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ABSTRACT

The Adaptive Optics module and the Calibration Unit of the Enhanced Resolution Imager and Spectrograph (ERIS) share a similar Instrument Control Electronics (ICE). The architecture was designed according to the ESO standards and specifications. The large number of functions of these two complex subsystems are ensured by the automation software running on a Beckhoff PLC based control system. This paper describes the AO and CU design, their Instrument Control Electronics, main functions of the two subsystems and the activities performed during the first period of the MAIV phase.

Keywords: Adaptive Optics, Control Systems, Electronics,

1. INTRODUCTION

ERIS[1] (Enhanced Resolution Imager and Spectrograph) is the new AO instrument that will be mounted at the Cassegrain focus of the VLT UT4. It will exploit the ESO Adaptive Optics Facility (AOF)[2][3] and the 4LGFS[4] to achieve high strehl ratio in the 1-5 µm spectral range. ERIS is composed of several subsystems deployed along the optical path. Figure 1 shows a schematic view of ERIS and its modules. The beam from the telescope is first split by an IR/VIS dichroic that transmits the IR wavelengths (1-5 µm) to the science instruments and the visible (< 1 µm) to the AO WFSs. Two science instruments are integrated in ERIS: NIX[5], a 53" x 53" diffraction limited imager that will provide sparse aperture masking and pupil plane coronagraphy in J-M' bands, and SPIFFIER[6], the 1-2.5 µm integral field unit spectrograph. The Adaptive Optics subsystem[7] provides NGS mode to deliver high contrast correction and LGS mode to extend high Strehl performance to large sky coverage. It includes NGS and LGS wavefront sensors and real-time computing facility, to operate in the following observing modes:

- LGS-mode: high-order aberrations measured by the LGS WFS, low-order aberrations by the NGS WFS;
- NGS-mode: the NGS WFS provides both high-order and low-order AO measurements;
- Seeing Enhanced mode: only the on-axis LGS is used to calculate the high-order corrections. This mode is used when no suitable NGS is available for the tip-tilt fast correction.

Finally, the Calibration Unit (CU)[8] provides facilities to calibrate the scientific instruments (remove instrument signature) and perform troubleshooting and periodic maintenance tests of the AO module.

The instrument is led by a Consortium of Max-Planck Institut für Extraterrestrische Physik (MPE), UK Astronomy Technology Centre (UKATC), Swiss Federal Institute of Technology (ETH-Zurich), European Southern Observatory (ESO) and the Istituto Nazionale di Astrofisica (INAF-Abruzzo, Arcetri and Padova).

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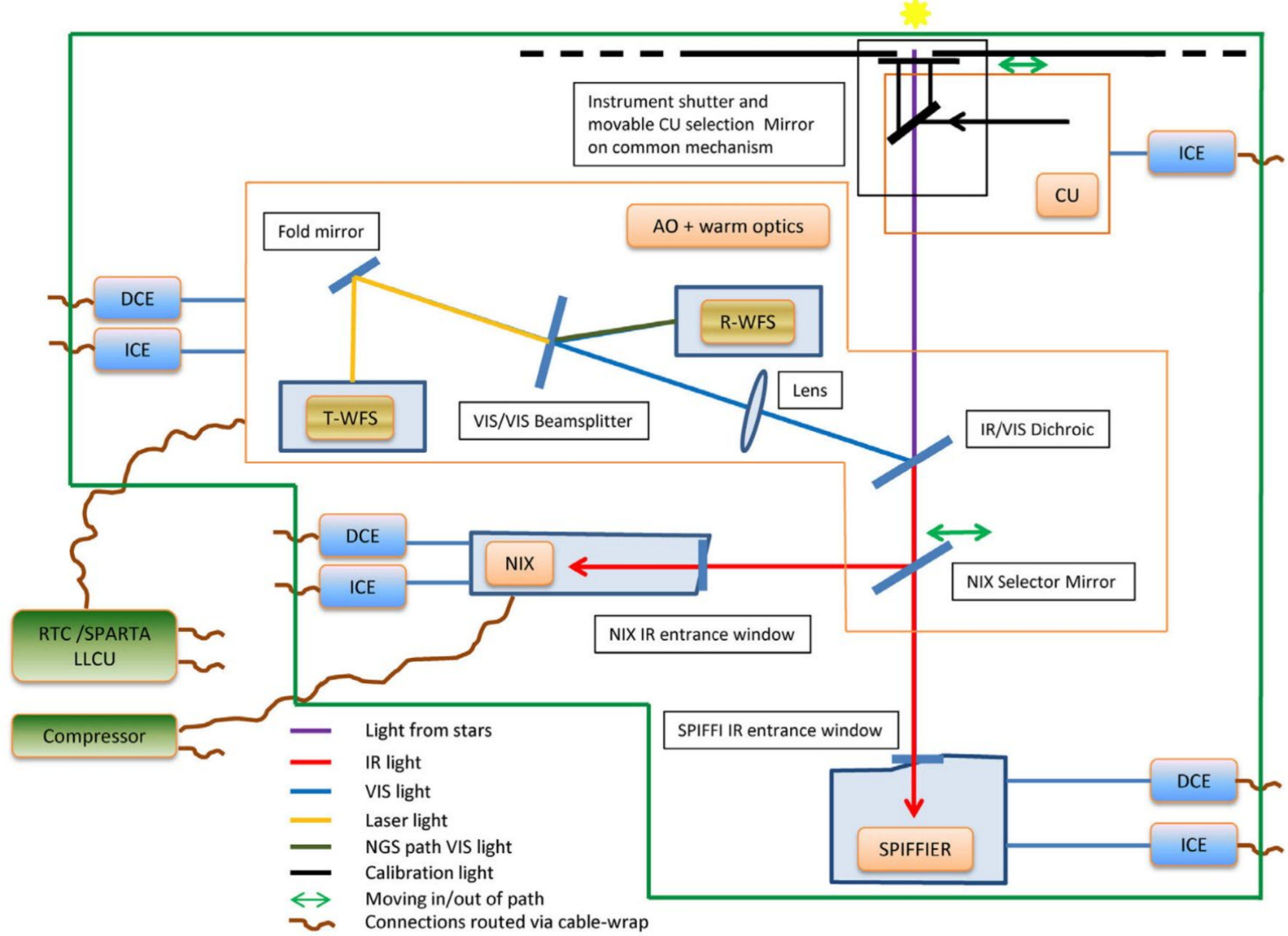

Figure 1. Overall layout of the ERIS instrument and its subsystems. Each module is provided with an Instrument Control Electronics (ICE) and, where acquisition cameras are used, a Detector Control Electronics (DCE). AO and CU subsystems are highlighted by yellow and orange boxes. SPARTA (the ESO Real Time Computer) is also considered as part of the AO module.

