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The ELT Control System

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ABSTRACT

The Extremely Large Telescope (ELT) is a 39 meters optical telescope under construction at an altitude of about 3000m in the Chilean Atacama desert. The optical design is based on a novel five-mirror scheme and incorporates adaptive optics mirrors. The primary mirror consists of 798 segments, each 1.4 meters wide[1].

The control of this telescope and of the instruments that will be mounted on it is very challenging, because of its size, the number of sensors and actuators, the computing performance required for the phasing of the primary mirror, the adaptive optics and the correlation between all the elements in the optical path.

In this paper we describe the control system architecture, emerging from scientific and technical requirements. We also describe how the procurement strategy (centered on industrial contracts at subsystem level) affects the definition of the architecture and the technological choices.

We first introduce the global architecture of the system, with Local Control Systems and a Supervisory Control layer. The Local Control Systems are astronomy-agnostic and isolate the control of the subsystems procured through industrial contracts. The Supervisory Control layer is instead responsible for coordinating the operation of the different subsystems to realize the observation cases identified for the operation of the telescope.

The control systems of the instruments interface with the telescope using a well-defined and standardized interface. To facilitate the work of the Consortia responsible for the construction of the instruments, we provide an Instrumentation Control Software Framework. This will ensure uniformity in the design of the control systems across instruments, making maintenance easier. This approach was successfully adopted for the instrumentation of the Very Large Telescope facility.

We will analyze the process that was followed for defining the architecture from the requirements and use cases and to produce a design that addresses the technical challenges.

Keywords: ELT, telescope control system, architecture, instrument control system

1. INTRODUCTION

The ELT design is based on a complex five mirror design and has five foci, with multiple instruments sitting on the Nasmyth platforms[1]. Figure 1 shows the main telescope subsystems following the optical path.

Some particular aspects of the complexity of the subsystems and their interactions through a control strategy are summarized below:

- The M1 is made of almost 800 hexagonal segments, actively controlled in position (piston and tip-tilt to a few nanometer accuracy) using actuators that act on the segments supporting frames. Position adjustments are deduced from edge sensors that measure relative displacements of the segments in real time.
- M2 and M3 are respectively a convex and a concave 4m mirrors. The mirror cells provide positioning capability for realigning the mirror within the telescope, and shape adjustment capability to compensate for constant errors.
- M4 is a 2.4m thin shell deformable mirror with about 5300 actuators used to compensate for fast wavefront distortions primarily due to atmospheric turbulence.

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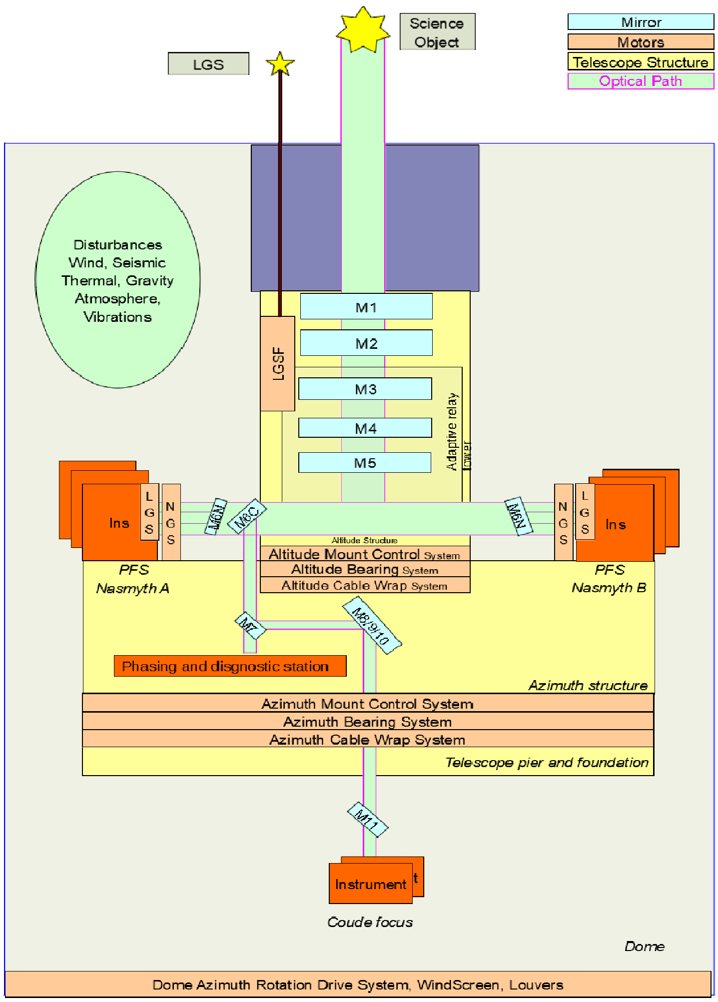

Figure 1. Telescope subsystems following the light path.

- M5 is a fast steering, ultra-lightweight mirror to compensate image motion at frequencies of up to a few Hz. Such image motion may be the result of a combination of errors introduced by wind, atmospheric turbulence, and residual tip/tilt errors beyond the capabilities of the telescope mount system.
- Wavefront control involves several subsystems and includes focusing, realignment and figure control of optical surfaces. Focusing is performed by axially translating the M2 (major, occasional re-setting), the M4 hexapod (large amplitudes, low bandwidth) or applying a small curvature term on the otherwise flat M4 (continuous, fine adjustments). Realignment -or rigid body motion- is performed by re-centering specific mirror units (e.g. the M2 unit). Figure control applies to the individual M1 segments, the M2, M3 and M4.
- Adaptive Optics (AO), which mainly focuses on compensating the effect of atmospheric turbulence, has a spatial and temporal bandwidth of the corrections of up to hundred Hz and about 50 cycles over the pupil diameter with a sampling rate up to 1 kHz. Sky targets may not be bright enough to allow sufficient sampling; lasers mounted onto the telescope will generate artificial guide stars in the sodium layer, at about 90 km altitude. Those will be re-imaged by the telescope alongside the scientific targets, towards dedicated wavefront sensors near the focal plane to determine the commands to be sent to the adaptive M4.
- Each Nasmyth platform can host several instruments, interfaced through a Pre-Focal Station (PFS) containing the wavefront sensors to control the telescope. The ELT instrumentation program[7] includes: two first-light instruments (a diffraction-limited near-infrared imager and a single-field near-infrared wide-band integral field spectrograph); additional three instruments coming after first-light (a mid-infrared imager and spectrometer, a high-resolution spectrometer and a multi-object spectrometer); one planetary camera and spectrograph. These instruments will require high performance in terms of image sharpness to reach their underlying scientific goals. This calls for higher order wavefront control than what can be delivered by the telescope itself. For this reason, post-focal AO modules will be developed to feed different science instruments.

The control of all these highly distributed devices, plus many others like the telescope dome, has to be coordinated with high precision in timing and across the large distances imposed by the dimensions of the telescope, in order to deliver a corrected wavefront to the instruments.

It is also important to consider that the ELT Telescope procurement strategy foresees the outsourcing of all components and services which can be efficiently performed by industrial partners from ESO member states, while maintaining in-house those tasks for which ESO has a specific domain expertise.

