The MAORY ICS software architecture

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ABSTRACT

The Multi Conjugate Adaptive Optics RelaY (MAORY) for ESO's 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 up to six Laser Guide Stars (LGS) and three Natural Guide Stars (NGS) for atmospheric turbulence sensing and multiple mirrors for correction, providing high Strehl and high sky coverage. In SCAO mode, a single natural source is used as reference, providing better correction but in a smaller field. MAORY will be installed at the Nasmyth focus of the ELT. It 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 and IPAG in France and is currently approaching end of phase B. In this paper we describe the preliminary design of the MAORY Instrument Control System Software (ICS SW). We start with an overview of the MAORY module and then describe the general architecture of the MAORY control network and software. We then describe the main software components, with particular emphasis to those managing the NGS and LGS wavefront sensors functions and the AO off-load and secondary loops, and the main interfaces to subsystems and external systems. We then conclude with a description of the software engineering practices adopted for the development of MAORY ICS SW.

Keywords: Instrument control software, software development process, software quality assurance, adaptive optics.

1. INTRODUCTION

The Multi Conjugate Adaptive Optics RelaY[1] (MAORY) is one of the four first-light instruments for the ESO's Extremely Large Telescope[2] (ELT). It is an adaptive optics module offering multi-conjugate (MCAO) and single-conjugate (SCAO) adaptive optics compensation modes. In MCAO, MAORY relies on the use of up to six Laser Guide Stars (LGS) and three Natural Guide Stars (NGS) for atmospheric turbulence sensing and multiple mirrors for correction, providing high Strehl with a uniform PSF in a relatively large scientific field of view with high sky coverage. In SCAO mode, a single natural source close to the science target is used as reference, providing higher peak performance than MCAO but in a smaller field.

MAORY will be installed at the Nasmyth focus of the ELT. It will feed the MICADO[3] first-light diffraction limited imager and a future second instrument. MAORY is being built by a Consortium composed by INAF in Italy and IPAG in France and is currently approaching end of the preliminary design phase. The SCAO mode is a joint development between the MAORY Consortium and the MICADO Consortium[4].

In this paper we describe the preliminary design of the MAORY Instrument Control System Software (ICS SW). We start with an overview of the MAORY module and then describe the general architecture of the MAORY control network and software. We then describe the main software components, with particular emphasis to those managing the
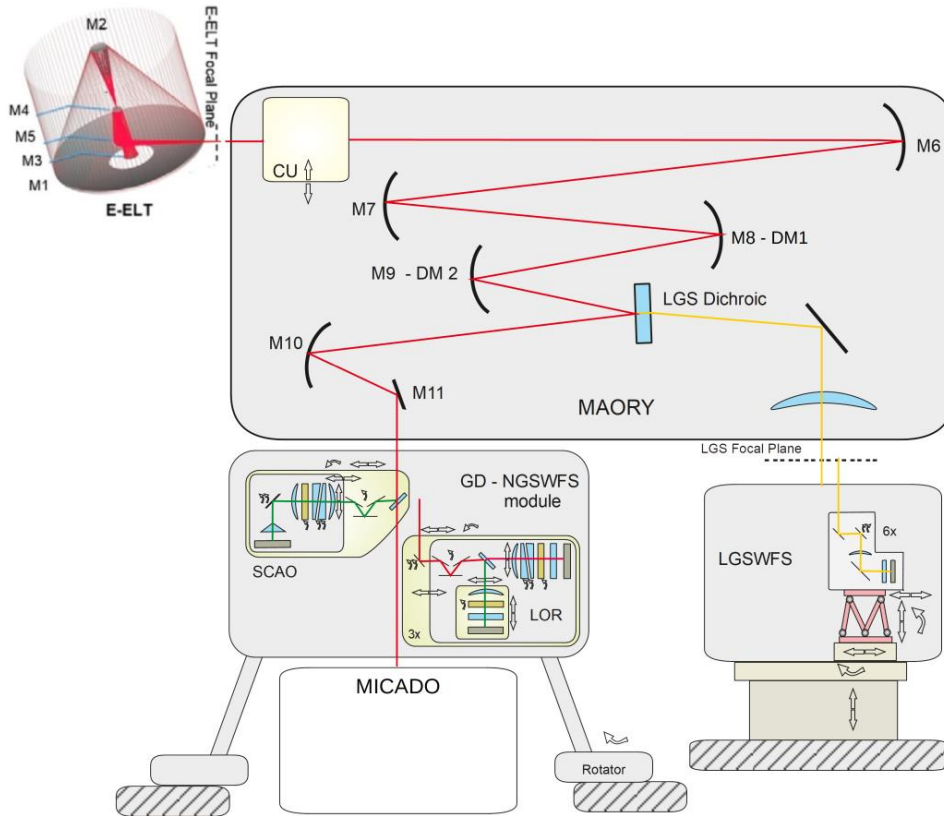
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Figure 1. Functional overview of the MAORY module in the context of the ELT and MICADO client instrument.

