 6 (baseline) or 8 (goal). Three probes collect light from Natural Guide Stars (NGSs), each is split in Low-Order (LO) and Reference (REF) WFSs. In total, MORFEO RTC has to receive pixel data from 12 (baseline)/14 (goal) WFSs: 6 (8) LGSs and 6 NGS (3 LO plus 3 REF). The RTC has to calibrate the pixel data, compute slopes, compute, combine and filter commands and, finally, send them to the corrective optics: ELT M4/5 system and up to two Post-Focal Deformable Mirrors (PFDM). In parallel, laser jitter corrections are sent to the launch telescopes.

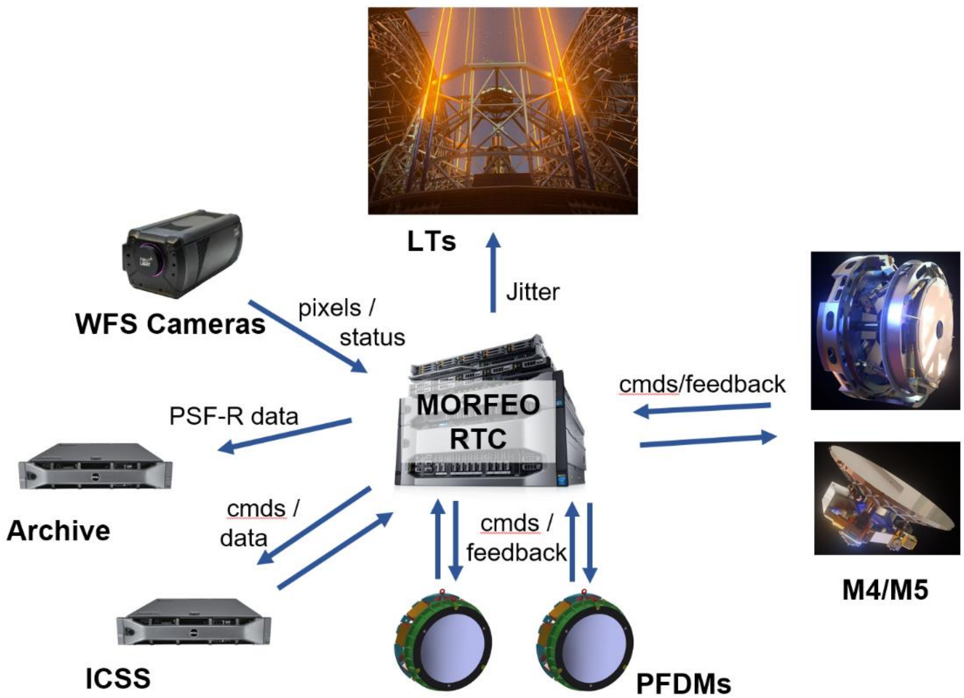

Figure 1. MORFEO RTC Context. The RTC interfaces with the WFS cameras to receive pixel data, computes corrections which are sent as modal commands to the corrective optics. Laser jitter is corrected by sending commands to the launch telescopes. All operations are coordinated by the Instrument Software (ICSS) which also receives statuses and offloads towards instrument actuators. Finally, RTC interfaces with the Archive for storing PSF reconstruction data.

All operations are orchestrated by the Instrument Control Software (ICSS), which also receives statuses for monitoring and for inclusion in the FITS header of the science data. RTC also provides to ICSS with offloads and secondary loop data to be applied by means of instrument actuators. Finally, MORFEO RTC interfaces with the Archive to store PSF reconstruction data collected during science observations.

2.2 Main AO Loops

Figure 2 illustrates the main control loops and tasks running in the MORFEO RTC. The baseline control strategy is based on Pseudo Open-Loop Control (POLC) algorithm[5]. Three loops are foreseen: the High Order (HO) and the 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 distortions, of low to medium order, poorly sensed and/or corrected by the other loops. 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. The HO loop runs at a fixed frequency of 500 Hz (nominal), while the LO one at 0.1-1 kHz and the REF loop at 0.1-100 Hz depending on the NGS magnitude. 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. Provisions are made in the HO and LO loops for correcting unwanted vibrations by means of the Adaptive Vibration Cancellation algorithm[6].