The project successfully passed the Final Design Review (PDR) in May 2017 and is currently in the Manufacturing, Assembly, Integration and Verification (MAIV) phase. This paper describes the ICE final design both for the AO and CU subsystems, the main functions of the two modules and the activities performed during the first period of the MAIV. Next steps will be the integration of the AO and CU subsystems in Arcetri in Q4-2018, the full ERIS integration at MPE in Q2-2019, and the Preliminary Acceptance Europe (PAE) in Q4-2019. The commissioning of the full instrument at the VLT is foreseen to start in Q2-2020.

In section 2 and 3 we give an overview of the AO and CU subsystems respectively; section 4 describes their Instrument Control Electronics; in section 5 is presented the Instrument Control Software while in section 6 is reported the current activities of the MAIV phase.

2. THE ADAPTIVE OPTICS SYSTEM

2.1 The Warm Optics

The AO module also comprises the set of optical components (Warm Optics, WO), that relays the telescope optical beam to the science instruments and to the AO WFSs. The only active actuator of the WO is the NIX Selector Mirror (NSM), a linear stage that allows to insert a 45° mirror in the optical beam to select the scientific instrument to be used.

2.2 The LGS Wavefront Sensor Unit

The LGS unit is composed of a main optical bench, mounted on a custom high precision gravity-variant stage, designed by Steinmeyer Mechatronik GmbH, used for tracking the focus of laser beacon and for compensating differential focus positions between SPIFFIER and NIX. Unlike the NGS WFS, the LGS unit operates only on-axis, therefore field patrolling is not required. The stage has a brushless motor with dual feedback configuration (a rotary encoder on the motor shaft and a high precision liner encoder on the load). All the WFS components are in turn mounted on the optical bench that can be detached from the stage for maintenance operations. Other active component of the LGS unit are:

- An optical shutter (SHU) to protect the CCD against over-illumination and to calibrate dark frames;
- a pupil rotator (ROT) to de-rotate the actuator pattern of the DSM on the SH lenslet array;
- a steering mirror (PSM) used for pupil stabilization against lateral decentering on the SH lenslet array;
- the WFS visible camera (CCD) having 240x240 pixel format, provided by ESO.

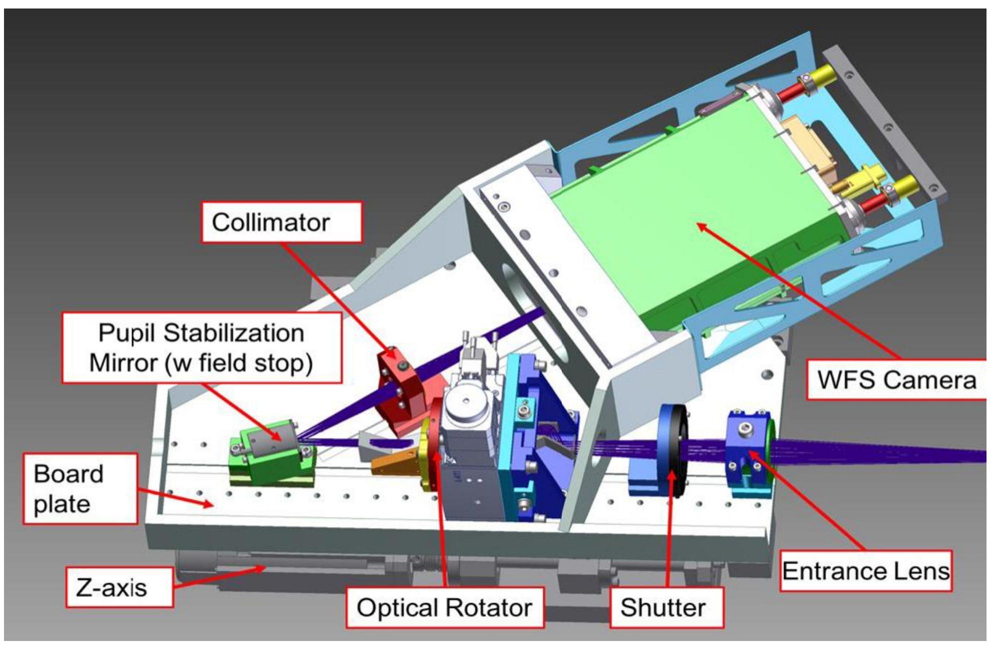

Figure 2. The LGS WFS unit. The optical bench and all its components are mounted on a custom high precision gravity-variant stage from Steinmeyer Mechatronik GmbH, used to correct de-focus.

The LGS unit is connected to its control electronics through moving cables that come from the supporting stage or have been sectioned on a side panel, while cooling pipes, power cables and optical fibers go straight from the CCD220 camera to the Peltier controller, power supply and the SPARTA RTC in the Bodega platform.

2.3 The NGS Wavefront Sensor Unit

As for the LGS unit (see 2.2), also the NGS unit is mounted on a high precision gravity-variant moving stage from Steinmeyer Mechatronik GmbH. It is a dual axis (XZ) board that allows defocus correction (Z-axis), and field patrol on the XY plane, through the combined motion of the X axis and a periscope (see the NGFP special device in 4.2 and 5). Figure 3 shows the detailed design of the NGS module. This unit provides the HO and LO NGS WFS functionalities for the NGS and LGS mode, respectively, by means of a High Order (40x40 subapertures) and a Low Order (4x4 sub-apertures) Shack-Hartmann (SH) lenslet that can be switched according to the selected configuration.