For the ELT Control System this same procurement principle applies. Thus, the overall system is constituted of components designed, built and delivered by many industrial partners distributed across Europe, as well as by the in-house construction projects. This geographic and organizational distribution of the development of the control system immediately enforces the need for clear identification of components and interfaces which should match not only a functional breakdown of the control system, but also reflect the organizational boundaries of the many development centers.

Instruments are similarly developed by Consortia from universities or astronomical research institutes, with technical support from ESO.

Since the ELT is set to enter new parameter spaces in terms of dimensions and control complexity for astronomical projects, it is anticipated that the control system will undergo significant changes in requirements over the construction period, as we discover how the components have to be operated together to reach the desired performance objectives.

The main requirements and challenges can be summarized as follows:

- Size: 10000 tons of steel and glass to control, 20000 actuators, 1000 mirrors.
- Number of control points: 60000 I/O points (M1 alone encompasses 10000 actuators).
- Number of interfaces: 12 subsystems, 10 focal stations, site operation.
- Number of instruments: 6 currently planned and 2 AO modules.
- Large data volume and computational requirements: 700Gflops, 17GB/s in real-time in AO.
- Multitude of interacting, distributed control loops: from 0.01Hz to kHz rates.
- Distributed control strategy requiring synchronization down to the microsecond level.
- Software-intensive distributed control strategy.

2. THE ELT CONTROL SYSTEM

The ELT Control System is responsible for the overall control of the telescope (and of the dome) in terms of both functional and performance requirements.

It includes the computers, communication and software infrastructure required to control the telescope, down to but not including the sensors and actuators. It defines standards for control and electronics hardware, software and data communication. It contains the high-level coordination software, wave front control computer and the archive for all engineering data collected during the lifetime of the observatory.

Use of the control system is not limited to science operations of the commissioned telescope: it is first used in the Assembly Integration and Verification (AIV) phases of the ELT construction project, as a support to commissioning and verification. After AIV, as maintenance activities are defined and implemented, the Control System supports daytime activities, monitors the telescope during coordinated activities and ensures safety. As a calibration tool the control system supports execution of defined calibration sequences.

3. ARCHITECTURE

The mentioned organizational and procurement requirements drive the architectural breakdown of the control system:

- Each telescope subsystem, individually contracted to industry, is associated with its own independent Local Control System (LCS). Each LCS contains all the required control software, unit(s), devices and local communication infrastructure to monitor, command and safely operate the whole subsystem.
- The Central Control System (CCS) contains computers, middleware and application software to integrate and coordinate all LCSs. It includes the external interface to operate the telescope and to communicate with the instruments. As such, it also includes the real time computer required to coordinate and interface with all wavefront control functions. Further, it contains definitions of standards applicable to all telescope central computers and software.
- Instruments are individually developed by Consortia of ESO partner institutes around Europe. Each instrument will include an independent Instrument Control System (ICS) developed following the ELT standards, and interfacing with the telescope through the CCS interface.
- The Time Reference System and the Networking Infrastructure are common services provided by the Control System to LCSs, CCS and ICSs.

The diagram in Figure 2 shows this conceptual architectural breakdown.

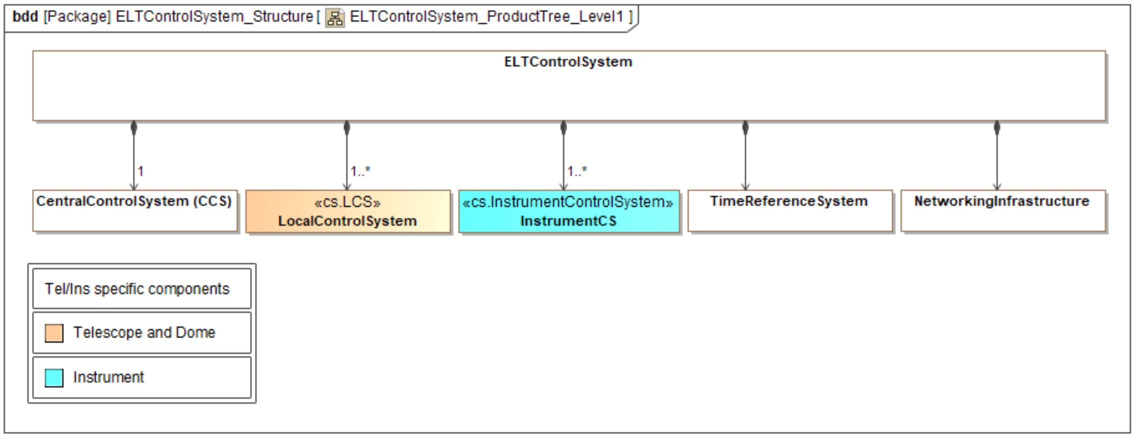

Figure 2. Control system top-level breakdown structure.

Concretely, for the ELT we have identified the main LCSs listed in Table 1:

Table 1. ELT Local Control Systems

Local Control System	**Description**
Dome LCS	Responsible for control of dome azimuth rotation, slit doors, windscreen, louvers, thermal regulation, power distribution, building management system, fluids provisioning and distribution, thermal regulation, handling devices and access control.
Laser Guide Star Unit LCS	Responsible for control of the Laser Guide Star Unit.
M1 LCS	Responsible for control of M1 Position Actuators, M1 Edge Sensors and warping harnesses, in situ or temporarily integrated in qualification test beds. It includes control of the electrical power and cooling distribution in the M1 cell.
M2 LCS	Responsible primarily for control of M2 hexapod. It includes adjustment capabilities for re-aligning within the telescope and shape adjustment capability, as required by the wavefront control strategy
M3 LCS	Responsible primarily for control of M3 hexapod. It includes adjustment capabilities for re-aligning within the telescope and shape adjustment capability, as required by the wavefront control strategy
M4 LCS	Responsible for control of M4. It includes control of the ~5300 actuators.
M5 LCS	Responsible for control of M5. It includes control of the fast tip/tilt steering functions.
Main Structure LCS	Responsible for control of Main Structure. It includes control of the main azimuth and elevation axis (with position and velocity control loops, brakes and clamps), cable wraps, M5 repositioning when changing observing focus and other auxiliary devices.
Metrology LCS	Responsible for control of the metrology systems allowing coarse alignment of the telescope optomechanical units.
PFS LCS	Responsible for control of PFS unit(s). It includes control of the sensor arms' azimuthal and radial motion, field curvature compensation, focusing, camera pupil centering, calibration unit, shutter and filter wheel as well as M6 mechanism to propagate the beam to the different instruments.

The LCS-CCS differentiation not only separates unit-level safety and control from telescope-level safety and control, it also matches organizational boundaries in-line with the ELT procurement strategy, where individual subsystems (mirror units, main structure, dome, lasers) are designed, built and delivered by external industrial partners while the integration of the subsystems to form the telescope system is carried out by ESO.

CCS interfaces with LCSs strictly via data communication over Ethernet. The interfaces are defined in a series of Interface Control Documents (ICDs)[2] specifying the logical addresses, data types, formats and rates and characteristics of the data communication. The LCS-CCS ICD specifications also separate control from safety.

The LCSs, CCS and instruments interface with infrastructure for power, networking and the observatory clock.