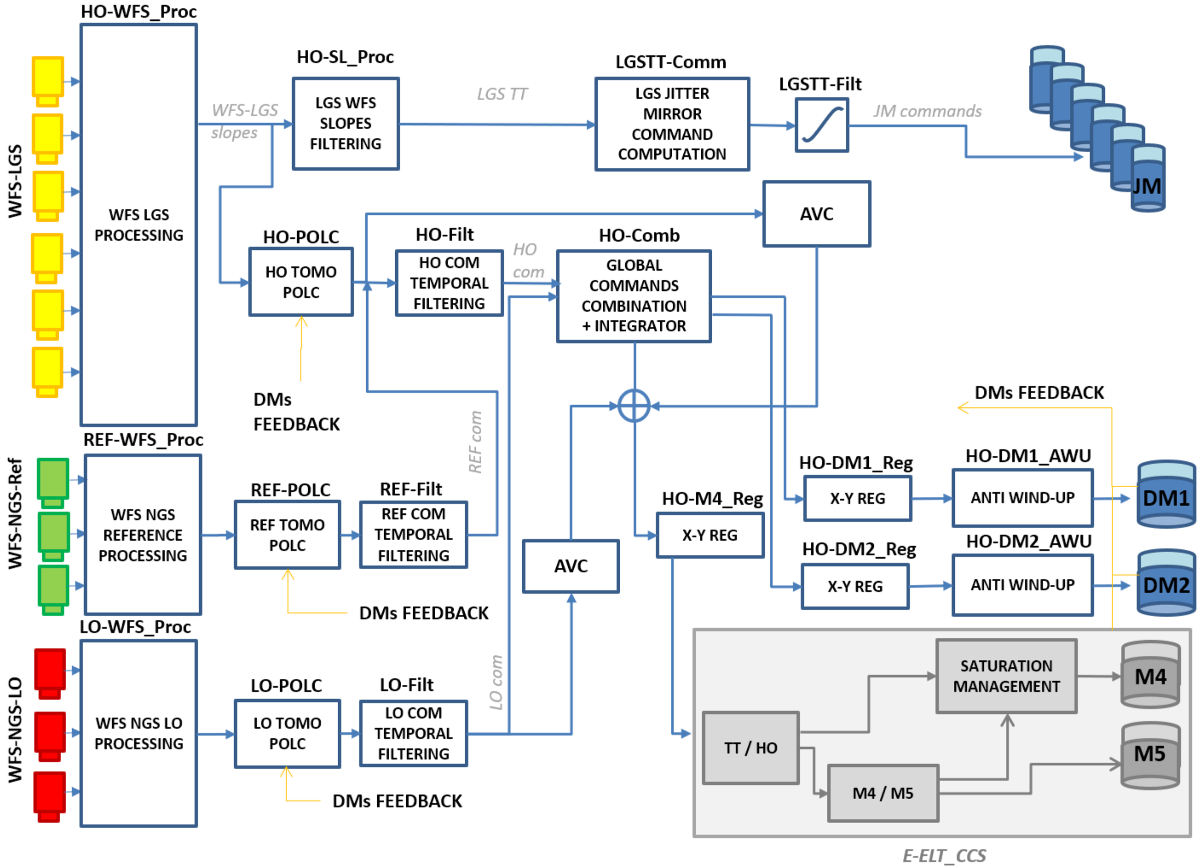

Figure 2. Main control loops implemented in the MORFEO RTC.

2.3 Functional Requirements

The functional requirements towards MORFEO RTC have been illustrated in a previous paper[3]. For the purpose of better understanding the design as discussed in the following sections, here we report a list summarizing the main functional requirements.

The MORFEO RTC shall:

- Receive and process, in real-time at loop rate, pixel data from the LGS and NGS WFS.
- Compute DM commands, by performing tomographic reconstruction and projection, temporal filtering, command combination, mis-registration correction.
- Periodically update the Control Matrices for the main loops.
- Update calibration matrices (background maps, WFS centroids weighting maps).
- Estimate atmospheric and system parameters (C_n^2 profile, r_0, τ_0, wind speed, Na profile, MCAO performance parameters, …)
- Provide means for suppression of vibrations. This includes identification of vibrations, estimation of filter parameters, application of filters in the main loops.
- Provide means for injecting slopes and commands disturbance (for calibration).
- Collect and archive data (slopes, commands, matrices) for PSF reconstruction.
- Compute and publish to ICSS secondary loops data and offloads.
- Provide means for storing telemetry (command and slopes at loop rate, pixels at subsampled rate).

