Conceptual design of the control software for the European Solar Telescope

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ABSTRACT

Aim of this paper is to present an overview of the conceptual design of the Control Software for the European Solar Telescope (EST), as emerged after the successful Conceptual Design Review held in June 2011 which formally concluded the EST Preliminary Design Study. After a general description of ECS (EST Control Software) architecture end-to-end, from operation concepts and observation preparations to the control of the planned focal plane instruments, the paper focuses on the arrangement devised to date of ECS to cope with the foreseen scientific requirements. EST major subsystems together with the functions to be controlled are eventually detailed and discussed.

Keywords: solar telescope, EST, telescope control, control software

1. PROJECT DESCRIPTION AND SCIENTIFIC MOTIVATIONS

The EST (European Solar Telescope) is a 4-meter class telescope optimized for the study of the magnetic field and dynamics from the deep photosphere to the upper chromosphere of the Sun. More than a single "stand-alone" telescope however, EST is intended to be an infrastructure in Canary Island (Spain)[1] to study the Sun with unprecedented spatial, temporal and spectral resolution. EST will improve by a considerable factor the presently achieved spatial resolution. In addition, the operation of several narrow-band tunable visible and near-infrared imaging instruments together with grating spectrographs, all with polarimetric capabilities, and large format broad-band imagers, will allow the simultaneous observations of photospheric and chromospheric layers and the study of the temporal evolution of the three-dimensional structure of solar magnetic fields. These aspects will make EST a unique infrastructure.

The EST project is promoted by the European Association for Solar Telescopes (EAST), which is a consortium with 15 research institution members from 15 European countries. The conceptual design study, aiming to demonstrate the scientific, technical and financial feasibility of the project, started on February 2008 with funding by the European Commission through an FP-7 Collaborative Project and completed in June 2011 with a Final Review held in front of an international board. The study involved 29 partners and 9 collaboration institutions from 14 countries and covered all key aspects of EST design, from optical configuration of the telescope and instruments, to dome and auxiliary buildings needed to operate the facility.

The technical design of EST has been driven by the main (observational) focus of the project which is the high-resolution, multi-wavelength, spectro-polarimetry of the solar photosphere and chromosphere photospheric. In particular the main scientific cases cover the studies of:

- Structure and evolution of the magnetic flux in the solar atmosphere;
- Photospheric/chromospheric magnetic coupling;
- Chromospheric structure, dynamics and heating;
- Magnetized plasma processes.

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With lower priority the EST design might also pursue the possibility of observing the solar corona, explosive events affecting space weather, and non-solar processes, if this can be accomplished at low additional cost for the project.

The EST science imposes two main requirements on the EST design: achieve high spatial resolution obtained by integrating in the telescope, since the beginning, a powerful multi-conjugate adaptive optics system (MCAO) and minimize polarimetric contributions through a polarimetrically compensated distribution of elements on the optical design.

Aim of this paper is to give an overview of the control software for this challenging and innovative infrastructure as emerged by the EST conceptual study. Emphasis is given in particular to the high-level overall software architecture able to cover various operational aspects ranging from observation preparation to the control of the telescope and its instrumentation. Main features of the challenging data handling and reduction tasks are presented elsewhere[2].

2. OBSERVATORY DESCRIPTION

EST is a 4-metre class altazimuthal solar telescope with an on-axis Gregory configuration. The telescope includes active and multi-conjugate adaptive optics integrated in the telescope optical path to maximize the telescope throughput and to provide a corrected image at the Coudé focus for three types of instruments simultaneously: broad-band imagers, narrow-band tunable filter spectropolarimeters and grating spectropolarimeters. Each instrument is composed of different channels to observe different wavelengths simultaneously. The telescope itself is placed on the top of a tower to improve the local seeing conditions. The tower supports the telescope enclosure that is designed to be completely foldable. Moreover, the EST facility includes an Auxiliary Full Disk Telescope (AFDT) used to give the observer a global context of the solar activity and for precise coordinate measurements.