NGS and LGS wavefront sensors functions and the AO off-load and secondary loops, and the main interfaces to subsystems and external systems. We then conclude with a description of the software engineering practices adopted for the development of MAORY ICS SW.

2. INSTRUMENT FUNCTIONS

Figure 1 shows a functional overview of the MAORY module in the context of the ELT and the MICADO client instrument. In the current baseline design, MAORY is composed of three major sub-systems: the Post-Focal Relay Optics (PFRO), the Laser Guide Star Wave-Front Sensor (WFS), and the Natural Guide Star WFS, containing the Low-Order and Reference (LOR) WFS and the SCAO WFS. Both the LOR WFS and the SCAO WFS modules are hosted in the MICADO mechanical structure, in the so-called Green-Doughnut (GD).

2.1 Post-Focal Relay Optics

The Post Focal Relay Optics (PFRO, Figure 2) subsystem includes the devices hosted by the main optical bench, that is the Post Focal Relay Optics and the LGS objective.

Light from the telescope enters the MAORY module through an entrance shutter. It is reflected by the M6-M9 mirrors, which include the deformable mirrors (DM), up to a dichroic which splits the light in two paths. Light of wavelength shorter than ~0.6 µm is directed towards six LGS wave-front sensors. Light of longer wavelength (0.6 -2.5 µm) is directed towards the NGS WFS and the science channel. Currently, only one client instrument, MICADO is defined, so a folding mirror (M11 in the Figure) sends the light to the NGS WFS module (which hosts the three LOR and the SCAO wave-front sensors) and MICADO. A deployable mirror can be inserted in the path to direct the light to the second client instrument.

For calibration purposes, the entrance shutter can be closed, and one or more calibration modules can be inserted in the path near the instrument entrance.
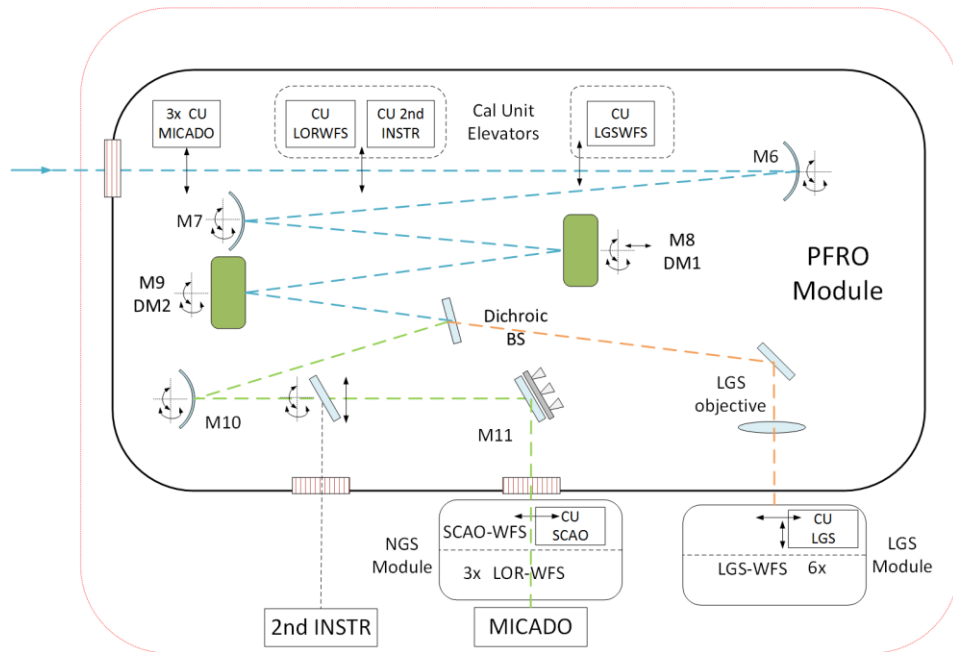
Figure 2. Functional view of the Post-Focal Relay Optics sub-system. See the text for details.

2.2 The Natural Guide Star Wave-Front Sensors

The NGS WFS sub-system[5] or Green Doughnut (GD) is a cylindrical volume located on top of the MICADO cryostat (Figure 3). This Green Doughnut holds the three off-axis NGS WFS for MCAO (so-called LOR WFS), the SCAO WFS, the SCAO dichroic plate and the SCAO calibration unit.