2.4 Real-Time Performance Requirements

Since, during the preliminary design phase, some trade-offs were conducted about the number of Laser Guide Stars (LGSs) Wave-Front Sensors (WFSs), number of sub-apertures, etc., two main scenarios were considered:

- Baseline: 6 LGS WFSs, 42000 slopes, 8000 commands.
- Goal: 8 LGS WFSs. 76800 slopes, 8000 commands.

AO analyses and simulations lead to the specification of a maximum loop delay (from measurement to application of corrections) of 5500 µs, or 2.75 frames at the LGS High-Order (HO) loop frequency, which is fixed to 500 Hz (nominal). From the analysis of the real-time pipeline and the knowledge or modeling of the delays introduced by its various stages, we derived an RTC latency (from the end of the WFS readout to the computation of the last command sent to the DMs) of 690 µs (baseline)/925 µs (goal), where the longer time available in the goal case comes from the smaller WFS detector readout area, which translates in a shorter readout time (the difference being available for computation).
The dominant computation in the LGS HO loop is the Matrix-Vector-Multiplication (MVM) which transforms the measured slopes in modal commands. The required number of operations is $\approx 2\, N_{cmds}\, N_{slp}$, i.e. ≈ 672 MFLOP in the baseline case and 1230 MFLOP in the goal case. If the "dominant" MVM had to be performed in the pure RTC latency time (690 µs and 925 µs respectively) the required computing power would be 974 GFLOPS for the baseline case and 1330 GFLOPS for the goal. In practice, the MVM computation can start during detector readout, so these numbers are, in a sense, upper limits.

Besides computing power, the requirements on memory bandwidth shall also be considered.

	Baseline	Goal
Control Matrix Size	1.34 GB	2.46 GB
Readout time	$1978\cdot10^{-6}$ s	$1745\cdot10^{-6}$ s
Required Aggregate Bandwidth	0.68 TB/s	1.41 TB/s
Required Bandwidth per WFS	113 GB/s	176 GB/s

The aggregate HO-LGS control matrix is 1.34 GB in size for the baseline case (2.46 GB for the goal). Assuming that the control matrix is read from memory in parallel with the WFS readout, this requires an aggregate bandwidth of ≈ 0.68 TB/s for the baseline and ≈ 1.41 TB/s for the goal. Considering that DDR5-6400 provides a bandwidth 51.2 GB/s and HBM2e about 410-460 GB/s, it is clear that the full control matrix, and thus the MVM, must be partitioned across computational units having separate memory channels.

2.5 Telemetry Requirements

Raw data recording at loop rate of all telemetry, including all WFS cameras pixels, will produce a data flow of ~7.7/8.1 GB/s. However, during normal operations, it is not required to store all pixel data. The decimated telemetry data rate (assuming a 1:100 decimation ratio for the HO-LGS loop pixels and 1:10 for the other) is estimated to be ~0.3-0.4 GB/s, which can be managed with standard hardware. Such data acquisition is performed whenever the RTC pipelines are active (starts during AO acquisition and proceeds until the next preset). Since it is required to store data for up to 10 hours, the maximum data volume is ~11-15 TB.

PSF Reconstruction requires collecting slopes and commands at loop rate, but not pixels, during the execution of an exposure/observation. Besides telemetry, relevant matrices employed in the control loops must be stored too. The resulting data rate of ~1.1-1.6 GB/s can be managed without the need of special provisions, i.e. with standard hardware. The expected data volume for 10 minutes of PSF-R data collection is estimated to be ~75-120 GB.

3. MORFEO RTC DESIGN AT PDR

Besides satisfying the functional and performance requirements, the design of an RTC for an ELT Instrument, like MORFEO, must follow the standards imposed by ESO. In particular, the RTC must 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.