4. LOCAL CONTROL SYSTEMS

A Local Control System (LCS) contains two key functional groups: control and safety. Control functions enable standard operation of the subsystem, while safety functions preserve its integrity and guarantee safety of personnel and equipment.

The control functions include Control Software, Local Control Unit(s), remote IO modules and a local communication infrastructure.

The safety functions include Safety Logic, Local Safety Unit(s), Safety IO devices and a fail-safe communication infrastructure.

The block diagram in Figure 3 shows the Local Control System as a component of the subsystem, and the various

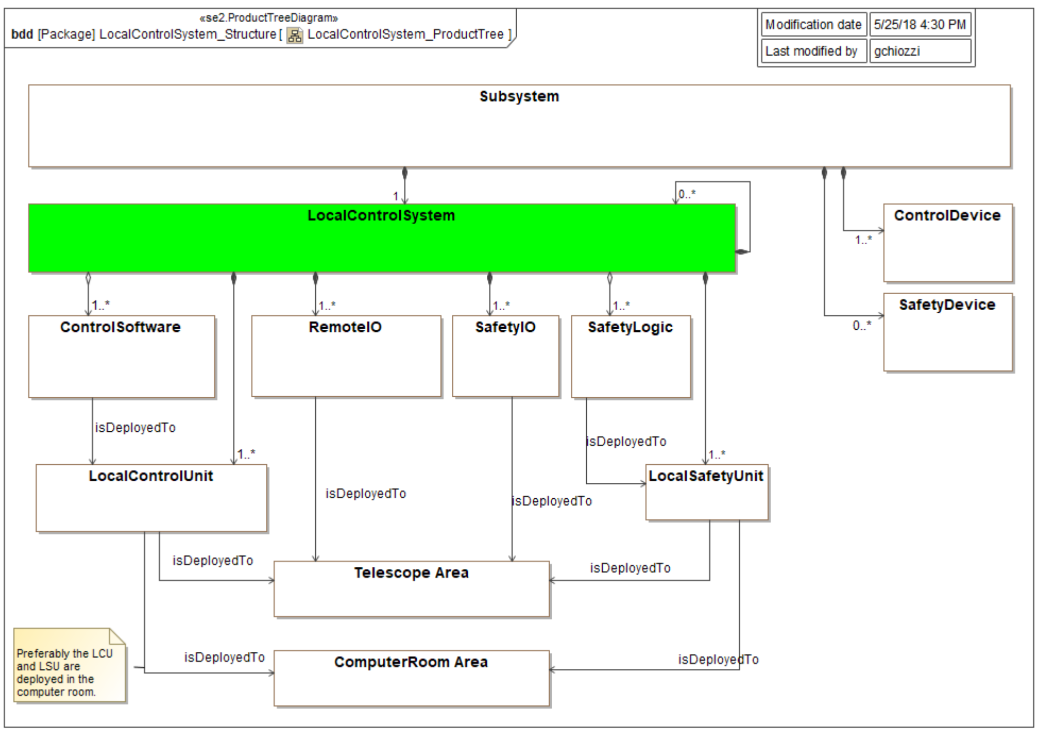

Figure 3. Local Control System architecture

components comprising a Local Control System.

The LCS enables safe control of the functions of the associated subsystem (e.g. M2 mirror cell). The functions provided by the LCS can make no assumptions as to the nature of the subsystem use in the context of the telescope control system (the operation and wave front control strategies being implemented by the CCS, external to the LCS). For example, the M4 adaptive mirror has to be available and operable to full performance irrespective of whether or not the telescope is observing or calibrating, or parked.

The LCS provides interfaces to CCS that enable individual control of all subsystem devices and functions, irrespective of intention or mode, to the limits of the safety system. All subsystem functions must be controllable individually and independently. For example, it must be possible to move the warping harness of an M1 segment irrespective of the status of the edge sensors and position actuators.

Local Control Systems and the example of the M1 LCS are described with more details in these proceedings in [4].

5. CENTRAL CONTROL SYSTEM

CCS integrates the many Local Control Systems into a single system implementing the coordinated control, system level safety, monitoring and user interfaces required to operate the ELT Telescope.

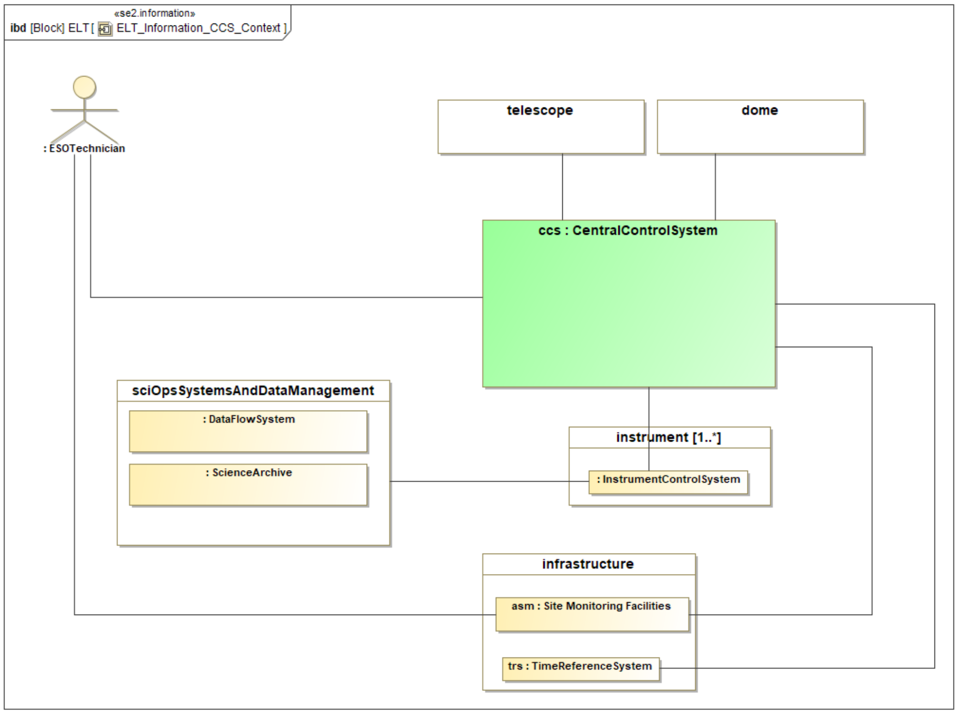

Figure 4. Central Control System context

The role of CCS in the information flow among the components of the system during operation is shown in Figure 4.

On one side, CCS interfaces with the hardware of the telescope through the LCSs, on the other side, it is the only interface to the telescope for instruments, operators, observation management and archiving systems and other infrastructure services.

The user, being anyone from commissioning engineers to telescope operators, when using the CCS interface, must be presented with the Telescope and not the Control System. CCS ensures the user's focus is fully available to the Telescope task at hand, and not be distracted or hindered by any complexities or restrictions of the CCS. At the same time, CCS should not prevent deeper access or direct local control of the subsystems, supporting lower level maintenance and verification with data collection and diagnostic tools.

One of the key principles adopted in the ELT Control System architecture is the strong separation between the roles and domains of the LCSs with respect to the CCS. While the LCSs (developed typically by industrial contractors) are responsible for the barebone control of the elementary functions of the devices, CCS (developed in house, to leverage our specific astronomical expertise) is responsible for coordination and for all what concerns the astronomical domain.