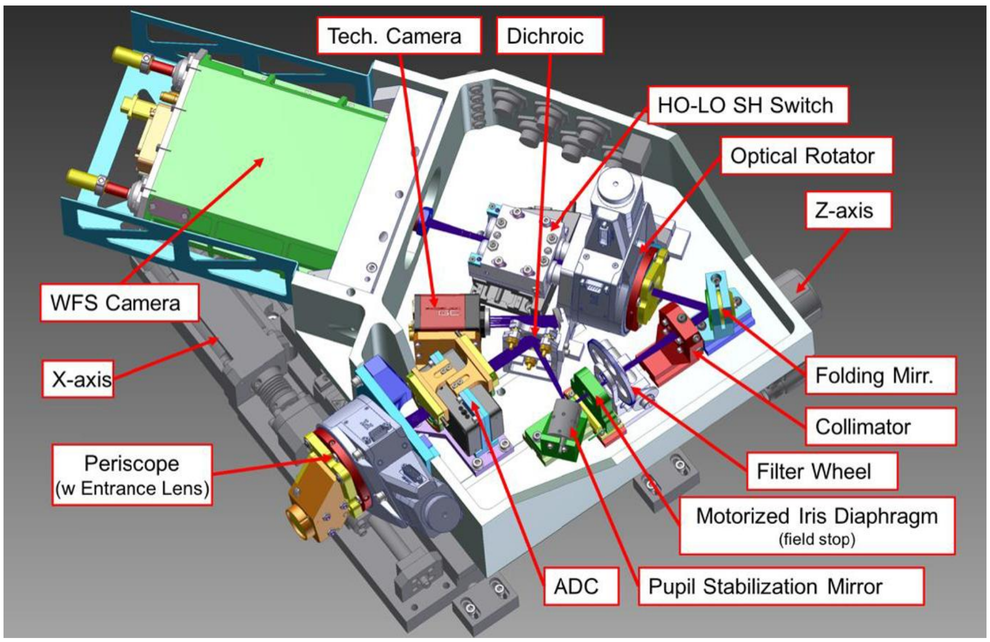

Figure 3. Detailed view of the NGS WFS unit and its components. The unit is mounted on a dual axis stage that allows to correct de-focusing and to patrol the NGS FoV by means of the combined motion of the X-axis and the periscope.

The main active components of the NGS WFS unit are:

- a periscope (PER), a rotary stage used to patrol a 2' field in the XY plane;
- an atmospheric dispersion corrector (ADC) assembly, composed by 2 rotary stages and 2 absolute rotary encoders;
- a technical camera (TCA), with GigE video output, used for field acquisition;
- a pupil steering mirror (PSM), used for pupil stabilization against lateral decentering on the SH lenslet array
- an adjustable motorized field stop (MFS);
- a 4-stop custom filter wheel (FWH);
- a pupil rotator (ROT) to de-rotate the actuator pattern of the DSM on the SH lenslet array;
- a linear stage (HLS) to switch between the HO and LO SH lenslet arrays;
- the WFS visible camera (CCD) having 240x240 pixel format, provided by ESO.

As for the LGS unit, the NGS WFS is connected to its control electronics through moving cables that come from the supporting stage or have been sectioned on a side panel, while cooling pipes, power cables and optical fibers go straight from the CCD220 camera to the Peltier controller, power supply and the SPARTA RTC.

3. THE CALIBRATION UNIT

The Calibration Unit (CU)[4] is composed of two main modules: the first, CU Main Bench (CUMB), is mounted inside the ERIS structure, while the second, CU Fiber Switchyard (CUFS), is located inside Cabinet 3 (see 4.1 for the cabinet description).

3.1 The CU Main Bench

The CUMB is provided with calibration lamps, temperature and humidity probes and actuators that are used to change the configuration of the subsystem, according to the selected operating mode. A detailed layout is shown in Figure 4.

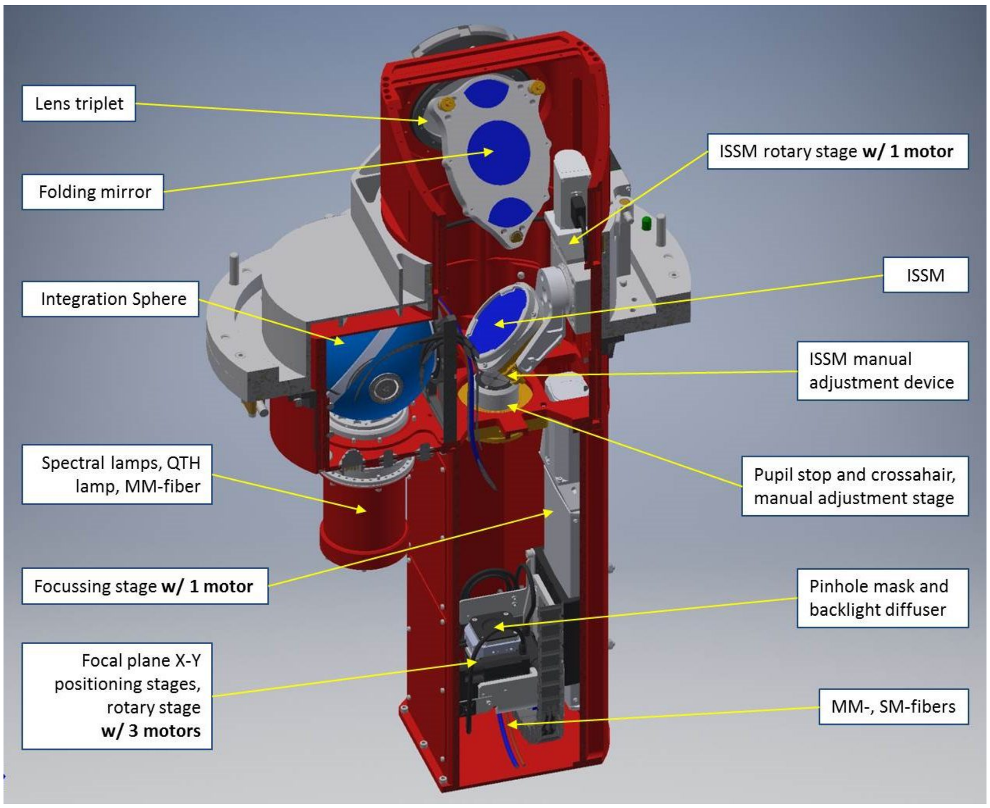

Figure 4. The Calibration Unit Main Bench (CUMB) and its internal components (see text for details).

The main active components of the CU Main Bench unit are:

- the Integrating Sphere Selector Mirror (ISSM), a rotary stage that allows to select between a uniform illuminated pupil and the plane light sources;
- two linear stages to move the Pin Hole Mask in the XY plane (PHMX, PHMY).
- a linear stage to select between the NGS and LGS focal plane and to correct the de-focus (PHMZ);
- a piezo rotary stage to adjust the Pin Hole Mask orientation around the Z axis (PHMR);

A further mechanism, the CU Selector Mirror (CUSM), a linear stage provided by MPE, is used to insert the output beam from the CU in the optical path and to stop the light from the telescope. It is a system device, but from the control electronics point of view, it is considered as part of the CU subsystem.