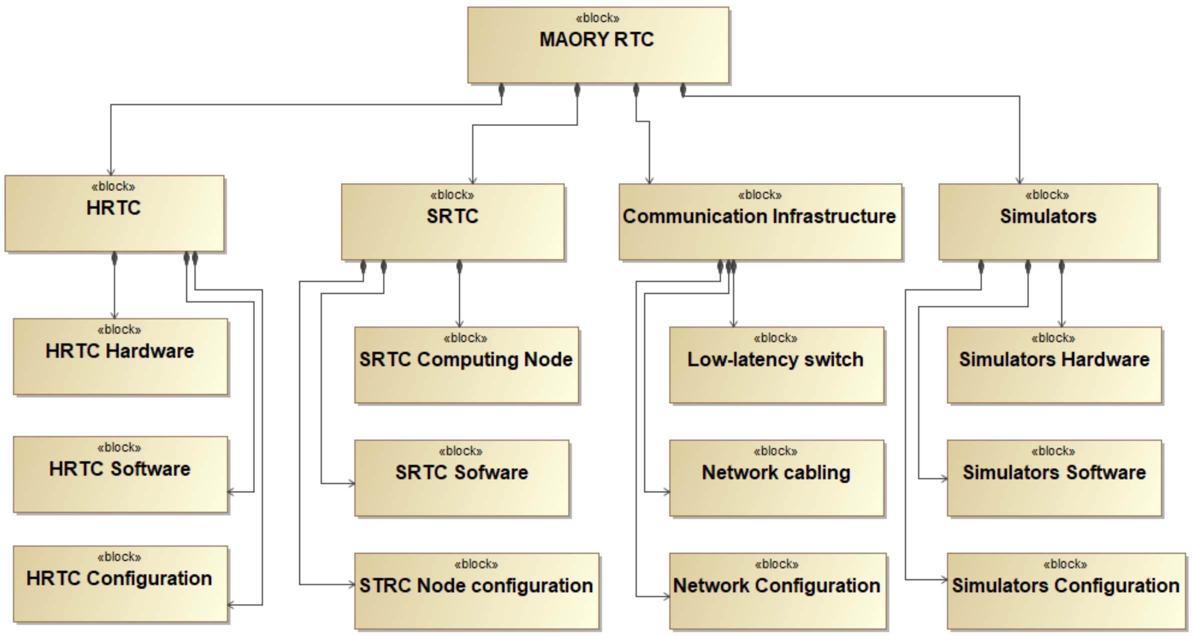

Figure 3. MORFEO RTC product breakdown structure.

Figure 3 illustrates the Product Breakdown Structure of the MORFEO RTC, developed according to ESO constraints mentioned above. Besides the subdivision in HRTC, SRTC and Communication Infrastructure, a further product is foreseen to support development, testing and verification: 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.

3.1 The Hard Real-Time Core

In order to allow maximum flexibility in the choice of the solution which can cope with the highly demanding hard real-time loops, ESO poses no specific constraints on the internal architecture of the HRTC, the only requirements being to support ESO standard interfaces towards WFSs and actuators, and to prepare an obsolescence plan covering the instrument lifetime. At the MORFEO project level it was decided to procure the HRTC externally, while maintaining in house responsibility for SRTC realization and overall system PA/QA, integration, and verification.

Therefore, during the preliminary design phase, two external studies were commissioned, to verify the feasibility of realizing the HRTC for MORFEO using two different technological approaches and estimate the required schedule and the cost.

The first study has been conducted by Microgate s.r.l. from Bolzano (Italy), for a design based on the COSMIC platform[7]. The resulting overall architecture, showing the HRTC integrated in the complete system, is shown in Figure 4. In this design, the HRTC is composed by a single server and one NVIDIA HGX A100 baseboard equipped with four GPUs. The expected performance has been estimated on the basis of prototyping and proper scaling of the results and show that the latency requirement is satisfied. Performance figures will be further verified during design, taking into account that there is the option to “upscale” the solution to eight GPUs, in case more bandwidth is required. The proposed design also features a smart NIC (μXLink board by Microgate) which provides direct transfer of data to/from GPUs through GPUdirect technology and the capability to handle non-mainstream protocols (e.g. ESO protocol used for real-time WFSs pixels and DM commands transmission).