In order to enforce this concept, ESO has decided that for each LCS there has to be a corresponding Local Supervisor (LSV) in CCS.

LSVs:

- are the only interface to the corresponding LCS from other parts of the system (are the LCS façade).
- perform any adaption of the interfaces needed to integrate the LCS into the control system in a uniform way, fully compliant with ELT development standards (are the LCS adapter to CCS).
- implement any functionality related with the astronomical domain; for example, the Main Structure LCS provides functions for the axes to follow a trajectory under position and velocity control in alt/az absolute coordinates. Tracking of sky targets, with the conversion from (ra,dec) to (alt,az) using positional astronomy algorithms is fully delegated to the Main Structure LSV.
- implement a standardized state machine and a set of standard states, to allow building up hierarchically the state of the whole ELT Control System and to allow performing, in a standardized way, common operations like startup and shutdown.

Figure 5 and Figure 6 show the relations between the interfaces of LCSs, LSVs and other components of the system. For more information on the structure of interfaces see [2].

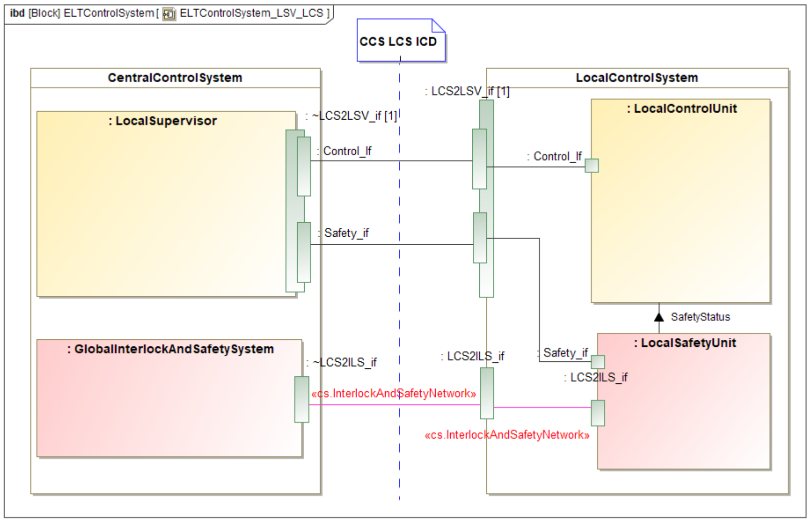

Figure 5. LCS/LSV interfaces

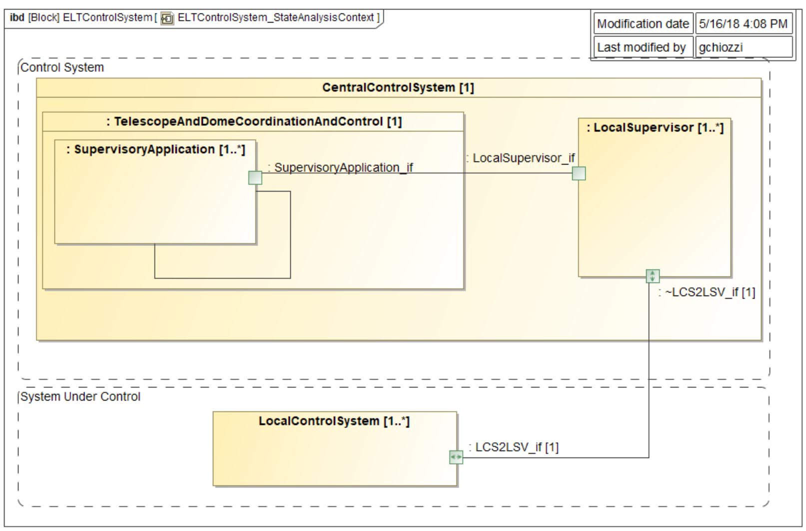

Figure 6. CCS interfaces with LCSs

As can be seen in Figure 6, the actual coordination between the activities of all subsystems, the interfaces with the external users of the telescope (i.e. operators, engineers, or the instruments performing scientific observations) and the general housekeeping activities are performed by higher-level supervisory applications that we logically group in the Telescope and Dome Coordination and Control package.

Supervisory applications are organized in a shallow hierarchy of loosely coupled cooperating components. Anonymous publisher-subscriber communication is used to keep the coupling as loose as possible.

The higher-level set of these supervisory applications will be developed around *features*, i.e. a supervisory application will be designed and developed to perform a complete operational function/use case of value to the users of the system.

This choice is driven by the awareness that we will have a long period of integration and commissioning, during which we will discover along the way how to operate our machine and how the elementary functions provided by the LSVs will have to be composed together to realize higher-level features. This has been our experience with previous projects and we believe it will be even more like that for the ELT.

Implementing *features* as independent lightweight components, using a scripting/interpreted language and with the possibility of executing and debugging them through an interactive script execution user interface allows us to change and evolve them in an easy way, with minimal impact on other *features* and without having to stop/restart parts of the system. Once stabilized, *features* can be eventually re-implemented using more efficient/performant languages, again without impact on other parts of the system.

In addition to supervisory applications, CCS includes other packages like:

- Software infrastructure components and development frameworks to be used for CCS supervisory applications and instruments. These include Core Integration Infrastructure and Instrument Control System Framework.
- Operator and Engineering user interfaces for the interaction with the system.
- Global Interlock and Safety System, to handle interlock conditions in the interaction between separate subsystems.
- Telescope Real Time Executor (TREX) to provide all AO-related functions needed outside the AO modules of

instruments, for general usage or for usage without instruments (like achieving seeing limited optical quality, perform calibrations or AIV-specific activities).

The complete breakdown structure is shown in Figure 7 and some of them will be better described in the following

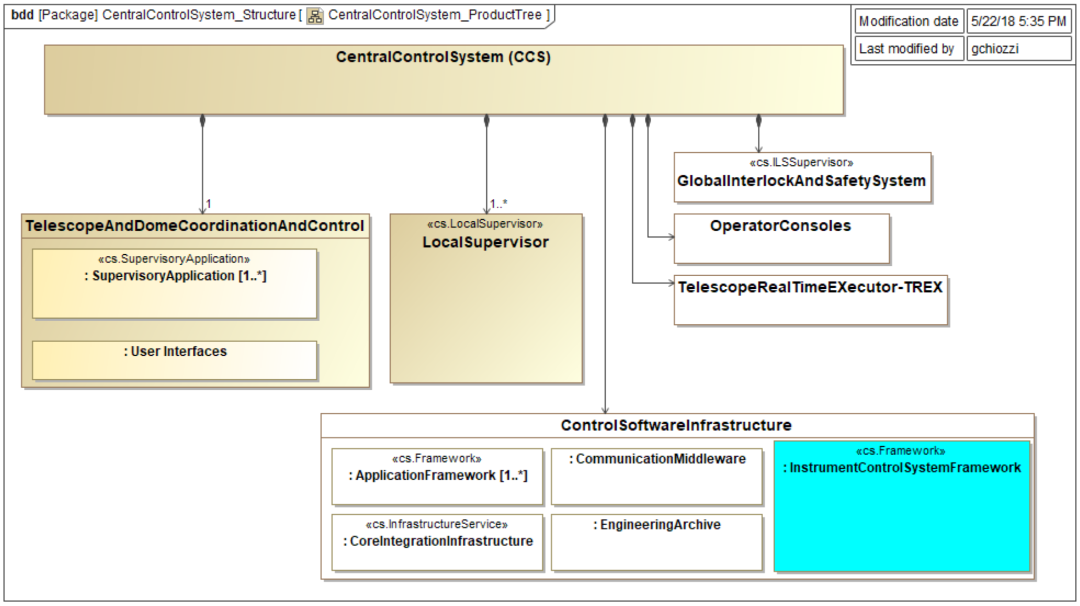

Figure 7. CCS breakdown structure

sections.