The SCAO dichroic plate is attached on the lower side of the SCAO bench, in the LOR WFS volume, sliding between two positions, either in the beam (for the SCAO mode) or in parking position, at the edge of the GD.
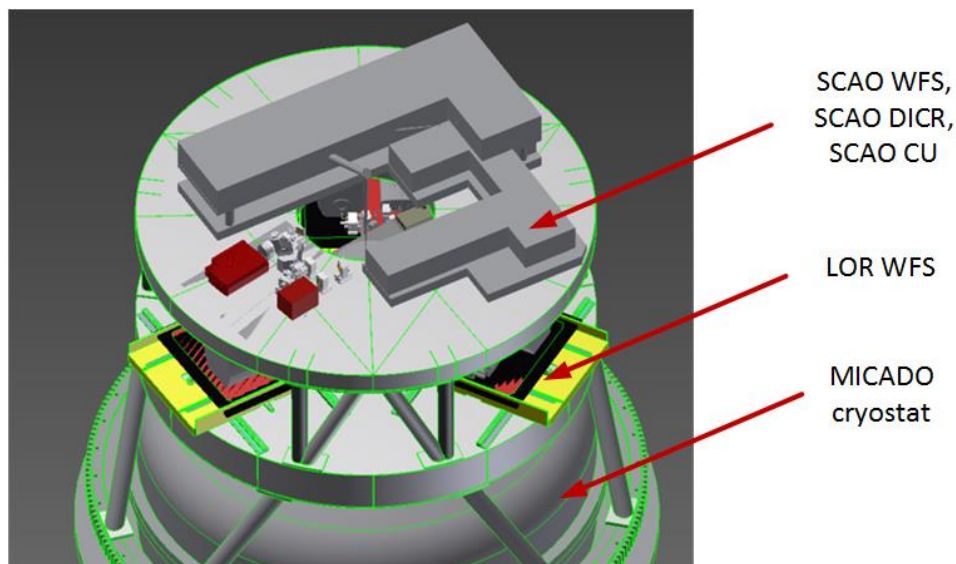

Figure 3. Preliminary mechanical design of the Natural Guide Star Wave-Front Sensors. As explained in the text, the SCAO and LOR WFSs are placed above the MICADO instrument, on two separate optical benches.
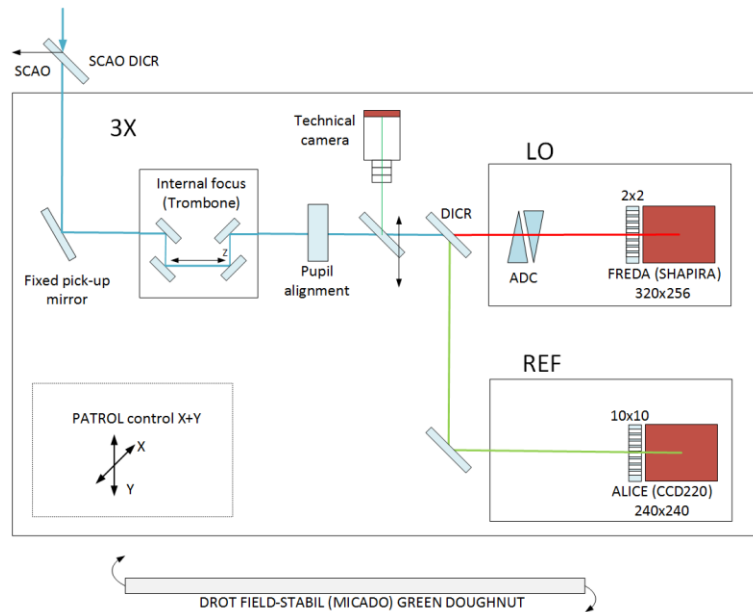
Figure 4. Functional view of one Low-Order and Reference WFS. See the text for details.

Inside the GD, SCAO and LOR WFS occupy vertically separated volumes and rest on a dedicated bench. The LOR WFS are on the lower bench while SCAO is on the upper bench. Both benches are interfaced to the MICADO cryostat thanks to a common mechanical interface.

The LORWFS module is composed of three identical units, placed at 120 degrees intervals. Each unit consists of an optical board mounted on two stages for X, Y positioning on the focal plane. The stages move in order to pick up the NGS, and will track during exposure in order to compensate for flexures, non-sidereal motions, etc. Figure 4 shows the opto-mechanical layout, together with a sketch of the optical path. Note that the patrol field of the three units may interfere with each other, therefore an interlock mechanism is foreseen.