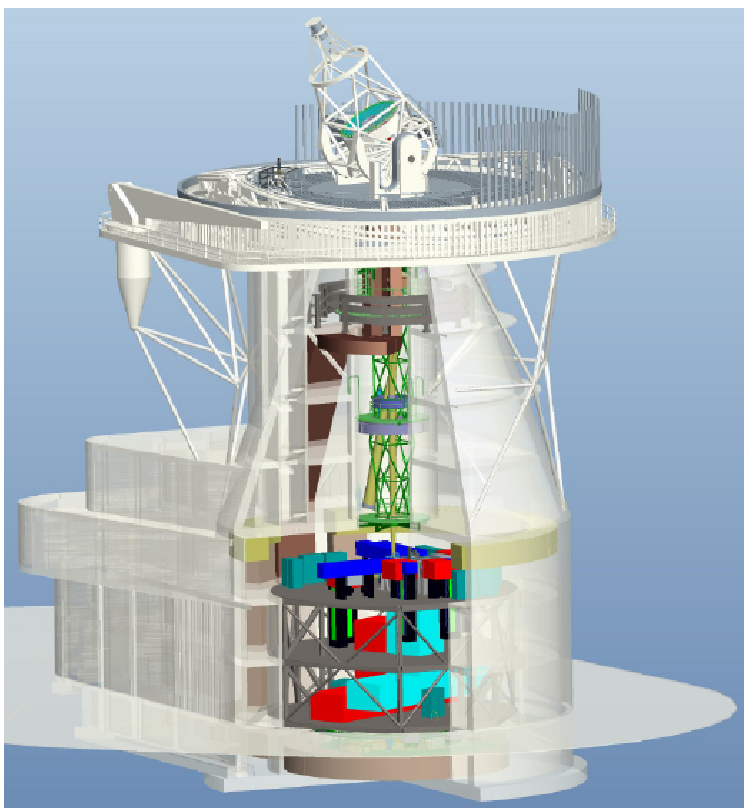

Figure 1. General view of the EST facility.

In the next sub-sections each sub-system is analyzed in detail emphasizing those aspects that are more relevant for the control. Note that this description does not exhaust all the possible dependencies among the various main sub-systems:

there will be necessarily a deep interaction among the telescope control software (TCS), the instruments, the archive and/or the data handling. Even though operationally a coordinated activity among all these sub-systems is mandatory, from the pure control point of view the telescope and its instrumentation should be able to operate disjoined from the archive and/or the data handling system. This interaction will not be described therefore in this paper (refer to [2] for further details).

2.1 Telescope and Dome

The main telescope/dome sub-subsystems, relevant for the control, can be summarized as follows:

- *Mount*; the telescope mechanical configuration is altazimuthal. For both axes, azimuth and elevation, it is proposed to use the same technology: direct drives or pinion-gear drives with position encoder and brakes included.
- *Primary Mirror (M1) with the Active Compensation system*; the primary mirror of EST is a parabolic mirror, actively compensated by a set of discrete axial active support points placed at the mirror back. This will be used to compensate for initial alignment tolerances, changes of the gravity vector with the elevation angle, temperature variations and wind buffeting. The M1 actuators will be electromechanical actuators (screws) with load cells to provide force feedback. Additionally to the load cells some linear encoders (e.g. three placed in three selected actuators) will detect rigid body displacement of the mirror in piston and tip-tilt.
- *Secondary Mirror (M2) with the fast tip-tilt and fast-focus capabilities*; the secondary mirror of EST is a complex system composed by a tip-tilt mechanism with fast-focus capabilities and by an alignment system. The alignment system is composed of a hexapod implemented by means of six linear actuators allowing six d.o.f. movements; the tip-tilt mechanism is instead based on three piezo actuators fixed directly at the mirror back.
- *Heat Stop*; the heat stop is placed at the prime focus and operates as a field stop. From the control point of view, at this phase of the project, it could be considered as a passive device, which requires software monitoring, but not direct high-level software control.
- *Transfer Optics*; it is responsible to bring the light into the instrument focal plane. The Transfer Optics includes all the optics between M3 and the instrument focal plane. Mirrors comprised between M8 and M14 are arranged in a cylindrical chamber that could act as an optical field-derotator. This solution avoids having a large rotating platform for the instruments in the Coudé room. Some of the mirrors could be placed moreover on translational stages for alignment purposes able to perform linear or tilt movements.
- *AO (adaptive optics) sub-system*; EST will be equipped natively with an integrated powerful AO system able to perform both GLAO (ground-layer adaptive optics) and MCAO corrections. It is foreseen to integrate the active optics with the AO system and both should work as a single system. The description of the internal details and the preliminary design of this part are however outside the scope of this paper.
- *Polarization Optics*; EST is conceived for the high-accuracy, high-resolution spectro-polarimetry. The polarimeter consists of a modulator, an analyzer and a demodulator. From the control point of view, the movements are concentrated in the modulator part. In the current design the polarimeter consists of two wheels equipped with a selection of modulation devices; among others they will host also rotating retarders driven by a single motor.

The EST TCS should also rely on the information provided by the following sub-systems for proper system operation:

- Site monitoring in charge of delivering detailed weather/environmental information;
- Enclosure; at present two possible use cases are foreseen: enclosure opening/closing (shutter-like) and wind-screen opening/closing and positioning with respect to the wind direction;
- Time Distribution System.