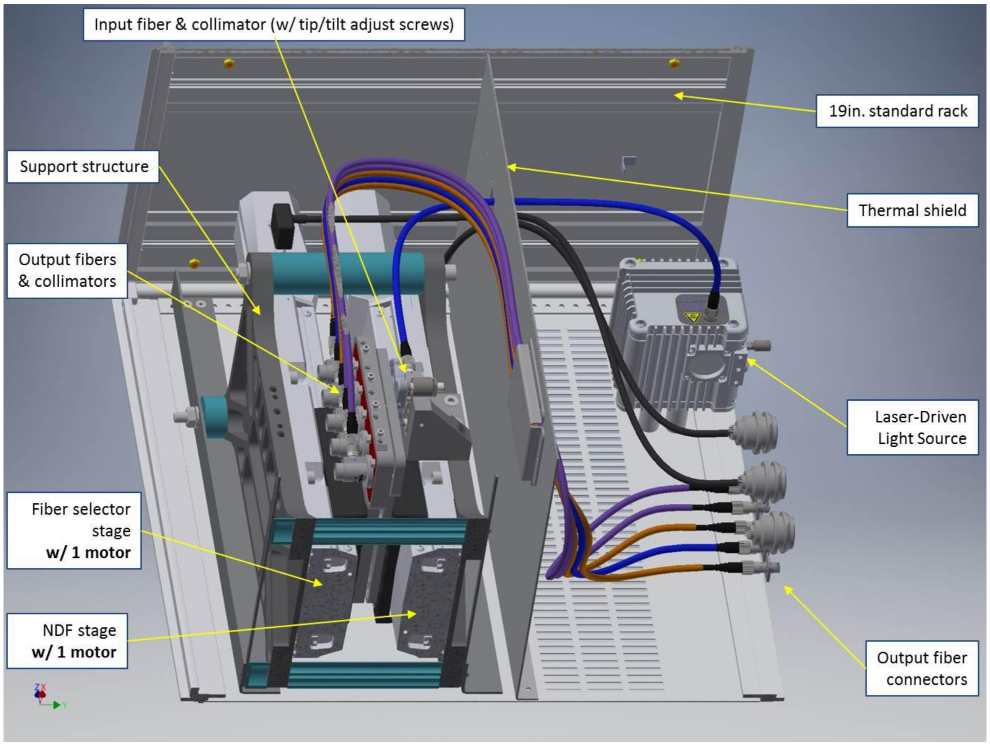

Figure 5. Detailed view of the CU Fiber Switchyard assembly (CUFS): it is composed of two linear stages (one for fiber selection and the other for sources brightness variation), a Lased Driven Light Source (LDLS), and temperature probes.

3.2 The Fiber Switchyard and Continuum lamps

Four sub-racks in cabinet 3 host the remaining CU modules. The first contains the four calibration lamps power supplies. In the second sub-rack is mounted the EtherCAT based control system (PLC, expansion terminals and power supplies). The third sub-rack hosts the Laser Driven Light Source (LDLS) power supply and its controller, together with a linear variable output power supply for the Quartz-Tungsten Halogen (QTH) lamp. Finally, the fourth sub-rack, called CU Fiber Switchyard (CUFS, see Figure 5Figure 5. Detailed view of the CU Fiber Switchyard assembly (CUFS): it is composed of two linear stages (one for fiber selection and the other for sources brightness variation), a Lased Driven Light Source (LDLS), and temperature probes. is used to provide a fiber selection mechanism to channel the flux coming from the LDLS head (mounted inside it) to one of the five collimators on a high accuracy linear stage, called Fiber Switch (FSW). Each collimator is then connected through dedicated optical fibers to the CUMB, to feed Diffraction Limited (DL) and extended sources (pin holes and slits) on the PHM. Another, identical stage is used to limit the sources photon flux through a variable Neutral Density Filter (NDF). In addition, temperature sensors are used to monitor the CUFS environment.

4. INSTRUMENT CONTROL ELECTRONICS

The ERIS System Electronics architecture is shown in Figure 6. In order to allow a parallel development of the subsystems, a modular design has been adopted for the control electronics. Instrument and cryo-vacuum control are based on Beckhoff Embedded PC and Siemens S7 PLC respectively, as required by ESO Standard.

The main part of the ERIS Controls Electronics is the Instrument Control Electronics (ICE). For each subsystem (SPIFFIER, NIX, AO, CU) a dedicated Beckhoff embedded PC is used (see Figure 7), each housed in a 19” sub-rack. They come with the TwinCAT (The Windows Control and Automation Technology) software, that is the responsible for transforming the PC-based system into a real-time controller (PLC). Moreover, Each PLC has a dual socket configuration, one used for the link with the ERIS Instrument Workstation, the other used to configure the PLC through a direct connection to a user laptop for maintenance, when operating at the telescope.

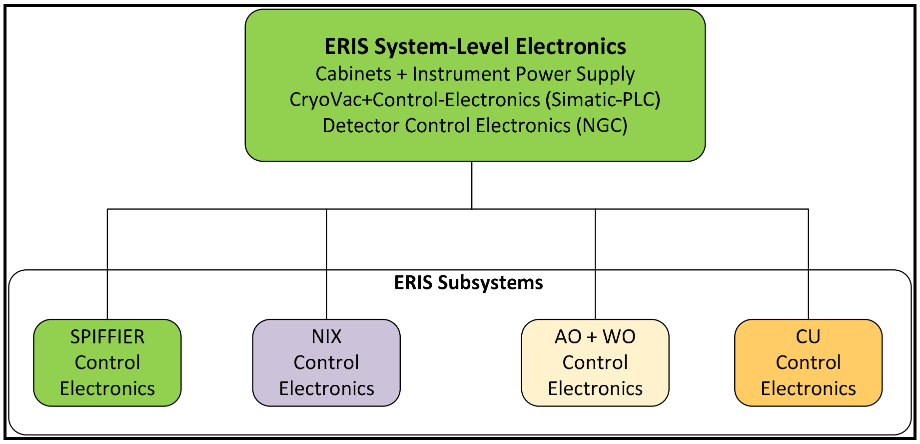

Figure 6. ERIS System Electronics architecture.

For both the AO and CU subsystems, the Instrument Control Electronics (ICE) is split inside several 19-inch racks, and uses EtherCAT as communication fieldbus. Two different systems based on CX2030 PLCs (one for the AO and one for the CU) are interfaced by the Instrument Control Software (ICS) of the ERIS Instrument Software (INS)[9].
The EtherCAT modular I/O system has allowed to extend the motion control design with functions provided by COTS products. A large number of terminals and third-parties drives have been chosen among different standards and technologies, thus allowing a wider selection of devices to provide solutions matching the project requirements.