Light from the telescope comes from the top, and is reflected towards the board by a pick-up mirror that moves rigidly with the board itself. A couple of 45 degrees folding mirrors mounted on a focus stage provide focus compensation, the so called 'trombone'. A piezo tip-tilt mirror in the focal plane adjusts the pupil position. After this, a dichroic splits the light into a visible (reference) and IR (low-order) path, the latter also features an ADC in order to correct for atmospheric dispersion.

The reference sensor is a 10x10 Shack-Hartmann (SH), using the ALICE camera, based on Teledyne e2v CCD220 and provided by ESO[6,7], with a FoV of ~2 arcsec. In the baseline, the low-order sensor is a 2x2 SH, using a FREDA camera, based on a SAPHIRA eAPD array detector also provided by ESO[6,7], with a FoV of ~1 arcsec.

2.3 The Laser Guide Star Wave-Front Sensors

The LGS module is an assembly of six wave-front sensor units aimed to measure the wave-front distortions on the laser guide stars. Figure 5 shows a mechanical and functional overview of the LGS module. The light, passing through the LGS objective in the PFRO module, enter each probe, where it is collected by a LISA camera equipped with an optical CMOS detector[6,7]. Each probe is mounted over a hexapod to control the movement in X and Y (change of asterism's diameter, pupil alignment) and Z (internal focus). All probes are mounted over a common de-rotator to follow the LGS constellation rotation and a common linear stage for the global focus adjustment.

On top of the structure, a fibre positioner mechanism can feed each sensor with the light coming from the dedicated LGSWFS calibration unit, hosted in the PFRO module and from the internal calibration unit, hosted in LSG WFS subsystem itself.
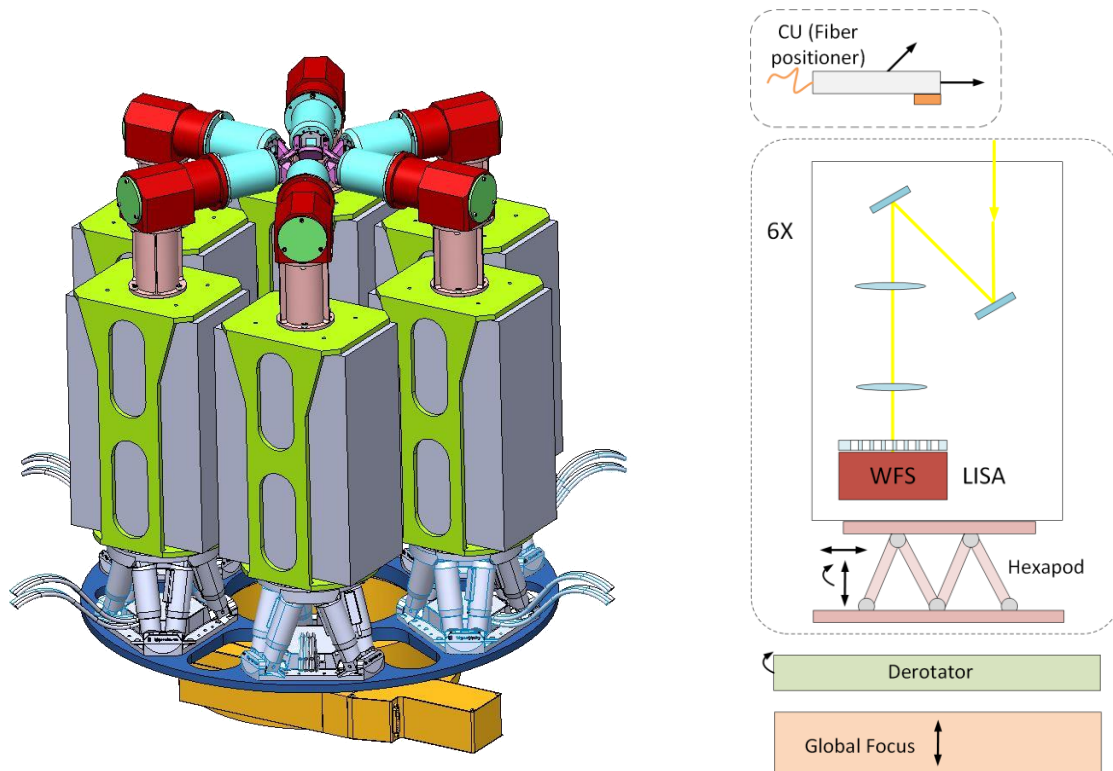
Figure 5: MAORY Laser Guide Star Wave-Front Sensors. On the left: preliminary mechanical design of the LGS WFS assembly. Right: conceptual view, showing the optical path past the pick-up mirror, the WFS detector and the hexapod for positioning and rotation, as well as the global de-rotator and focus mechanisms and the internal calibration unit.