2.2 Instrumentation

The light coming from the telescope will feed different instruments. In the baseline design EST hosts three different instruments:

– a *Broad Band Imager* (BB), responsible for photospheric and chromospheric observations at selected (non-tunable) continuum wavelengths and spectral line cores;

– a *Narrow Band tunable filter spectropolarimeter* (NB), able to spectrally isolate narrow bandpass images of the Sun at the highest possible spatial and temporal resolution. Observations with this instrument should allow rapid imaging spectrometry, Stokes imaging polarimetry, accurate surface photometry, and spectro-heliograms that will result in Doppler velocity maps, transverse flows, and imaging magnetograms that track evolutionary changes of solar activity;

– a *Grating Spectropolarimeter* (SP) that allows to obtain spectra of all points in a given field of view, with a spectral resolving power of 300,000 and with polarimetric capabilities.

The light distribution among the instruments is based on a division of the main beam coming from the transfer optics by a main dichroic in two spectral stations: one for visible wavelengths and another for near-infrared. The baseline design includes the following instruments channels:

− 3 visible broad band imager channels;

− 5 narrow band imager channels: 3 operating in visible wavelengths and 2 in the near infrared;

− 4 grating spectrographs: 2 for the visible spectral range and 2 for the near infrared.

Figure 2 shows a functional diagram of this distribution

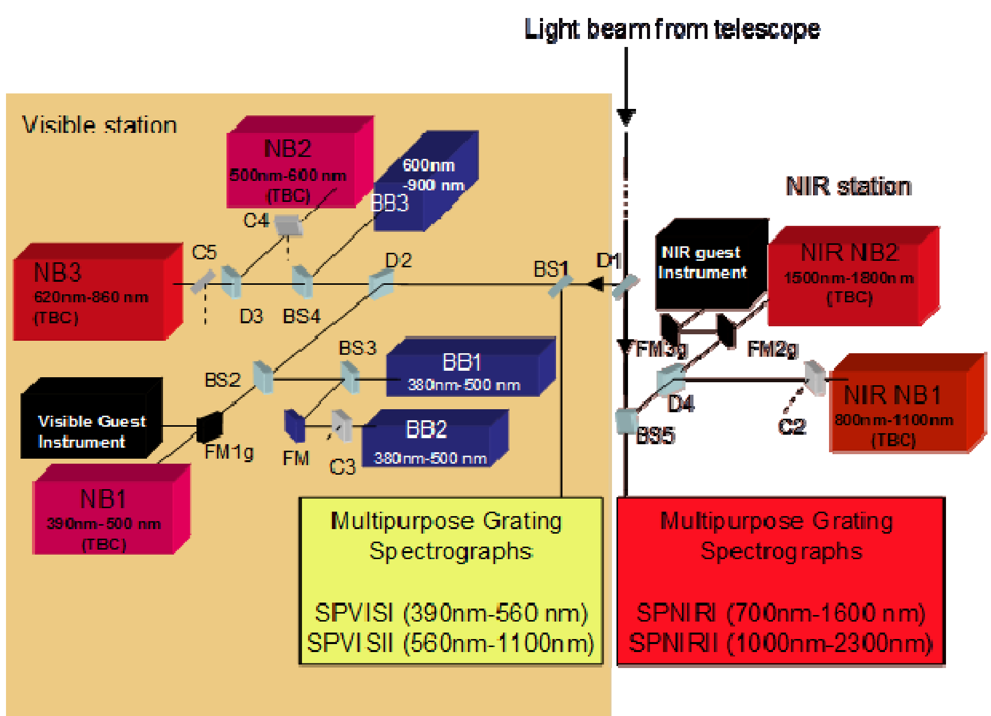

Figure 2. Functional diagram of the light distribution for instruments/channels at the Coudé focus.

2.3 Auxiliary Full Disk Telescope

The AFDT will be used for the orientation of the observer on the solar disc and its surroundings and for an easy acquisition of a selected target by the main telescope. With the AFTD it will be possible to know accurately the absolute pointing position of the solar disc center or of any selected feature (e.g. a sunspot) on the disc. The current baseline assumes that the EST Main Telescope and AFTD will work autonomously and the motion of one will not affect the motion of the other. There will be however an interchange of data between AFDT and EST: EST shall pass to AFDT continuously various data like the position of the Sun center and the size and the orientation of its FOV, whereas AFDT shall pass to EST (on demand) target coordinates and possible corrections. From the control point of view the AFDT consists of two rotational movements: one around its longitudinal axis and one responsible for the rotation of a flat mirror.

3. ECS ARCHITECTURE

The system in charge of EST control (hereafter referred to as EST Control System, ECS) is used for the operation and supervision as a whole of all the sub-systems, components and elements forming the EST facility (briefly described in section 2). At the level of the conceptual design phase, the ECS architecture has been analyzed by splitting it in four different models each looking at different aspects:

1. The *package model* meant to describe all high level sub-systems forming ECS;
2. The *reference model* meant to describe the high-level functionality expected from ECS;
3. The *logical model* meant to describe the connections among the various sub-systems forming ECS;
4. The *physical model* meant to describe the arrangement of the control hardware forming ECS.