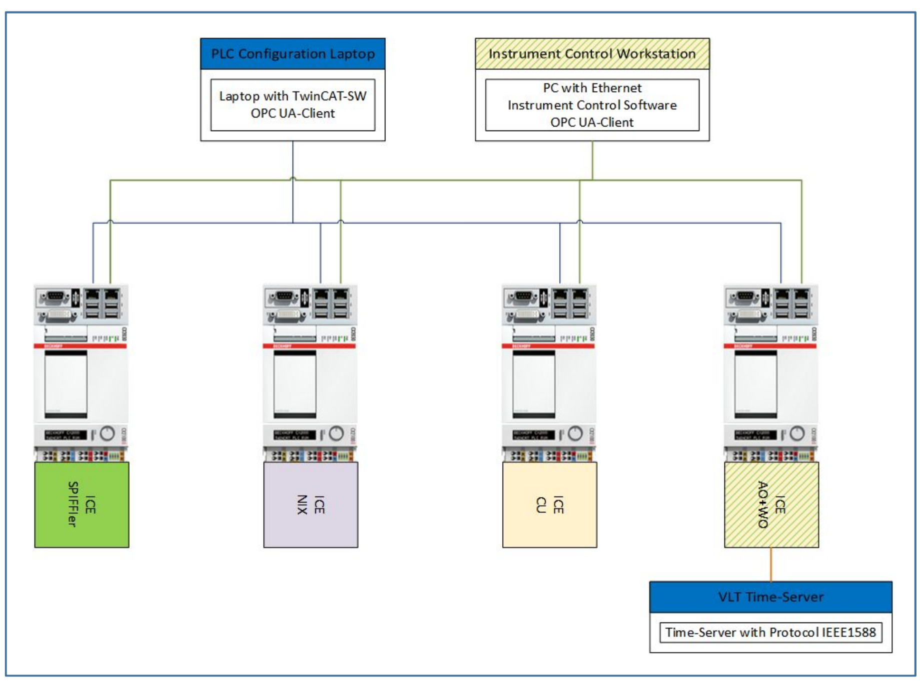

Figure 7. Block diagram of ERIS Instrument Control Electronics based on Beckhoff PLCs.

All AO and CU motorized stages (stepper, brush, brushless and piezo) have been provided with high resolution position feedbacks for open loop or (when required) closed loop operation. In addition, special cables have been customized to reduce connections and interfaces among all ERIS subsystems. They combine power and feedback conductors, but also signals from sensors. Temperature and humidity probes have been distributed inside and outside the two subsystems to monitor environment and critical devices, minimizing possible risks.

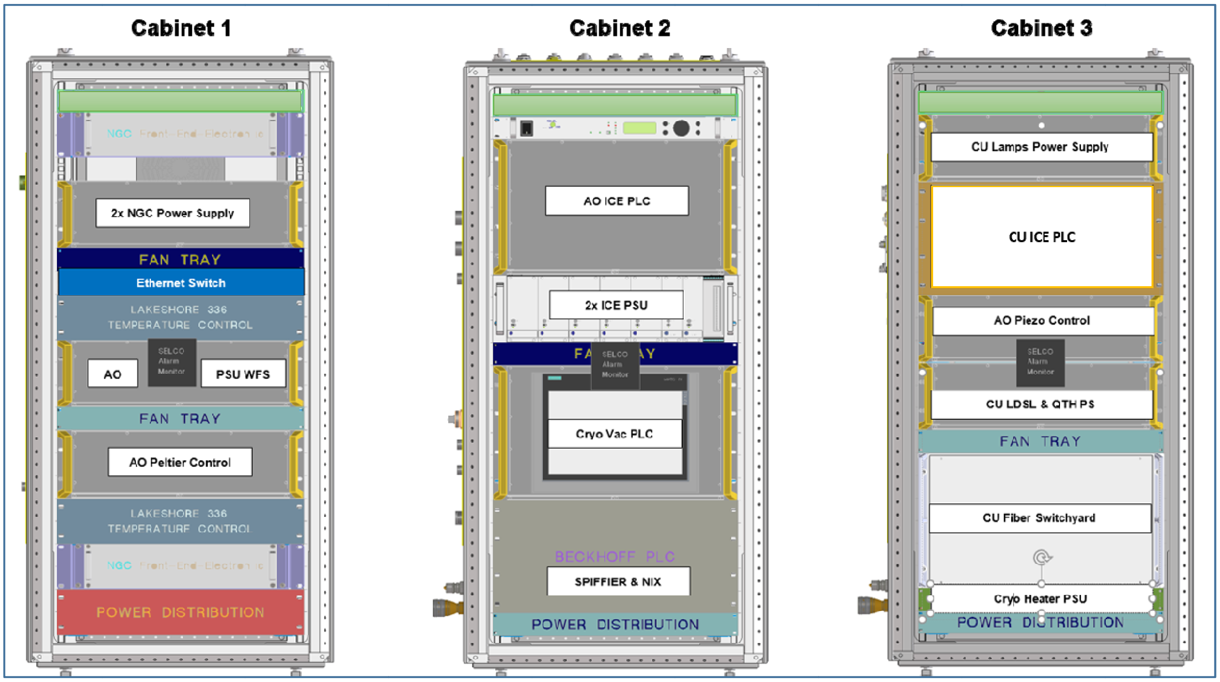

Figure 8. The three moving cabinets mounted on the telescope structure hosting the ERIS Electronics.

The architecture has been identified as the best trade off among the instrument hardware complexity, standards compliance and volume constraints. Despite the compact design, this solution allows high modularity and easy access for maintenance.

4.1 ERIS Cabinets

All ERIS electronics is accommodated in 4 cabinets. Three of them, hosting the main control and readout electronics, are directly mounted on the telescope moving structure (see Figure 8) . The forth cabinet at the BODEGA platform underneath, hosts the SPARTA RTC, connected through optical fibers to the AO WFS cameras for high speed (up to 1kHz) readout.