3. CONTROL NETWORK

Figure 6 gives a conceptual overview of the baseline MAORY Instrument Control System architecture. The architecture is still preliminary and is strongly influenced by the design currently in use at VLT Paranal Observatory. It is likely to change as the design advances and more details are clarified. It should also be understood that the diagram is purely conceptual, i.e. it aims at showing the nodes on the network and their location, without dealing with the details of the exact number of connections, switches, etc. For the control network, the ELT standards mandate for Ethernet technology, with capacities ranging from 100BASE-TX to 10GBASE-T, depending on the requirements.

The instrument functions will be controlled by four PLCs[9], shown on the left, which will also be in charge of monitoring the instrument sensors. Each PLC will be dedicated to one sub-system, thus facilitating integration and testing.

MAORY will have no science detector, but thirteen WFS cameras: one each for the LGS WFS, one each for the LOR WFS and one for the SCAO WFS. During AO operations, when the loops will be closed, the WFS cameras will transmit data to the Real-Time Computer over 10 Gb Ethernet on a deterministic network (not shown in the figure), separate from the instrument control network. The WFS cameras will be controlled by MAORY ICS SW through the control network, via Linux Local Control Units (LLCUs). At the time of this writing it is not defined whether one LLCU will be needed per camera or one LLCU will be able to control several cameras.

Each NGS-based WFS will also be equipped with a Technical Camera, to support target acquisition operations. Also in this case the details are not defined yet, but it's likely that they will be COTS components, possibly based on the GigE Vision standard as currently in use at the VLT Observatory[8].

The MAORY Real-Time Computer[10] (RTC) will be located in the ELT Observatory Server Room and connected through a deterministic network to the WFSs and the actuators (instrument and telescope deformable mirrors). The RTC
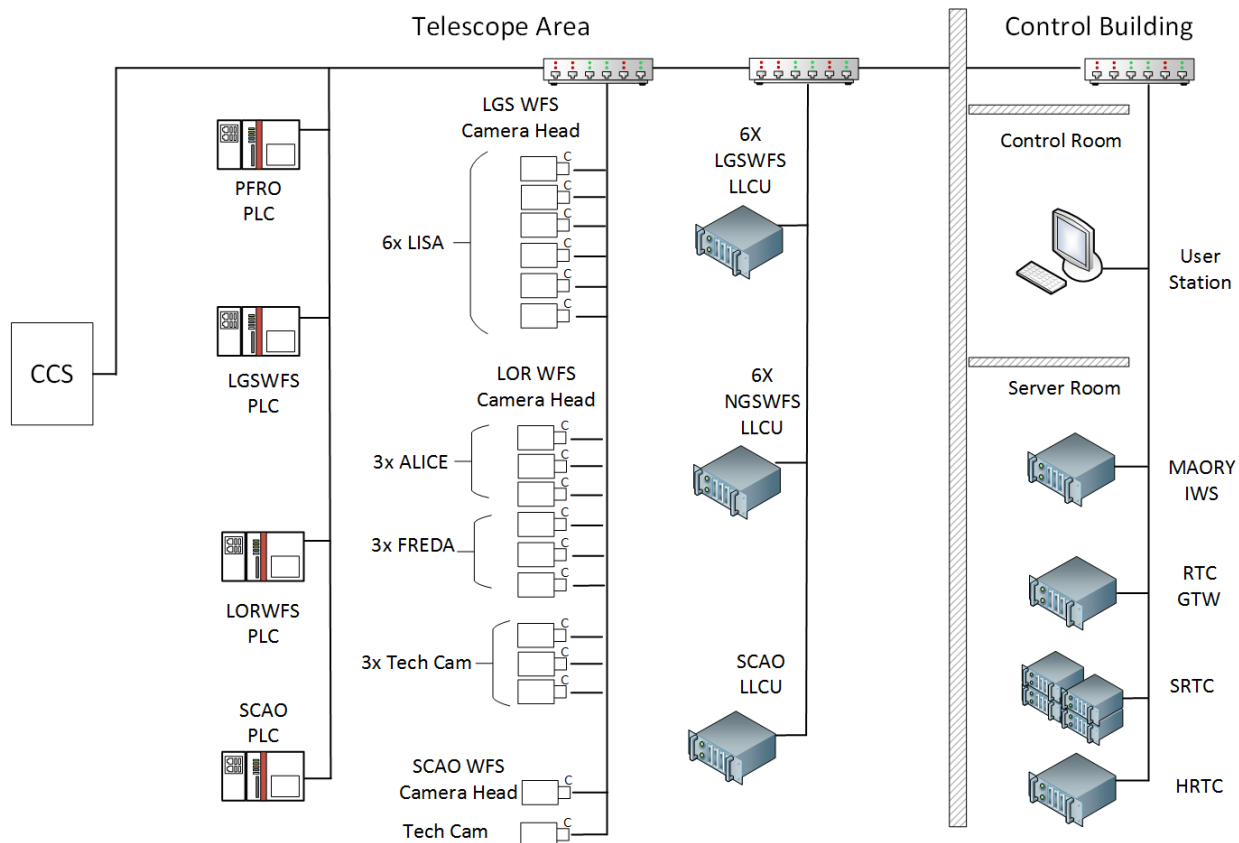
Figure 6: MAORY Instrument Control System conceptual architecture. See the text for details.