3.1 The package model

At the very high-level, ECS consists of four main blocks (shown in Figure 3) that have to work in coordinated way to fulfill the observatory needs: the Observatory Control, the Telescope Control, the Instrument Control and the Data Handling.

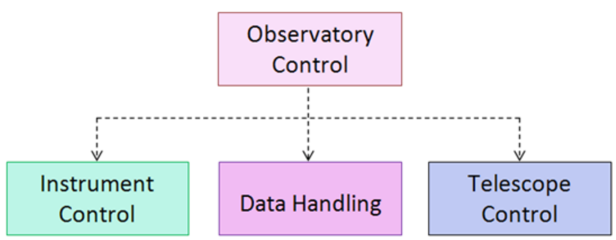

Figure 3. ECS main blocks

The Observatory, Instrument, and Telescope Control blocks are required to enable EST to execute various operation modes (classically scheduling, queue observing service, engineering mode) and observation (day-time solar observation, day-time non-solar observation, night-time observation) by various users (engineers, technical operators, staff astronomers, visiting astronomers, responsible of EST operation - ROE). On the other hand, the Data Handling block ensures the recording of all the data and metadata acquired by the telescope and instruments, the access and display of the data needed to facilitate telescope operations, and the transfer of the data produced away from the telescope to intermediate and then to long-term data archiving facilities.

The four main blocks of ECS has been further detailed in 16 sub-systems, able to fulfil with enough granularities all the identified requirements. Figure 4 shows the arrangement devised for these packages; their main purpose is shortly described below (for brevity reason only packages that are not self-evident are mentioned):

- The **Supervisor Sub-system** (SS) allows EST Actors to manage actions affecting the functionality of the whole EST infrastructure (start-up, shutdown etc.), as well as to report and to act on the state of each component and software block running in the system;
- The **Inspector Sub-system** (IS) provides EST Users with the graphical tools required to interact with EST at the very high level (i.e. status of the executed observation, foreseen scheduling, high-level control GUIs etc.);

– The **Scheduler Sub-System** (SCS) is responsible for establishing the sequence of operations that forms the observation queue by matching the conditions requested for a given observation (target, instrument configuration, observing conditions) with current or expected conditions;

– The **Sequencer Sub-system** (SES) guarantees safe and coordinated work of the various parts;

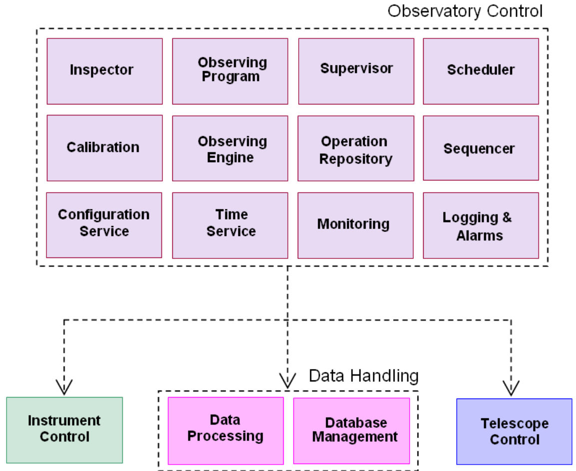

Figure 4. ECS high-level packages

– The **Operation Repository Sub-system** (OR) manages and store all the data generated by the EST operations;

– The **Observing Engine Sub-system** (OE) manages the coordination among various sub-systems responsible for the operation of the whole telescope and of the instruments.

3.2 The reference model

The requirement analysis shows that the standard concept of proposal submission/approval/execution and then data retrieval applies also for EST in order to exploit its scientific outputs at optimum level. Figure 5 shows the reference model considered for the operation of the EST infrastructure.

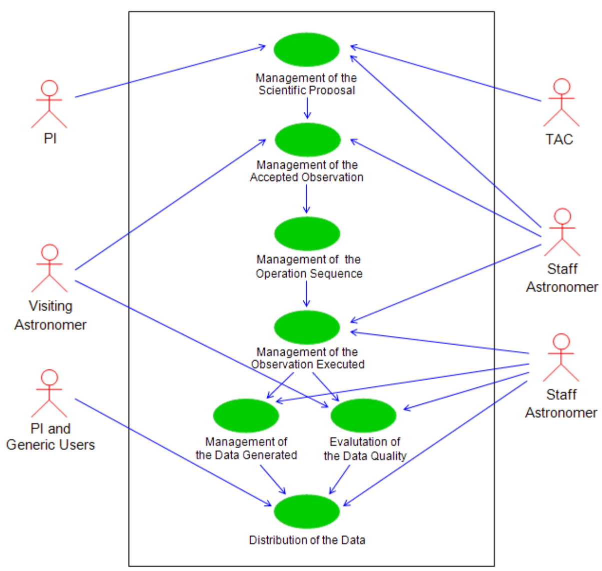

Figure 5. Reference model for observation submission, execution and data retrieval.