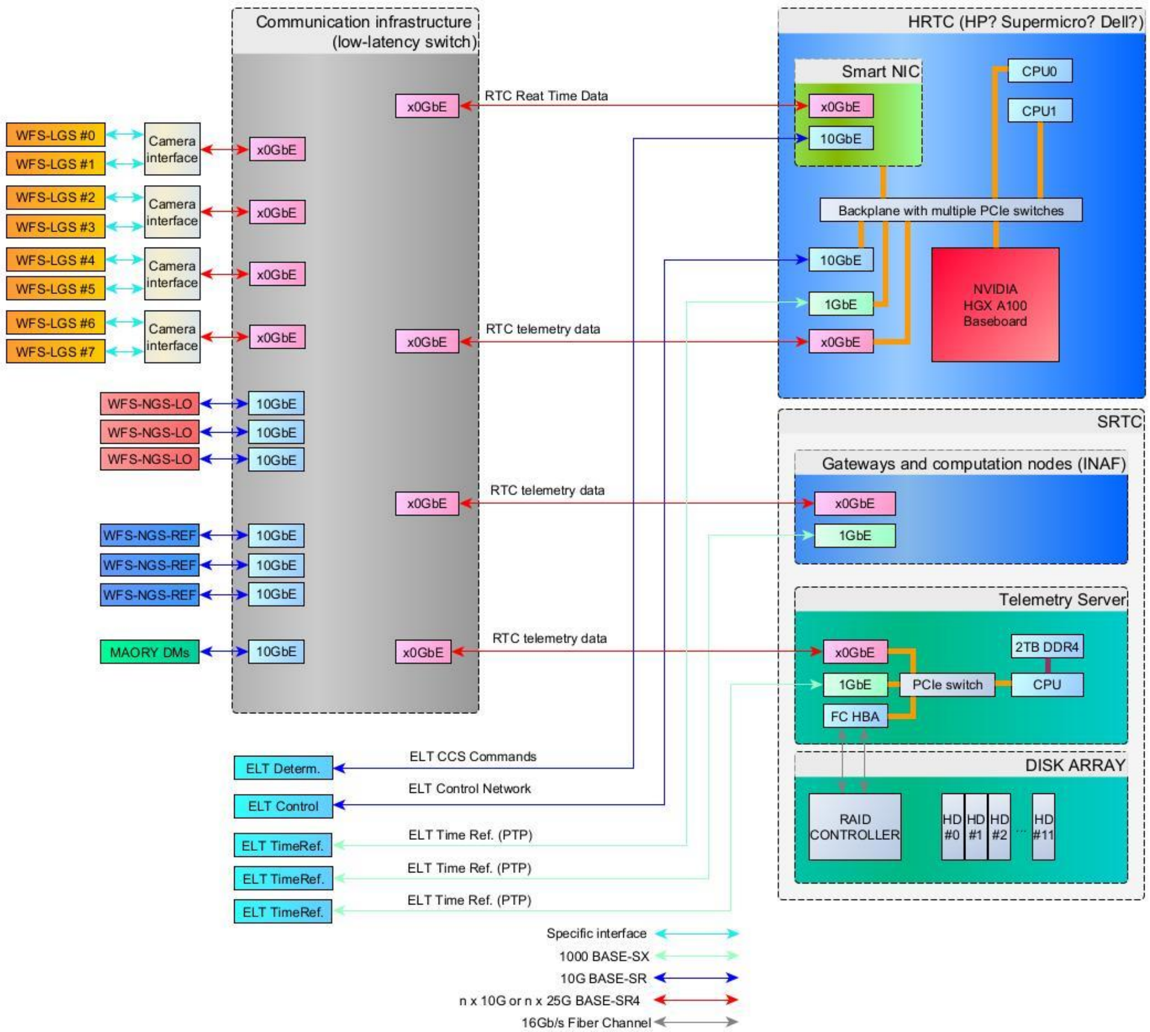

Figure 4. MORFEO RTC design including the HRTC based on the COSMIC architecture.