4.2 Adaptive Optics ICE

The main characteristics of the AO (LGS+NGS) and WO instrument electronics are listed in Table 1. Since the limited number of components of the WO, for simplicity, it is considered as part of the LGS module, unless otherwise specified. The ICE of the LGS and the NGS modules is split in six 19'' (84HP) units. In cabinet 2, a 6U, 19inch rack from HEITEC (HeiPac 3684161) hosts the CX2030 PLC and most of the EtherCAT terminals, while a 3U rack hosts five 24VDC/5A Kniel low-emission power supplies in redundant (n+1) configuration. A further 1U Kniel VE1PUID 52.40 programmable power supply is used for the motors of the two WFSs moving stages.

Using a EL1122, a star topology has been adopted to connect the PLC to a second small EtherCAT extension in cabinet 1 (for the connection with the Peltier Controller through the EL6022 RS-422 terminal) and a third extension in cabinet 3 (for the RS-232 communication with the Smaract controller through an ES6001 terminal, and the control of the PSMs position through the ES4104 and ES3164 analog I/O terminals). The last 19'' unit is a sub-rack hosting two dual channel (XY) amplifier and sensor inputs (PI E-500 series) for the two PSM tip-tilt steering mirrors.

Table 1. List of the AO (LGS+NGS) and WO instrument electronics (main components).

Device Name	Description	Product	Actuator Type	Feedback Type
WO				
NSM	NIX Selector Mirror (linear stage)	PI L-509	stepper motor	1Vpp encoder
LGS-WFS				
SBZ	Support Board (Z axis)	Steinmeyer (customized)	Brushless motor	RS422 + 1Vpp
ROT	K-Mirror	PI L-611	stepper motor	1Vpp encoder
SHU	Beam Shutter	Uniblitz DSS35B	ring coil	digital output
PSM	Pupil Stabilization Mirror	PI S-334	piezo tip-tilt	strain gauges
CCD	WFS Camera	ESO CCD220		digital output
TMP	Temperatures Sensors	PT1000		analog output
RHU	Relative Humidity Sensor	HMP110		analog output
NGS-WFS				
SBX	Support Board (X axis)	Steinmeyer (customized)	brushless motor	RS422 + 1Vpp
SBZ	Support Board (Z axis)	Steinmeyer (customized)	brushless motor	RS422 + 1Vpp
PER	Periscope moving in the X-Y plane	L-611.9ASD	stepper motor	1Vpp encoder
ROT	K-Mirror	L-611.9ASD	stepper motor	1Vpp encoder
TCA	Technical Camera	Prosilica GE-2040		digital output
PSM	Pupil Stabilization Mirror	S-334.2SL1	piezo tip-tilt	strain gauges
FWH	Filter Wheel	2232S024BX4-IE31024L	brushless motor	RS-422 encoder
ADC	Atmospheric Dispersion Corrector	2x 8MPR16-1 2x RLS AKSIM	stepper motor	SSI encoder
HLS	High-Low Order Switch	M-122	DC motor	RS-422 encoder
MFS	Motorized Field Stop	SID-7	piezo	1Vpp encoder
CCD	WFS Camera	ESO CCD220		digital output
TMP	Temperatures Sensors	PT1000		analog output
RHU	Relative Humidity Sensor	HMP110		analog output

In Figure 9, a schematic view of the NGS control electronics and main connections with the WFS components are shown. For each component belonging to the module (left part of the figure) the corresponding I/O and control electronics communicating through the EtherCAT bus is shown (right part of the figure). All stepper motor devices are controlled by ES7031 terminals, combined with the proper encoder terminal (ES5001 or ES5021 according to the feedback signal type). The only exception is for the periscope that is controlled by an iPOS4808 from Technosoft. This has been preferred in order to keep the same hardware for the development of the NGS Field Patrol (NGFP), a new special device for the VLTSW, that combines the motion of the periscope and the NGS X axis. The two WFS moving stages need powerful AC brushless motors. For this reason, they are also controlled by the iPOS4808-BX-CAT from Technosoft. These have been chosen by Steinmeyer Mechatronik GmbH to provide the fully configured and tested control electronics, based on EtherCAT fieldbus, together with the customized stages. Since the earlier prototyping activity no major issues arose about the compliance of the selected drives with the VLTSW library.

The filter wheel (FWH) is interfaced by an iPOS4808 too, because of the need of a servo drive for the brushless motor used for this device. Only one DC motor stage is present (HLS) and is interfaced by an ES7342 terminal coupled with an ES5101 encoder terminal for the digital RS422 feedback. An AC/DC power supply provides 12V/3A to operate the AVT Prosilica GE-2040 technical camera (NGS-TCA) and a beam shutter (LGS-SHU) used for CCD safety during NGS operation. Analog input terminals (ES3204 and EL3208) acquire temperature and humidity values. Digital output terminals (ES2004) are used to switch ON/OFF piezo controllers and secondary power supplies, while digital input terminals (ES1124) detect limit and reference position signals and failures. Finally, the EL6688 terminal provides the IEEE1588 time synchronization signal for all tracking devices (LGS- and NGS-ROT, NGFP).