3.3 The logical model

The logical model is intended to provide the relationships among the various sub-systems described by the package model. To this purpose the ECS high-level and the equipment sub-systems can be ordered in three blocks:

- the **Observing Workshop block** comprising the sub-systems with the graphical applications that allow users to access any component of the EST facility. This block includes the Inspector, Observing Program Management and Database Management sub-systems, which are not required to provide services to other ECS sub-systems;
- the **Operations Coordination block** comprising the various sub-systems that provide all the high level services related to the operation of the telescope, e.g. scheduling of observations and sequencing of operations, execution of observations, data processing, etc. This block includes e.g. the Observing Engine in charge of the real-time coordination of several lower-level control sub-systems and the Sequencer responsible of high level observatory operations;
- the **Equipment Control and Monitoring block,** that is the logical equivalent of the various low-level control devices of the EST facility.

Figure 6 shows the ordering of the high-level and equipment sub-systems on the three logical blocks introduced above.

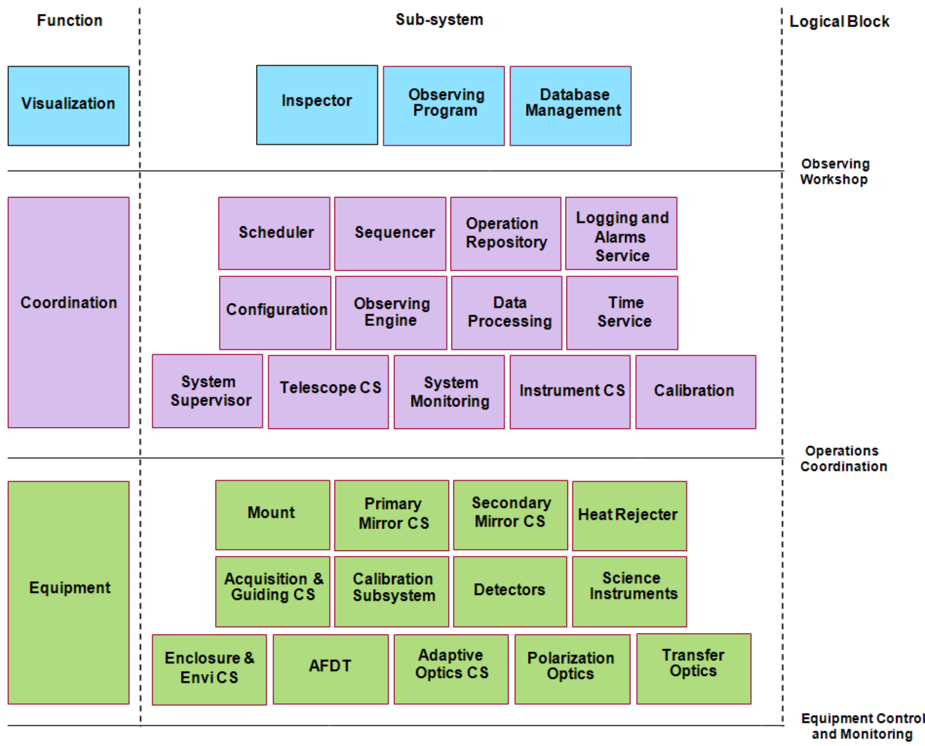

Figure 6. ECS logical model

Figure 7 shows the most important interactions among the various logical blocks involved in the system.