In the HEART-based design, shown Figure 5, the Hard-RTC is composed of a cluster of High-Order Processors (HOP) and one Wavefront Corrector Controller (WCC). Each HOP receives and processes pixel data from one LGS WFS, and performs a portion of the MVM to produce partial HO commands vector. There are as many HOPs as High-Order LGS WFSs. The WCC receives partial HO vectors, combines them and performs the remaining steps in the HO pipeline. The WCC also receives pixel data from all NGS WFSs (LO and REF) and executes the corresponding pipelines. The WCC combines results from the LGS and NGS pipelines to produce the final commands which are sent to the actuators.

It is to be noted that the HEART solution is entirely based on CPUs, using Commercial Off The Shelf (COTS) servers, and doesn't make use of accelerators (e.g. GPUs). The required performance is achieved by partitioning the load across servers and CPU cores. Also in this case, performance has been estimated by means of prototyping and proper scaling, which show that the latency requirement is satisfied.

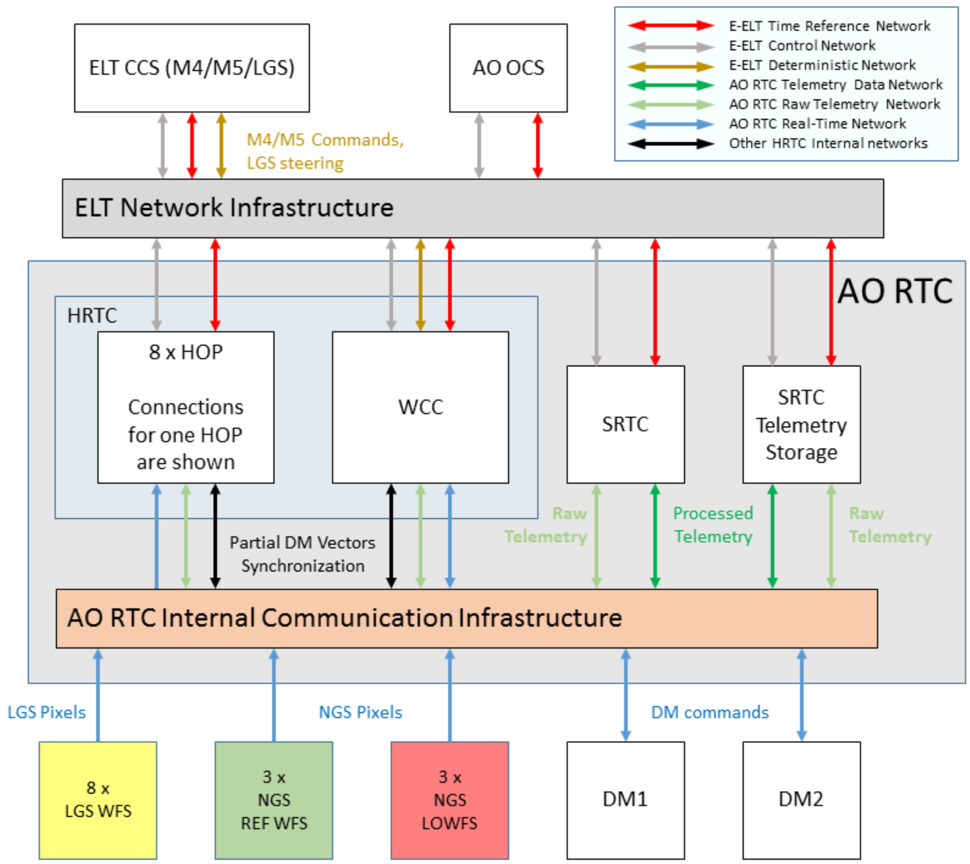

Figure 5. MORFEO RTC design including the HRTC based on the HEART architecture..