will be composed of a Hard-Real Time part (HRTC), in charge of real-time wavefront reconstruction and correction, and a Soft-Real Time part (SRTC), in charge of performing auxiliary computations concerning loop optimizations or offloads. At present, it is expected that the RTC will communicate with MAORY ICS SW through a "gateway" (RTC GW). Again this is done by analogy with the VLT practice, with the aim of clearly separating the two systems, which can then evolve in parallel (as long as they conform to the same interface).

The MAORY Instrument Workstation will also be located in the Server Room, and connected, through the control network to the RTC (via the gateway), the WFS cameras LLCUs, the Technical Cameras and the PLCs.

4. INSTRUMENT SOFTWARE ARCHITECTURE

The preliminary architecture of the MAORY ICS Software is illustrated in Figure 7. It has been derived after the analysis of the requirements and taking into account the constraints imposed by the ELT Project, in particular those dictating the general architecture of ICS Software for ELT instruments.

MAORY ICS SW consists of common software components and two specialized software sub-systems: one devoted to MCAO and one to SCAO. This subdivision has been chosen because of the clear separation of devices to be controlled in the two modes, the very different operational requirements and because the two software will be developed by separate teams.

4.1 Coordination Software

The coordination level includes a main component, the MAORY Observation Coordination Manager (OCM), which is in charge of coordinating the MCAO and SCAO sub-system managers (SSM) and managing the interfaces with the client instrument, the telescope and the RTC. The MAORY OCM is supported by a Data Product Manager component, which responsible for preparing the final data products for archival. Since MAORY has no science detectors and will not

perform science observations by itself, it is foreseen that data products will be archived only during calibration and maintenance operations.

During operations, MAORY OCM will receive commands either from MICADO or the second client instrument ICS software. On the other hand, when operating in standalone, i.e. for calibration and maintenance, the corresponding procedures, implemented as templates, will be run through a sequencer, which is also considered part of the coordination level of the software.

Secondary loops and offloads will be handled through a dedicated Manager component. In most cases, input will come from the RTC, transformed as required, and correction will be performed using the module actuators or sending commands to the telescope CCS. The component is also in charge of handling alarm conditions which might arise during observations. In this case, the loops will be opened, and the client instrument software will be notified of the alarm situation. It is worth noting that it is still under discussion whether to have a single Secondary Loops and Offload Manager at the coordination SW level, or to separate it in one manager per sub-system. Further analysis of the operational scenarios will provide the input for a final decision.

4.2 External interfaces

As already mentioned, MAORY OCM is in charge of managing interfaces with external systems. In particular, MAORY OCM will interface with the client instrument OCM to receive commands, provide status information and AO data, collected during an exposure, required for proper data analysis, to be archived with the science frames.

It is worth noting that a number of AO operations, especially during target acquisition, will consist of sequences of actions, which are best implemented as functional units callable form templates scripts. These "functions" will have to run in the client instrument's sequencer, as part of the target acquisition or observation templates. On the other hand, their implementation requires intimate knowledge of the inner workings of MAORY and the AO loops. For these reasons, such functions will be implemented by the MAORY team and provided as a template library to the client instrument ICS SW developers. This has been agreed with the MICADO team, and the library specification is part of the corresponding ICD.

A similar situation arises for MAORY calibrations which require access to the client instrument focal plane. In this case, MAORY ICS SW would need to be "shielded" from the details of setting up and performing exposures with the client instrument science array. Provided that such calibrations are still being defined, a possible solution would be for the client instrument ICS SW developers to provide a template library allowing to acquire the necessary data, albeit for a limited, well-defined, subset of possible configurations. This interface is still under discussion and not formalized yet in an ICD.

MAORY OCM will interface with the Telescope Central Control System (CCS) during target acquisition for coordinating the handover of the Telescope deformable mirrors (M4 and M5) control and, in MCAO mode, to setup the LGS constellation. It is expected that all telescope operations, typically performed for the execution of an observation like telescope preset, offsets, etc., will be managed by the client instrument ICS SW.