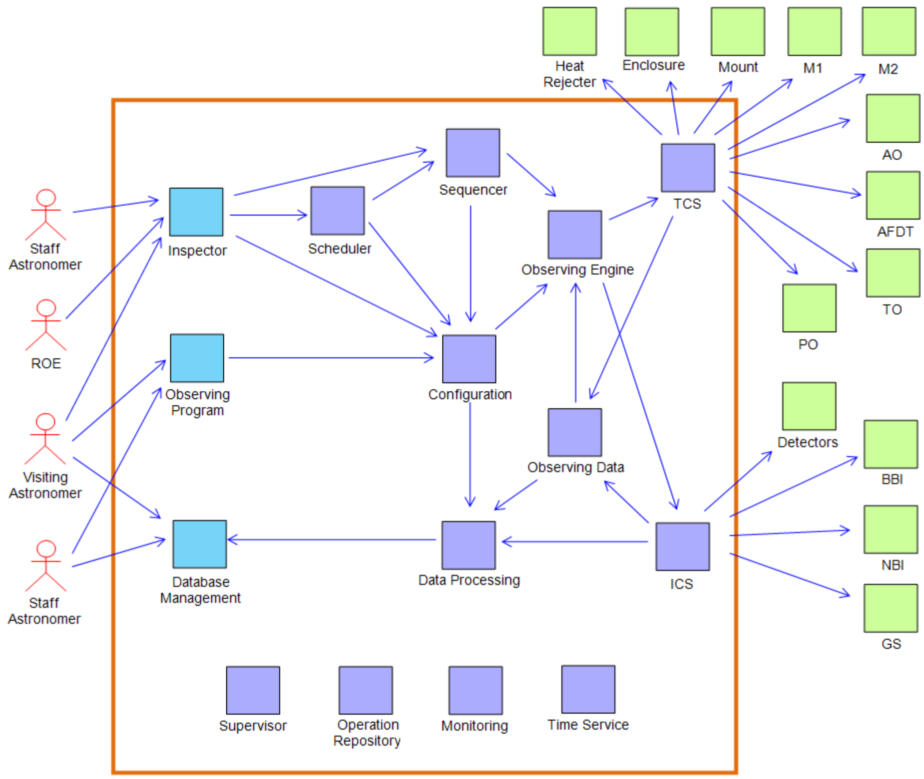

Figure 7. Interaction among the high-level and low-level sub-systems of ECS belonging to the observing workshop, the operation coordination and the equipment and control blocks, respectively.

3.4 The physical model

The hardware components of ECS, referred also as control nodes, comprise computers, local control units (LCUs), electronic equipment, sensors and actuators. The various nodes are responsible for the direct control of all EST devices; some nodes have moreover real-time processing capacity. The node hierarchy includes:

- a top layer with **Human Machine Interfaces** (HMI) that is used by the user(s) to access, operate, and monitor the EST facility;
- a **middle layer** comprising Programmable Logic Controllers (PLC) and other controllers (PLC, VME, PXI, custom controllers); note that in this design phase possible hardware (electronics) solution has not been studied in detail and therefore, from the software point of view, only general considerations can be drawn;
- a **low-level layer** comprising sensors, actuators, electric motors, switches and contacts connected via field buses (e.g. CAN bus, Profibus, EtherCAT).

Figure 8 shows a possible arrangement of the ECS physical model.

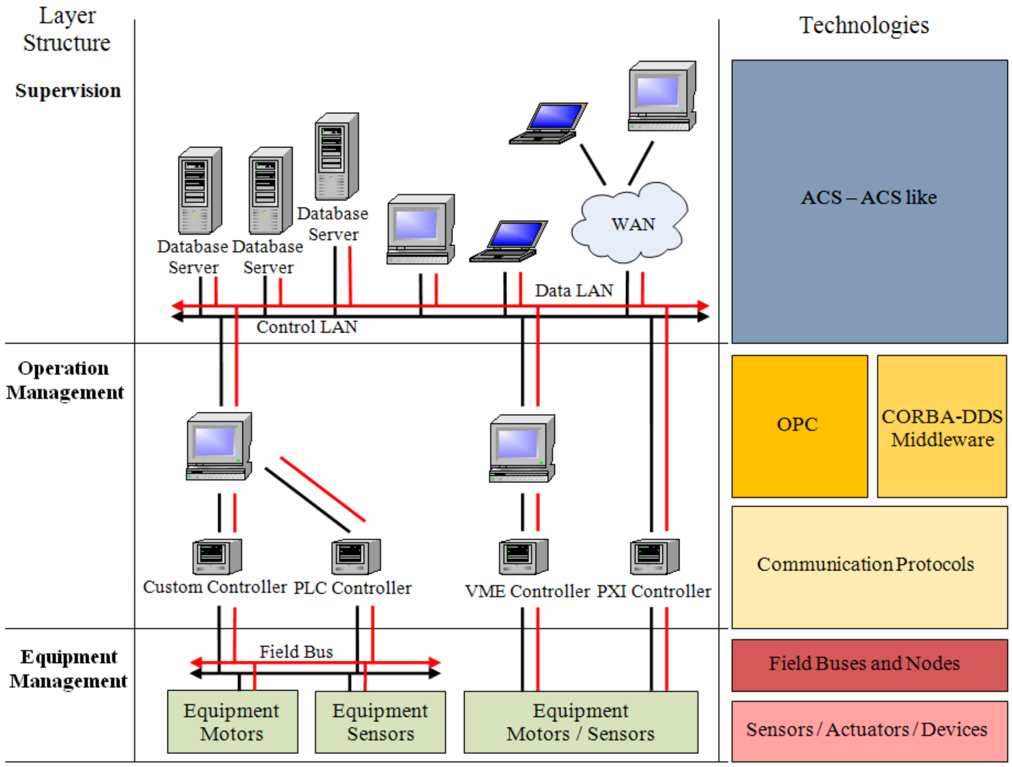

Figure 8. ECS control network and hardware layout.