6. NETWORK AND DEPLOYMENT

The ELT Control System components, including LCSs and CCS, are distributed over four areas:

- The Telescope area, in proximity of the main structure and mirror units.
- The Computer Room, in the dome basement auxiliary building.
- The On-site Control Room, adjacent to the Computer Room in the dome basement.
- The Paranal Control Room, about 30km away, from where science operations will take place after commissioning.

These areas are connected by the Networking Infrastructure, a network of fiber optics cables, copper cables and networking equipment.

To minimize the introduction of vibrations and thermal energy into the telescope structure and surrounding air volume, equipment in the Telescope area should be limited to field electronics (the components interfacing directly with sensors and actuators). All other computing nodes must be hosted in the Computer Room in the Dome Auxiliary Building. Exceptionally, controllers in proximity to the field electronics might be considered for safety or performance reasons.

The Computer Room will be equipped with racks for blade servers, network and other IT equipment. All network fiber cables will terminate in the Computer Room. Except if prevented by latency or computation power requirements, software shall be hosted on virtual machines, deployed on blade servers in the Computer Room and connected over a switch to network storage which provides hard disks in RAID configuration. Virtualization provides the possibility to pool hardware and computing resources and allocate the resources as required to the many CCS applications. The environment further provides rapid deployment of virtualized images, disaster recovery and fail-over options.

During commissioning the telescope will be first operated from a protected hut inside the dome, to ensure direct visibility of the telescope, and then from the On-site Control Room.

After commissioning, the whole operation of the ELT is planned to be done from Paranal control Room, with local intervention only if needed.

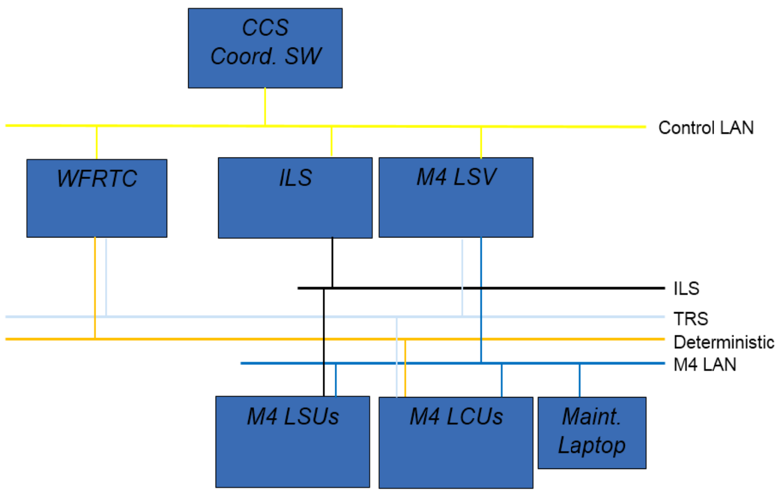

Figure 8. Configuration of LANs for M4 control

Based on the analysis of the control, safety and timing communication requirements, we have identified four logical LANs with specific QoS requirements:

- Control LAN: Control and data communication between the systems, general services.
- Deterministic LAN: Deterministic communication between subsystems.
- Time Reference System (TRS) LAN: Time distribution.
- Interlock and Safety (ILS) LAN: Fail-safe interlock distribution.

Given the fast evolution of technology, the final decision on the mapping of these logical LANs to physical hardware will be made at the time of the final design.

Figure 8 shows as an example how the different logical LANs are used in the control of the M4.

The ELT Control System foresees the use of two major Ethernet flavors of field bus for the control of field devices: PROFINET IO and EtherCAT. However, in addition, several high-performance distributed control loops will be implemented using UDP/IP (possibly DDS/RTPS) over dedicated virtual LANs. Some examples are the AO loop and the M1 Edge Sensor control loop.

Extensive prototyping has proven that with appropriate switch hardware and configuration, a dedicated Ethernet LAN/VLAN can reliably meet the microsecond level maximum latency and low jitter performance requirements of the ELT CS distributed control loops, with negligible data loss.

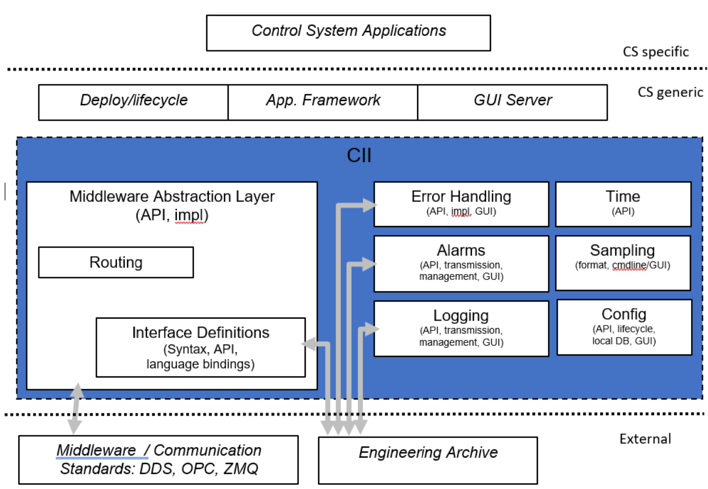

Figure 9. Core Integration Infrastructure

7. CORE INTEGRATION INFRASTRUCTURE

One of the key principles of the Central Control System is the abstraction of communication middleware and other generic control system services such as component configuration, logging and alarms. This abstraction and implementation is provided by the Core Integration Infrastructure (CII).

The embracement of this principle is in-line with the positive experience in the adoptions of equivalent concepts for most projects in our domain and in particular for the VLT with CCS and ALMA with ACS[5]. After an evaluation of the available platforms, ESO has decided to develop a new infrastructure relying on recent but well-supported technologies to leverage the new capabilities and with the perspective of having a well-supported middleware for the lifetime of the project.

CII, described with more detail in [3], decouples the business logic, i.e. the control system applications, from the other components in the control system (subsystems, logging systems, database, etc.). The decoupling focusses the engineer on the task at hand (building an application to solve a problem) by hiding details of communication and interfacing; it eases as well the task of obsolescence management and upgrades by decoupling the components.

CII is designed with the objective of making it easier replacing the underlying middleware technology during the lifetime of the project by supporting from the beginning different technologies (DDS, ZeroMQ and OPC/UA).