3.2 The Soft Real-Time Cluster

The MORFEO SRTC is physically composed by a number of ESO-standard IT servers connected through a switch. Figure 6 shows the nodes and their connection to the telemetry network. To avoid clutter, only the data links are shown, while connections to the control and the time reference networks are not shown, all machines are assumed to be connected to both. The "storage node" machine is also connected to the AO Real Time network, in order to be able to record raw data at loop rate.
Briefly, the cluster will consist of:

- A high-performance server hosting the most computing intensive tasks and equipped with GPU accelerators. It will run, e.g., periodic control matrices update, DMs mis-registration, etc.
- A high-performance server for computing tasks which do not require accelerators and are based on sub-sampled pixel data, e.g.: background following, weighting map, threshold optimization, Na profile determination, etc.
- A high-performance server hosting computing tasks which do not require accelerators and operate on slopes and/or commands telemetry. E.g.: atmospheric parameters estimation, turbulence profile determination, MCAO performance parameters estimation, etc.
- A standard server hosting the supervisory components, interface with ICSS and configuration data services.
- A standard server that acts as a gateway between the HRTC and SRTC networks, for telemetry and disturbance. Collects raw telemetry in unreliable, real-time, HRTC format and publishes it for consumption by SRTC nodes, re-publishes on HRTC network disturbance received from disturbance publishers.
- A standard server with high storage capacity for telemetry recording. Records raw data at loop rate (e.g. for troubleshooting), pre-processed telemetry (e.g. for calibrations) and PSF reconstruction data. Hosts also components for disturbance injection and for collecting metadata to populate FITS headers.
- A network switch providing interconnection among the SRTC nodes and with the HRTC with proper use of VLANs to separate traffic and guarantee the required performance.

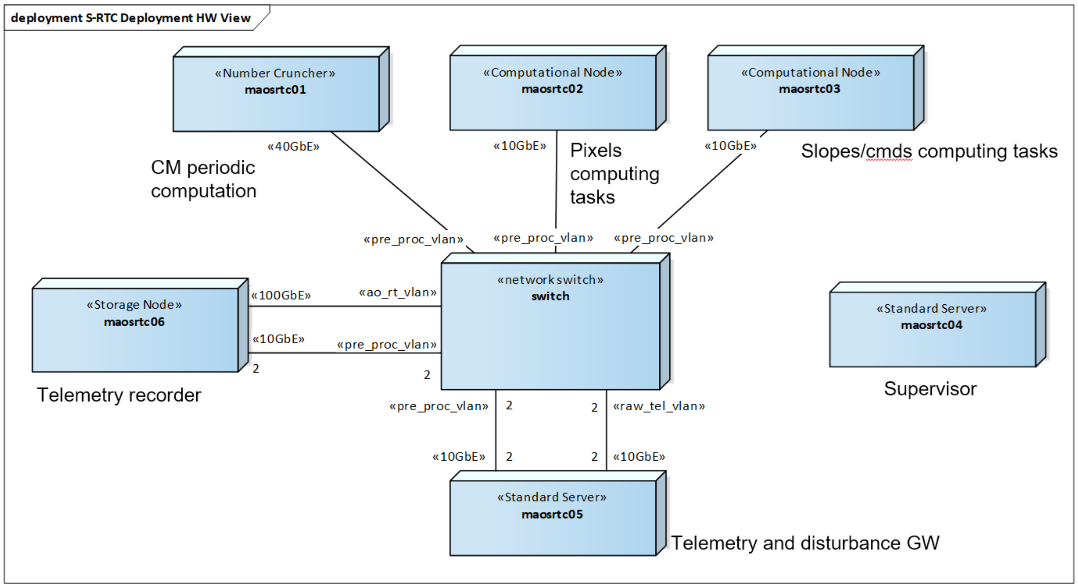

Figure 6. MORFEO Soft Real-Time Cluster

4. PRODUCT AND QUALITY ASSURANCE

MORFEO is subject to the Product Assurance and Quality Assurance requirements established by the ELT Project, which in turn apply to the RTC as well. In order to ensure that these requirements are met, a PA/QA plan has been adopted. Since the RTC is part of the Instrument Control Software and both are subject to the same requirements, the plan developed for latter will be used for the RTC too.

The PA/QA plan for MORFEO RTC identifies a PA/QA responsible, which manages the PA/QA process and ensures it is correctly applies. The plan defines a quality model, in terms of functionality, reliability and maintainability, and the development process (development life cycle, configuration management and documentation plan). A number of metrics are defined to allow quantifying both the progress of the development and to monitor the quality of the product. Procedures are also defined for problem and defect reporting and for the corresponding corrective actions.

The software tools required for supporting all these activities (e.g. requirement tracing, defect tracking, metric collections, automatic tests) are not fully defined yet, they will identified during the final design phase.

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