Various alternatives have been considered for the control software; both full open sources as well as hybrid solutions (open source with the addition of commercial products) fulfil the system characteristics. The current design expects that an **open**, **flexible**, **distributed** and **object-oriented architecture** shall be adopted for ECS in order to provide location-transparent access to the set of physically distributed interconnected sub-systems forming the EST. The implementation of the ECS architecture shall be simplified through the use of a **distributed middleware** that shall ensure availability of necessary resources to all the tasks accomplished by ECS.

In the baseline design, ECS is characterized by distributed, open source and object-oriented architecture based on the Component/Container model (either ACS[3] or ATST[4]) using as middleware services provided by CORBA (ACE/TAO, ICE) and Data Distribution Service (DDS) for the flow of operational and science data, respectively. Connection with the hardware could be assured e.g. by adopting the Open-Connectivity Unified Architecture standard (OPC UA[5]), which is a platform-independent standard able to connect various kinds of systems and devices by means of client-server architecture. Note that the platform-independency is particularly interesting in this phase since an electronic standard for EST has not been adopted yet. The final decision on ECS architecture will however require further evaluation and prototyping of the system, as well as a detailed design phase for the whole infrastructure.

4. TELESCOPE CONTROL

The role of the TCS is to provide coordination of the various telescope sub-systems (responsible in turn to control the associated hardware), point and track the telescope in a range of coordinate systems fulfilling given requirements in terms of accuracy and stability, monitor and control thermal loads and the adaptive optics sub-system in order to deliver high-quality scientific products. Figure 9 summarizes the proposed EST TCS Architecture based on the technologies and model described in section 2.

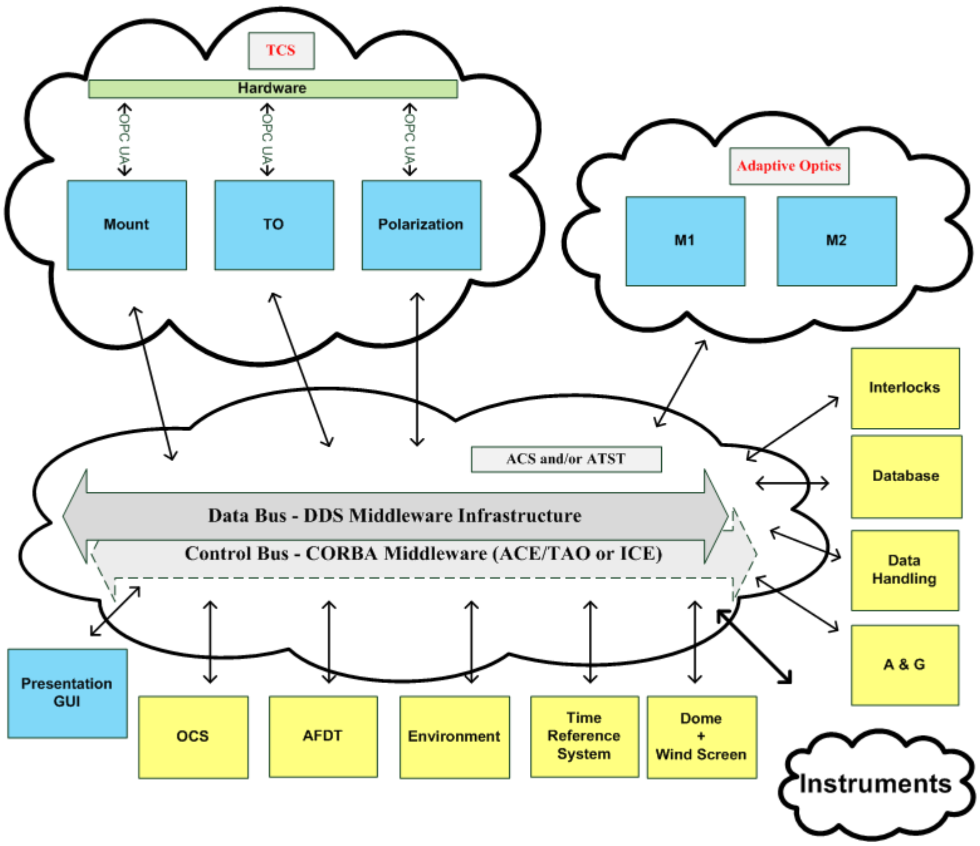

Figure 9. EST TCS Control Architecture

The common infrastructure is represented by an open-source framework implementing the Component/Container paradigm. It could be based either on the ACS or on the ATST common framework; for EST the proposal is to add (or substitute) the respective middleware with the DDS, mainly for efficiency reason. The functionality of each of the various sub-systems (shown in blue in Figure 9) is designed (and implemented) in terms of several collaborating Components living inside different Containers. To abstract the hardware layer, the usage of the OPC UA standard to communicate with Commercial-Off-The-Shelf (COTS) electronics is proposed.