The main services provided by CII are:

- **Middleware Abstraction Layer -**Abstracts the communication middleware products and present the communication patterns (pub/sub, request/reply) through a uniform API.
- **Routing** - For locating data points, and functionality common across all communication standards.
- **Interface Definitions** - To express control system interfaces, mapping them to all supported programming languages.
- **Error Handling** - System-wide, cross-language, consistent way to report application errors and diagnostics in a manner permitting traceability across the distributed control system.
- **Alarms** - Configurable data monitor system to create and manage system-wide alarms based on conditions and states of the system under control.
- **Logging -** Generic text messages for human consumption, relating to either the control system or the system under control. Includes transmission to send log messages, and API to store logs in an archive.
- **Time -** Component to manage time (conversion from TAI to UTC), arithmetic based on time.
- **Sampling -** Tools to monitor sets of data points over a period of time and display and/or log the captured data.
- **Configuration -** System-wide model for the expression, management and handling of control system configuration data (binary and text).

8. INTERLOCK AND SAFETY

The ELT Interlock and Safety System (ILS) implements the logic ensuring integrity of the telescope equipment and safety of personnel. The system is a hierarchical system of Local Interlock and Safety Systems responsible for subsystem level safety, and the integration of these Local ILSs in the Global ILS System, responsible for Telescope level safety and the coordinated interaction between subsystems (for example, lasers cannot be switched on if people are inside the dome and doors are not locked).

Requirements driving the design of the Interlock and Safety System are largely identified through a Hazard Analysis. This analysis is performed once a system design is mature enough to enable the identification of hazards to equipment and personnel through failure or unintended command of the equipment. The resulting assessment criteria for each identified hazard drives the mitigation strategies and the design of the Local ILS. The Hazard Analysis likewise guides the selection of the safety integrity level (SIL) rating required for safety equipment in the Local ILS and drives the requirements for safety certification.

ESO has selected Siemens Failsafe SIMATIC S7 as the standard general technology for telescope subsystems, and TwinSAFE technology as acceptable option.

As shown in Figure 5, the Local Safety Unit, responsible in each subsystem for the implementation of Local ILS functionality, interfaces to CCS over two channels: one interface to the Local Supervisor (control component) and one to the Global ILS (safety component).

The Local ILS makes available safety commands and measurements to the Local Supervisor over OPC/UA. Through this interface, supervisory applications may monitor and command safety functions as part of coordinating the subsystem.

The measurements (digital outputs representing interlocks, limits, alarms) enable the Local Supervisor to estimate the state of the subsystem and thereby to proactively prevent the user commanding the subsystem such that an interlock is triggered. For example, a user interface may not offer the option to move an axis when the brakes are still applied (brakes status being a signal from the ILS).

The commands (digital inputs) enable the Local Supervisor to control the state of the subsystem, for example powering drives or releasing brakes under responsibility of the ILS.

In parallel, the ILS provides safety commands and measurements to the Global ILS in the form of discrete I/O signals. The use of a discrete I/O permits complete abstraction and decoupling of the Local ILS from the Global ILS. This allows the integration of Failsafe SIMATIC S7 and Beckoff TwinSAFE and ease simulation of the interfaces during development.

9. TIME SYSTEM AND SYNCHRONIZATION

The Time Reference System (TRS) is the service responsible for keeping and propagating the absolute time; the TRS includes the centralized Observatory Clock, the components of the Networking Infrastructure necessary to distribute the absolute time and the synchronization of the system clock in the computing nodes with the grandmaster clock.

The TRS network protocols are Precision Time Protocol[2] (PTP) for accuracy in the microsecond range and the Network Time Protocol (NTP) for accuracy in the 10's of milliseconds range. The Networking Infrastructure is required to permit (given correct end-point interface hardware and clock control) synchronization over PTP between the Observatory Clock and a peripheral clock of 0.5 microseconds maximum average error.

The ELT has selected the International Atomic Time (TAI) timescale as the *monotonic clock* to measure elapsed times.

The *wall-clock* time standard to manage timestamps is UTC, with UNIX epoch (Midnight, 1 January 1970). Timestamps are encoded using 8-byte double precision floating point numbers, representing the number of seconds since epoch. This timestamp well covers the lifetime of the observatory at microsecond accuracy. Display of timestamps is standardized on the ISO8601 combined date and time representation (the "T" display format), for example, "2007-04-05T14:30.023"

CII libraries will provide the standard conversion between TAI and UTC in the different representations.

The degree of synchronization and accepted communication latency between two components are defined in their ICD or technical specification (synchronization requirements are specified with respect to the Observatory Clock and therefore the total de-synchronization of two units is the sum of the de-synchronization of each unit with respect to the Observatory Clock).

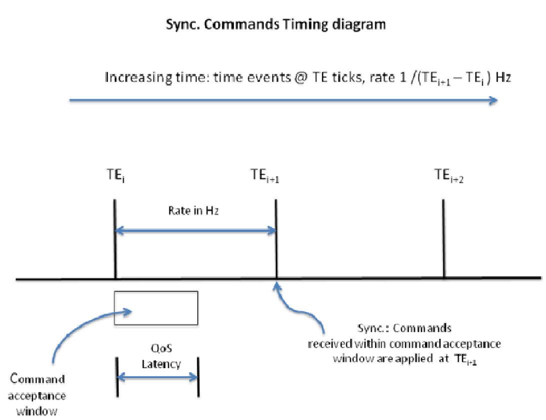

Figure 10. Synchronous command timing diagram

In particular, in the LCS ICDs is it possible to specify two types of commands:

- Asynchronous Commands are not associated with absolute time, they can be received at any time at the network interface and are to be applied immediately.
- Synchronous Commands are frequency-locked to absolute time ticks with zero offset. A Synchronous Command may be received at any time within the time window (from TEi to TEi+1) determined by the command rate and latency and is expected to be applied at the next time event following the reception of the command (TEi+1) (Figure 10).

It is also possible to add to commands an *at* parameter specifying the time in the future when the command will have to be executed.

[2] https://en.wikipedia.org/wiki/Precision_Time_Protocol

10. INSTRUMENT CONTROL SYSTEM FRAMEWORK

An Instrument Control System (ICS) consists of a combination of hardware and software components providing the functions to control and operate all its own subsystems that enable the acquisition of scientific images for each of the different instrument modes. The ICS is directly responsible for the control and monitoring of technical and scientific detectors and instrument functions, as well as the coordination of external systems like the telescope and the post-focal AO module.

The ICS interacts with its users through graphical interfaces designed to automate the observations and to continuously display the status of the instrument and its subsystems.

As illustrated in Figure 11, the ICS is typically composed of the following subsystems:

- Cabinet Management
- Cryogenic Control
- Local Safety Unit
- Detector Control
- Co-rotation Control
- Built-in AO Control
- Function Control
- Supervision System
- Maintenance System

As for the VLT, ESO is providing an ICS FW to support the development teams and to have uniform solutions for all instruments (Figure 12).

The VLT experience and, in particular, the second-generation instruments will be used as a reference architecture for the ICS FW[6].