4.3 The sub-systems software

The MCAO and the SCAO sub-systems software are structured according to the same basic architecture. At the top, the Sub-System Manager (SSM) component is responsible for coordinating operations of the lower-level components.

Sub-system functions are managed by Function Control System components. For MCAO, there will be FCS for the Post-Focal Relay Optics, LGS and LOR WFS functions. For the SCAO module, FCS will be provided for the WFS and Calibration Unit functions.

The WFS Detector Control Systems will also be managed by SSM. Through the DCS, the SSM will setup the readout modes and cycles. During AO operations, pixels will be sent directly from the WFS cameras to the RTC, while during camera maintenance and calibration operations, pixel data will be transmitted to the IWS for storage and analysis.

SSM will also manage the Technical DCS. As already mentioned, it is expected that the Technical Camera will be a COTS component, possibly implementing the GigE Vision protocol. Therefore the camera will be directly connected to the IWS and employed during target acquisition operations to visualize the target field and support operator interaction.
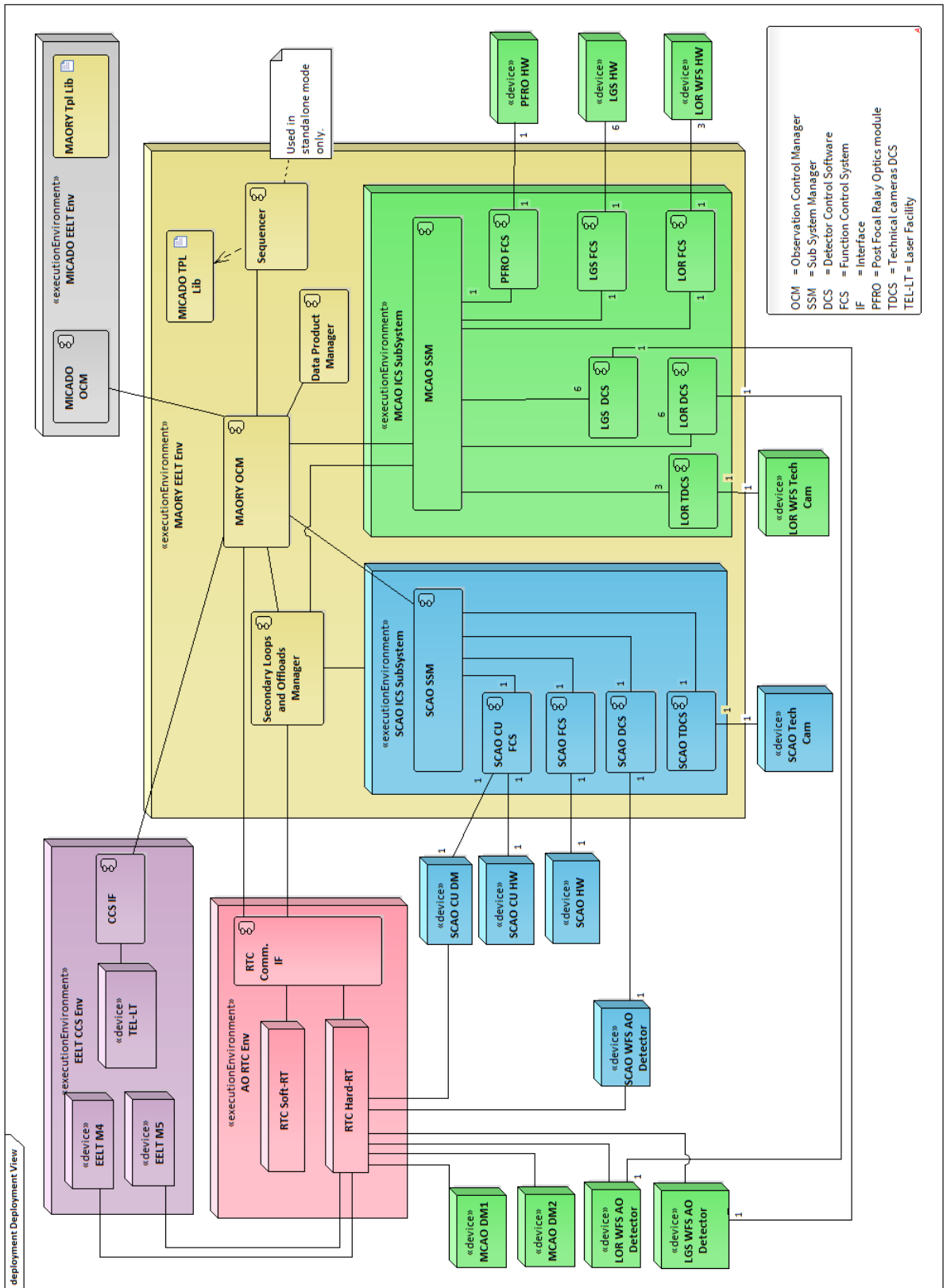
Figure 7: MAORY ICS Software Architecture.