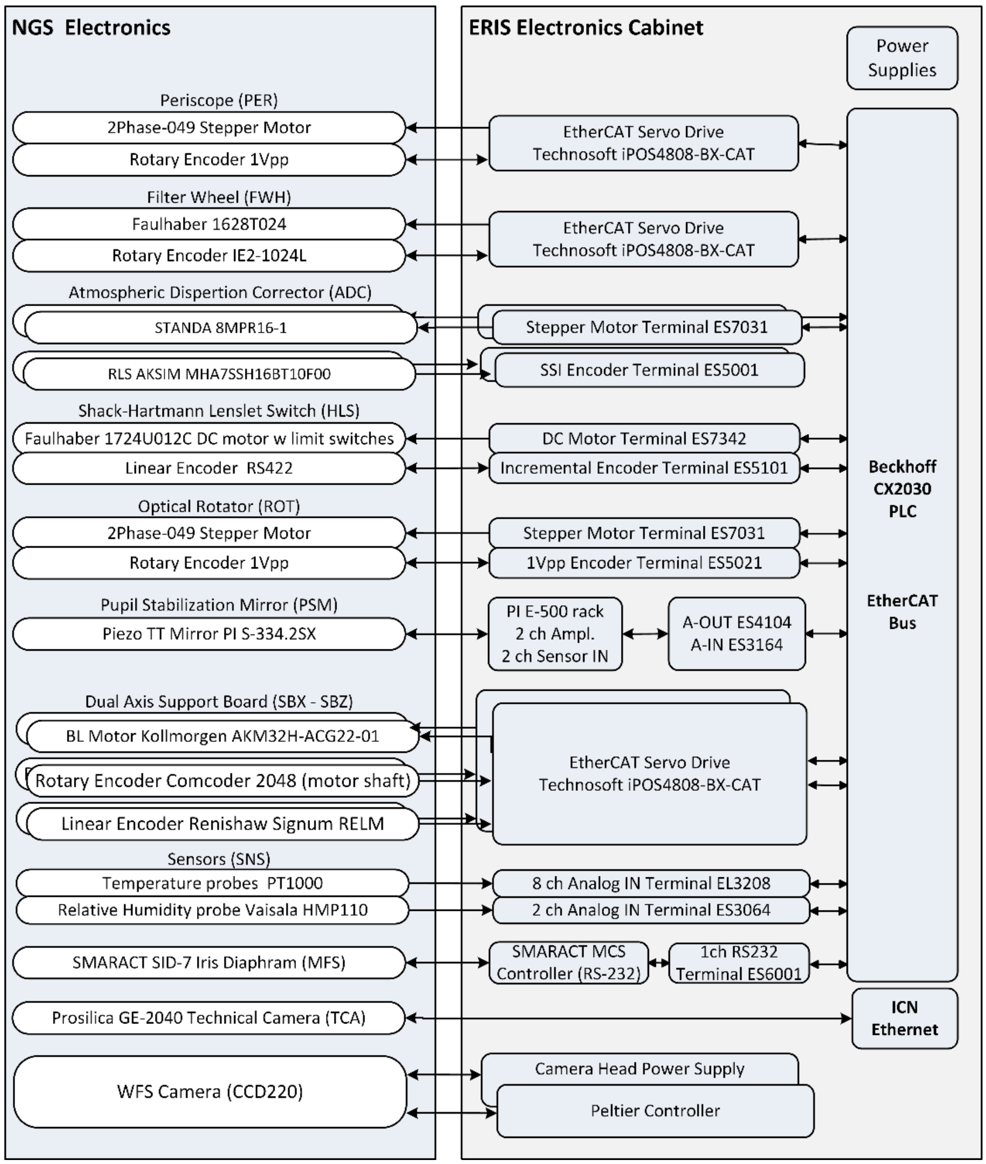

Figure 9. Schematic view of the AO ICE (right) and WFS NGS controlled devices (left).

4.3 Calibration UNIT ICE

All the four 19'' units of the CU subsystem are located inside cabinet 3. Three of them host the ICE that interfaces the CU instrumentation (see Table 2) contained both in the CUMB mounted at the telescope structure, and in the CUFS inside cabinet 3 (the ladder being the forth 19'' unit). As for the AO ICE, also the main CU PLC electronics is mounted inside a 6U 19inch sub-rack, from HEITEC (HeiPac 3684161). It is based on a Beckhoff CX2030 with several EtherCAT expansion terminals. The architecture (see Figure 10) has been identified as the best trade off among the instrument hardware complexity, standards compliance and volume constraints. Components arrangement allows easy access for maintenance operations. To fulfill design and project requirements, all motorized stages have been provided with high precision position feedback. The PLC-based system uses two KNIEL CAA24.5 power supply. One is for the logic and the other for the load (a stepper motor, several analog and digital I/O terminals and the MMC-110 piezo controller).

A low emission AC/DC power supply (KNIEL CA 12.5) provides power for 6 DC motors through three ES7342 terminals. Moreover, analog I/O terminals are used to monitor the calibration lamp flux at the Integrating Sphere (IS) exit, temperature and humidity values, while digital terminals are used to switch ON/OFF the spectral lamps, the secondary power supplies, to detect limit and reference switch signals, to control the LDLS and to monitor possible failures.

Table 2. List of the CU instrument electronics (main components).

Device Name	Description	Product	Actuator Type	Feedback Type
CUSM	CU Selector Mirror	MPE customized	stepper motor	RS-422 encoder
CU Main Bench				
ISSM	Integrating Sphere Selector Mirror	PI M-060	DC motor	RS-422 encoder
PHMX	PinHole Mask X axis	PI M-122	DC motor	RS-422 encoder
PHMY	PinHole Mask Y axis (linear stage)	PI M-122	DC motor	RS-422 encoder
PHMZ	PinHole Mask Z axis	PI L-511	DC motor	RS-422 encoder
PHMR	PinHole Mask Rotary stage	Micronix PR-50	piezo rotary	RS-422 encoder
ARL	Argon arc lamp	Newport 6030		flux sensor
KRL	Kripton arc lamp	Newport 6031		flux sensor
NEL	Neon arc lamp	Newport 6032		flux sensor
XEL	Xenon arc lamp	Newport 6033		flux sensor
QTH	Quartz-Tungsten Halogen lamp	ILT L6416		flux sensor
FLX	Photon Flux Sensor	Osram BPW34		analog output
TMP	Temperatures Sensors	PT1000		analog output
RHU	Relative Humidity Sensors	Vaisala HMP110		analog output
CU Fiber Switchyard				
LDLS	Laser Driven Light Source (lamp house)	Energetiq EQ-99X-FC		digital output
NDF	Neutral Density Filter	PI L-511	DC motor	RS-422 encoder
FSW	Fiber Switch	PI L-511	DC motor	RS-422 encoder

5. INSTRUMENT CONTROL SOFTWARE

Since ERIS is an instrument for the VLT, the software must follow the standard architecture of a VLT Instrument Software (INS). The main components of the ERIS INS are: the Instrument Control Software (ICS), in charge of controlling all hardware functions of a subsystem except detectors, a Detector Control Software, and the Observation Software (OS), in charge of the coordination of ICSs and DCSs for the execution of scientific and calibration exposures.