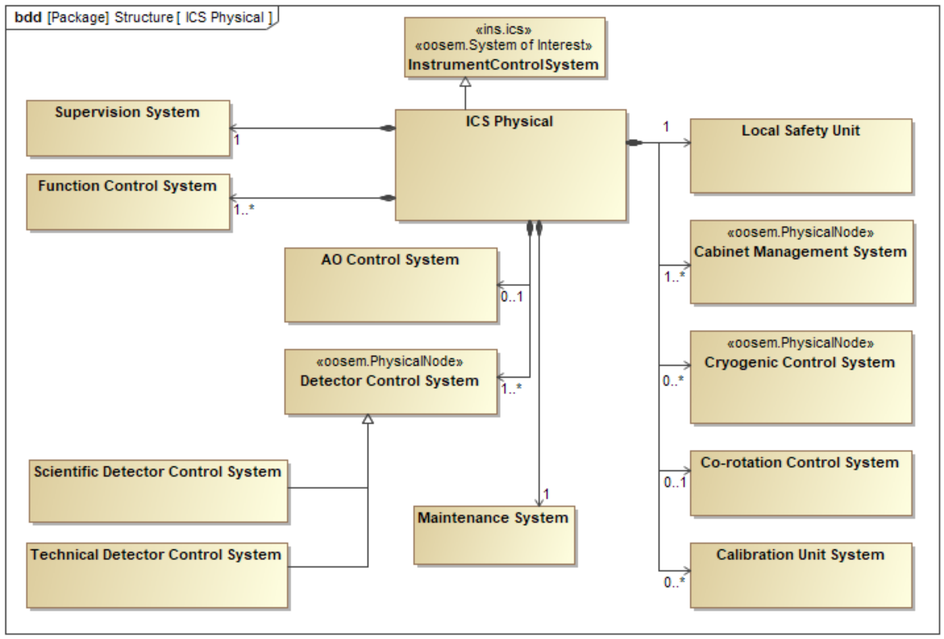

Figure 11. Instrument Control System components

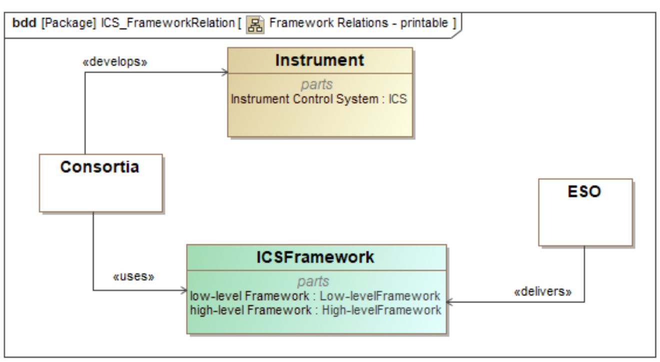

Figure 12: Relation between ICS and ICS Framework.

The most important design principles of the ICS FW are:

- Customizability: generic software components can be tailored to the need of the instruments by means of adapting configuration parameters
- Extensibility: framework components can be extended by developers overriding or specializing the framework solutions to provide instrument specific functionality.

The ICS FW is divided into a high-level and a low-level framework, plus an *ICS Control Model* (see section 11).

The high-level framework (components are described in Table 2) is the software framework intended as baseline for the construction of the instrument control system software and it includes all the software and communication infrastructure required for the control and monitoring of the instruments functions.

Table 2. High-level ICS framework components

FW component	Description
Application Framework	Software framework for building other framework components.
Function Control Framework	Library providing the implementation of a set of generic devices like sensors, motorized functions and digital and analog controllers.
Widget Library	Library of graphical interfaces to develop the engineering and operational interfaces for the various components in the ICS.
Observation Coordination Framework	Software responsible for performing observations by taking exposures in coordination with other systems. It covers two additional packages: • The Guiding Manager component is responsible for implementing and coordinating instrument guiding capabilities. Different instances of this manager might be controlling instrument secondary guiding or AO off-loading loops. • The Data Product Manager is responsible for gathering final image and header data and composing the data product.
Technical Camera Control SW	Software that implements the control of technical CCDs.
Data Display Tool	Display tool for raw images, spectral data and FITS files.
Data Interface Library	A set of classes that implements the interface to the cfitsio library and the handling of ICS dictionaries.
Sequencer	The software executing the observations sequences defined by the astronomers for the different instrument observation modes.
Template Library	Library of scripts to facilitate the implementation of Observation Blocks. It provides the facilities to coordinate and monitor all instrument subsystems during observations.
Online Data Processing	A software component implementing some specialized image-processing routines that are generally required during the instrument acquisition process.
Calibration Framework	A tool for generating calibration and health check observation blocks.
Test Framework	Instrument testing framework allowing integration tests of the instrument software with different levels of hardware availability.
Configuration Generator Tool	Software responsible for the generation of the instrument configuration based on a textual or graphical representation.
Miscellaneous Libraries	General-purpose libraries for instrument software.

The low-level framework (components are described in Table 3) includes the standard equipment list, development tools, and templates for design and construction of hardware specific solutions.

Table 3. Low-level ICS framework components

FW component	Description
Cryogenic and Vacuum System	A template cryogenic and vacuum controller based on PLC technology. This system will handle all basic functions like: evacuate, cool down, stabilize and re-pressurize as well as interlock, safety and human interfaces, regardless of the cryostat type. In addition to these high-level generic functions, the controller should offer also template control functions capable of handling the different cryostat types, ensuring coherence between all developed systems. The package includes a standard PLC component list, a library of PLC function blocks and templates for design and construction of cryogenic and vacuum systems
Interlock and Safety System	A template for the instrument local Interlock and Safety System (ILS), providing system integrity and safety both when operated stand alone and in coordination with the operational scenario.
Cabinet Management System	A specification of a cabinet cooling system that provides supervision of the thermal conditions internal to the cabinets and controls the external surface temperature of the electronic cabinets in order to minimize heat transfer to the dome environment. The system includes also the specification of the power control and measurement for instrument cabinets.
Technical CCDs	A system to control and monitor COTS TCCD cameras. This package includes a list of supported COTS cameras and guidelines for design and construction of such systems.

11. CONTROL MODELS AND SIMULATION

Most of the ELT subsystems will be sent directly to Armazones and integrated directly on the telescope. There will be therefore very little, if any, opportunities for testing them with other subsystems before.

At the same time, it will not be possible to test CCS supervisory software with the real LCSs and the associated hardware or to test the interfaces of the control software of the instruments with CCS before on-site integration.

In order to minimize the associated risks, we require the implementation of extensive simulation capabilities and we will provide several "ELT Control Models" (ECM) partially replicating representative elements of the ELT control system hardware, software and infrastructure to enable testing and verification activities.

We plan to have: an ECM in ESO Garching Integration Hall, a Portable ECM to test sub-systems and instrument in European facilities, one in the Paranal Auxiliary Telescope Hall, one in the Paranal ELT Technical Facility, one in Paranal New Integration Hall and one in the Armazones Instrument Integration Area.

The ECM architecture will be modular and, depending on the needs, might include CCS hardware and software, Local Control Units, Local Safety Units, auxiliary diagnostic tools, Time Reference System, Interlock and Safety Systems.

To enable building and testing LCSs in environments disconnected from the subsystem field electronics and/or actuators and sensors in the Control Model or other development environment and to later effectively carry-out maintenance (software and hardware upgrades or trouble shooting), the ELT Project requires the implementation of a simulation mode. The mode would be activated through configuration or command and enable exercising the majority of the LCS functions without field electronics.