5. SOFTWARE ENGINEERING

For what concerns the MAORY ICS Software development process, a ICS Software Management Plan (ISMP) is in preparation. The document is being produced in accordance with ESO guidelines but taking also in account ECSS standard ECSS-E-ST-40C[11] and ECSS-Q-ST-80C[12]. ECSS is the organization "European Cooperation for Space Standardization" and is a "cooperative effort" among ESA, National Space Agencies and industry. Its set of documentation is of paramount importance for space related standards, also including software. ECSS-E-ST-40C is the standard that defines best practices and objectives to be reached when developing software for space applications while ECSS-Q-ST-80C is the standard that deals, in the same way, with Product Assurance for software projects of the same type. The benefit of applying this type of standards also to ground based projects is straightforward and is acknowledged also by ESO. Of course, the "full load" of all ECSS indications may be excessive for ground-based projects, however, one of the advantages of the ECSS standards is that they explicitly foresee tailoring, therefore adaptation to a ground-based scenario becomes a relatively easy "cherry picking" activity.

MAORY ICS Software development plan, in accordance with the afore mentioned standards, describes the chosen approach for management and development of the software items. One of the main constituents of the plan is the work breakdown structure for the different phases of the project and the effort allocation. Phases, schedule and milestones are of course defined at a higher project level.

The core part of the document deals with the organization of the development process and with its Quality Assurance (QA) aspects. It should be noted that only a small subset of the QA related aspects is detailed in the ISMP, while general aspects are treated more explicitly in the ICS Software Quality Assurance Plan (ISQAP). No information is duplicated in the documents and, when necessary, cross references are used.

The ESO typical development process for instruments foresees a waterfall-like approach in the initial stage where a design phase is confined between two major milestones: the PDR and the FDR. For what concerns software, no actual development (apart from prototyping) is foreseen between these two milestones. The consequence of such procedure is that after FDR a well understood set of requirements and a sound design are in the hands of the software developers. This model is therefore well suited for an incremental development process.

Incremental development is a strategy in which only a set of functionalities are implemented for each release, adding more functionalities at each delivery. Each release of the software must be usable and testable. A critical part of this strategy is clearly the division of requirements for each build to have consistent (and testable) releases and must be carefully dealt with by developers in cooperation with the QA responsible.

For what concerns the tool environment to deal with continuous integration, version control, unit testing, static analysis etc., it is foreseen to take advantage of the infrastructure available at ESO with its predefined set of tools.

QA will of course be an integral part of the development life cycle and its activities shall be present along all the process life cycle.

Verification activities (i.e. controlling that everything is being done in the right way) shall be implemented by interaction of the QA responsible with the developers, formalized in meetings to be held regularly. In addition, a set of automated tools will be run during integration runs to verify that e.g. coding standards have been applied or unit tests coverage is adequate.

Validation (i.e. controlling that the right thing is being done) shall be carried out by the QA responsible mainly by means of functional tests. Where possible, tests against a hardware model shall be performed. In any case the QA responsible will ensure that the software product implements the agreed design and satisfies the given requirements. To help in this tracing activity, the usage of Magic Draw, a modeling tool by NoMagic, is foreseen.

Magic Draw is foreseen to play a key role in the development of the code both for its capability of requirement tracing and for its functionalities as UML tool.

6. FINAL REMARKS

In this paper we have presented the preliminary architecture of the MAORY ICS Software as it is being elaborated in preparation for PDR. The architecture has been devised on the basis of the user requirements and taking into account the constraints imposed by the ELT standards. Following the decomposition foreseen for ELT ICS SW, the architecture of

MAORY ICS SW includes a main coordination component (OCM), which oversees the operations of two major sub-systems: one devoted to the management of MCAO functions and detectors and the other to SCAO functions and detectors. The coordination component is also in charge of managing interfaces with the Telescope, the client instrument, as well as the RTC. Finally, the need to perform in client instrument sequence of operations using MAORY and, vice-versa, to acquire images with the science array from MAORY, has been addressed by means of template libraries.

Although we foresee the architecture to evolve, as requirements and constraints are clarified, we think that the overall partitioning of functionality and some key decisions will remain substantially unchanged, providing a solid base for the next phase of software design.

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