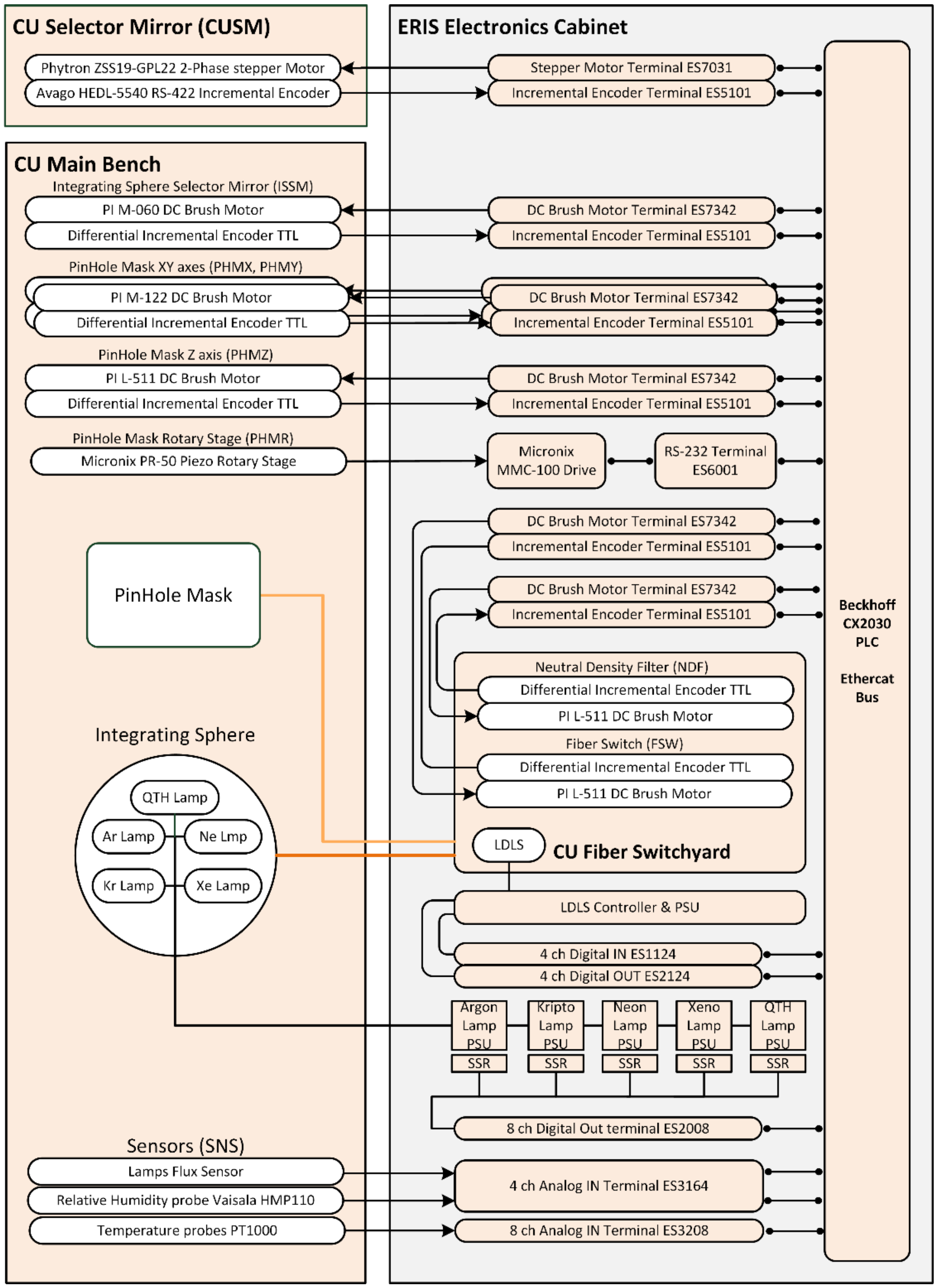

Figure 10. Schematic view of the electronics architecture of the CU. For each component of the instrument electronics (left part of the figure) the corresponding control electronics and connections are shown (right part of the figure).

The AO and CU PLC are then operated by their Instrument Control Software, running on the Instrument Control Workstation. The PLC code is based on the PLCopen Motion Control standard, that has been used by ESO to develop a set of library for devices of common type (identified as "standard devices"). The PLC motion library implements the interface with the high-level instrumentation software via OPC UA[10]. The library simplifies the implementation of instrument motorized functions by instrument developers following the philosophy of the VLT Instrumentation

Framework. Moreover, the TwinCAT eXtended Automation Engineering (XAE) provides an integrated environment with graphical tools that facilitate the configuration, control and validation of the motor response. If a hardware device requires a different software implementation that is not already present in the ESO VLT Software, then it is marked as "special device" and the development of the new code (following the VLT standards) is in charge to the engineering team of the subsystem.

The NGS WFS channel contains two "special" devices, the Field Patrol (NGFP, already mentioned in 4.2) and the NGS Iris (NGIR). The Field Patrol is composed of a linear and a rotary stage and is in charge of picking up the light from the NGS, which can be off-axis, and track it. Tracking is required when the NGS is off-axis and the observation is performed in pupil-stabilized mode. Tracking is also required when either the target or the natural reference source is a non-sidereal source. The NGIR, is the software implementation for the control of the MFS, used as a spatial filter.

From a control-software point of view, most of the Calibration Unit operations require a set of standard calibration functions: light path and fibers selection (through the movement of mirrors and/or collimators), activation of calibration lamps and neutral density filter variation. The most complex function in the ERIS CU is the positioning of the pinholes mask (PHM), which needs to be moved in three orthogonal (XYZ) directions and rotated around the Z-axis. An implementation of a "special" device communicating through a RS-232 connection with the PLC (as for the NGIR) is also required to interface the PHM piezo rotator.

The overall coordination of all ERIS sub-systems and the interface with external systems is a task of a Super-OS (SOS) that allows the ERIS INS to manage the interfaces with the hardware functions, the detectors, the SPARTA RTC, the telescope control system, the Four Laser Guide Stars Facility (4LGSF) and the data archive.

6. THE MAIV PHASE

During the first months of the MAIV phase, a large number of tests have been performed on all electronic devices, with particular attention to custom and commercial motorized stages. Some minor changes to the design have been also necessary to improve signal reliability during operations. The manufacturing of mechanical parts is now at its final phase. The current work is mainly focused on the assembly and integration of electronic components, and on the optimization of the cabling inside and outside the ICE racks. The latter is of extreme importance, in order to minimize any possible noise, increasing EMC when all subsystems will be present, and avoiding dangerous grounding loops in such a compact architecture. In the meantime, the development of "special devices" required for the combined motion of NGS X-axis and the Periscope, and for controlling non-standard piezo devices has already started.

7. CONCLUSIONS

The Assembly and integration phase of the Instrument Control Electronics of the AO and CU subsystems is started in March 2018. The first steps of the MAIV phase allowed to verify the design and the compliance of each component. The preliminary test of the AO electronics was performed in Arcetri, while the test of the CU components and the assembly of both AO and CU control electronics is currently undergoing in Teramo. The assembling phase usually takes a lot of time to check all interfaces and to verify that all components have been correctly built and mounted. Then all the electronics modules of the two subsystems will be integrated in the Arcetri lab to test the complete hardware interconnections and the PLC software, before the PAE verification.

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