Two general levels of simulation are recommended:

- Field Electronics Simulation: Local Control/Safety Unit simulation of field electronics. In this scenario the LCUs/LSUs are disconnected from field electronics. The LCS enables simulated operation of the subsystem by implementing a simulation of the field electronics connections (for example digital and analog I/O).
- Actuator/Sensor Simulation: Local Control/Safety Unit simulation of subsystem actuators/sensors. In this scenario the LCUs/LSUs and field electronics are present, but not connected to the sensors and actuators of the subsystem. The LCS enables simulated operation of the subsystem by simulating the sensors and actuators.

The control model in Garching will be extensively used for CCS development to test the interaction with the LSVs, installed there in simulation mode.

In a similar way, the ICS Control Model is intended to be a control system mock-up of a generic instrument, sufficiently representative to be used to test the high and low-level frameworks. The ICS Control Model is an integral part of the ELT Project Control Model. The ICS Control Model will be used for simulations and debugging purposes during and after the ICS Framework development and maintenance.

The control model consists of:

- All software needed to run a generic instrument (incl. the ICS high-level framework).
- Computers/workstations to host the software.
- Network equipment to interconnect the control model units and to interface to external systems.
- Sample hardware defined to be included in the ICS low-level framework.
- Mock-up versions of units interfacing with ICS, i.e. TCS, AO, detector controllers, dataflow systems, etc.

Another very important test bench for the ELT Control System currently under development is the Minuscule-ELT[8] (MELT). MELT is an optomechanical test-bench with the purpose of testing and validating key functionalities to be used on the ELT. It includes, shrunken to bench size, a segmented M1, an M2 on hexapod, an adaptive M4 and a fast tip-tilt M5. The ELT Control System will be deployed on MELT as on a Control Model and used to test control recipes in advance to the integration at Armazones. This concept follows the path of the NTT big-bang, where the VLT Control System was first deployed and tested on the NTT in La Silla.

12. CONTROL SYSTEM STANDARDS

A consistent level of quality throughout the control system and seamless integration of subsystems are ensured by the selection and strict adoption of standards for the elements of hardware and software.

During the past few years we have carefully analyzed the technical requirements in the different areas of the project and done extensive prototyping with the available technologies to select and present manufacturers and developers with a (small) variety of solutions to design and implement their component(s) of the CS. For example, Local Control Units (LCU) may be implemented on either Programmable Logic Controller (PLC), embedded computers running real-time or standard Operating System (OS).

This selection has solid roots on our previous experience and values well-established industrial standard and commercial off-the-shelf products, with a life expectancy in the time scale of the project or with the perspective of being replaceable with new, equivalent, products at a reasonable cost/effort. The use of alternative solutions for a well justified particular purpose is not excluded, but is subject to approval by ESO.

A quick overview of the most important standards adopted is given by the following list:

- Communication technologies: Ethernet, EtherCAT, PROFINET, PROFISAFE, Unicast and Multicast UDP/IP.
- Middleware/messaging: OPC/UA, DDS, ZeroMQ.
- Time synchronization: PTP and NTP.
- Runtime platforms:
  - Linux CentOS/Linux RT for WS applications.
  - Beckhoff PLCs running TwinCAT, SIMATIC S7, LabVIEW RT for LCS software.
- Local safety units: SIMATIC Safety Advanced, TwinSAFE.
- Programming languages: C++, Java and Python at workstation level, Structured Text and Function Block Diagrams for PLC code, MATLAB/Simulink for control engineering applications, LabVIEW-G.
- Google Protocol Buffers for serialization/deserialization of data in messages.

- SCXML for state machines specification.
- Graphical user interfaces: Qt Widgets in C++ and Python for operator interfaces, LabVIEW or touch panel HMI for Engineering UIs and hardware control panels.

The standards are collected in a set of documents that are applicable to any ELT control system development.

13. DEVELOPMENT PROCESS

To enable external suppliers to leverage established in-house development processes, we do not mandate a specific process methodology and instead promote flexibility in the development of the control systems for the subsystems contracted externally, tailoring an appropriate method based on the supplier's practices and the size and nature of the control system.

The supplier must present the proposed development process as part of the Project Management plan and satisfy the following basic requirements:

- Requirements of the control system should be traceable from the top-level requirements of the associated subsystem. This applies to control analysis, risk and reliability analysis. Regarding safety systems, for which few top-level requirements are provided, it is requested that the supplier performs a hazard analysis and elaborate safety system requirements traceable from the outcome of the hazard analysis.
- The control system design shall be documented in a Design Description which is subject to a formal preliminary and final design review, enabling early inspection of the proposed final control system.
- During control system construction the supplier is requested to make periodic submissions of source code to the ESO code repository. This enables ESO to build and inspect the control system software at early stages in the development, and throughout the development life cycle.
- The supplier shall ensure that all control system software is verifiable by test. The control system software shall be built and integrated from source code automatically and regularly. It is thus essential that the build and test execution be unattended. The build and test suite cannot make use of manual interaction.
- Closed loop control systems have additional test and verification requirements to evaluate robustness and stability as part of control system design, verification and maintenance. Control systems must be equipped with means to measure different responses, e.g. frequency response, step response, permit the injection of excitation signals and enable recording of time series data up to the servo loop rate. These test functions must be readily executable remotely (i.e. from the computer room or control room) and not require physical access to the device.

These same principles apply also to ESO internal development. As part of the required process specialization, we have defined for the control system software implementation phase a process using agile/iterative methods. We have also adopted the following tools to support the internal development process:

- DOORS[3] (at ELT project level) for requirements management
- MagicDraw[4] for modeling
- Jira[5] for task tracking and planning (with agile plugins)

14. CONCLUSION

The development of the ELT Control System is now very quickly ramping up.

Most subsystem contracts have been issued, with the corresponding Local Control System.

Requirements, architecture and design for CCS and the Instrumentation Frameworks are being iteratively stabilized, supported by intensive prototyping, while the CII development has been contracted to an external company.

At this stage there are many activities going on in parallel. With CII and the building and deployment tools still under development, we are slowly approaching a complete platform. As the underlying tools are developed and all pieces of

[3] https://www.ibm.com/us-en/marketplace/rational-doors
[4] https://www.nomagic.com/products/magicdraw
[5] https://www.atlassian.com/software/jira

the puzzle fall in the right place, we will refactor our code and retrofit it to consistently use final products and design patterns.

The adopted agile development process should give a substantial help and fits very well with a scheme where we will decide in short iterations what will have to be implemented or refactored in the subsequent phases.

The adoption of new technologies and development methodologies with respect to the VLT and ALMA will allow us to implement a more reliable and performant system in a more efficient way and with the perspective of an adequate lifetime expectancy. But, at the same time, it implies a non-negligible learning curve for all people in the team that has been working for several years using VLT and/or ALMA technologies, even if the basic principles are mostly the same. There is therefore a price to pay now for a better efficiency in the future.

The MELT project will also play a fundamental role in allowing us to arrive to the AIV times with a reliable and reasonably tested control system architecture.

But we have still several years before going to Armazones for the first light in 2024: comparing our status with the experience from VLT and ALMA we are in a similar situation on a similar timescale.

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