The main package for the TCS is the *TCS coordinator*, which represents the only entry point for all the external communications (*Sequencer*, *Operator*, *GUIs*). It is responsible to verify and validate the correctness of the received configurations (delegated to the *Configuration* package) and to supervise the monitoring and switching between different TCS states (*Mode switching* package). The TCS coordinator is then in charge to communicate/apply the received configuration to all the other EST sub-systems. Each <<*sub-system*>> (shown in blue in Figure 9) is in turn responsible to execute/apply the configuration received and signal every success or failure. In case of non-recoverable errors, task of the sub-system is to create a full error trace with all the relevant information needed to figure out the reason of the failure. It is then responsibility of the *TCS coordinator* to pass this information back to the external actor.

The Pointing kernel is responsible to deliver all the required pointing and tracking information to all the other TCS sub-systems.

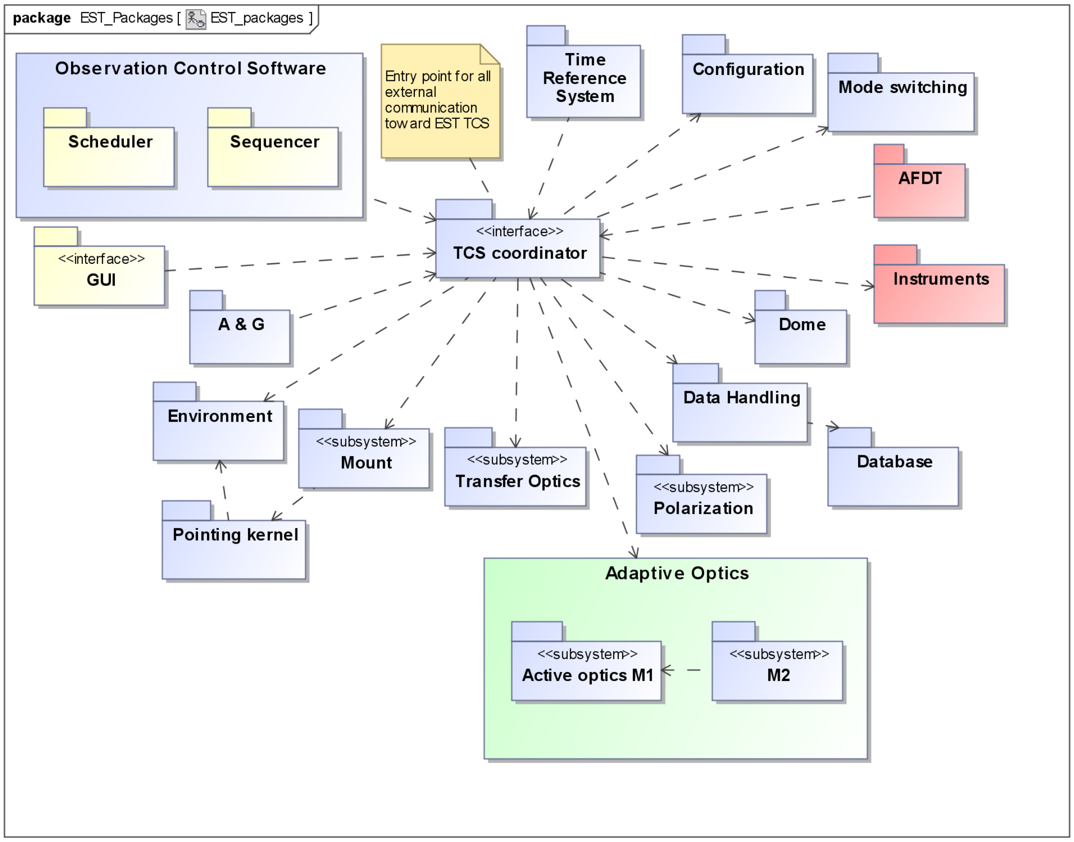

Figure 10. EST TCS Package diagram

In Figure 10 three more packages are shown that do not belong directly to the EST TCS but requires a direct interaction with it:

- the AFDT which depends on the EST TCS in the sense that some information flows between the two systems, even though it could operate as a standalone telescope;
- the Instruments that require some information flow both for synchronizing some of their controlled devices to the MT and for getting observational data;
- the AO sub-system, which is considered here as a stand-alone sub-system with a clear defined I/f.

5. INSTRUMENTS CONTROL

The Instrument Control Software (ICS) is responsible of managing the instruments at the EST focal plane and to fulfill their operations in terms of accuracy and data delivery required by the project. Taking into account the description given in section 2.2, the current design of ICS foresees three main sub-systems, each of them corresponding to one of the instruments. The control of the detectors is demanded instead to a specific package. There will be also a deep interaction among the ICS and external sub-systems like the TCS, the Time Distribution System, the Alarm and Interlock Management (AIM) and the Database Management System (DBMS). Figure 11 outlines the most important packages foreseen for the ICS high-level architecture.

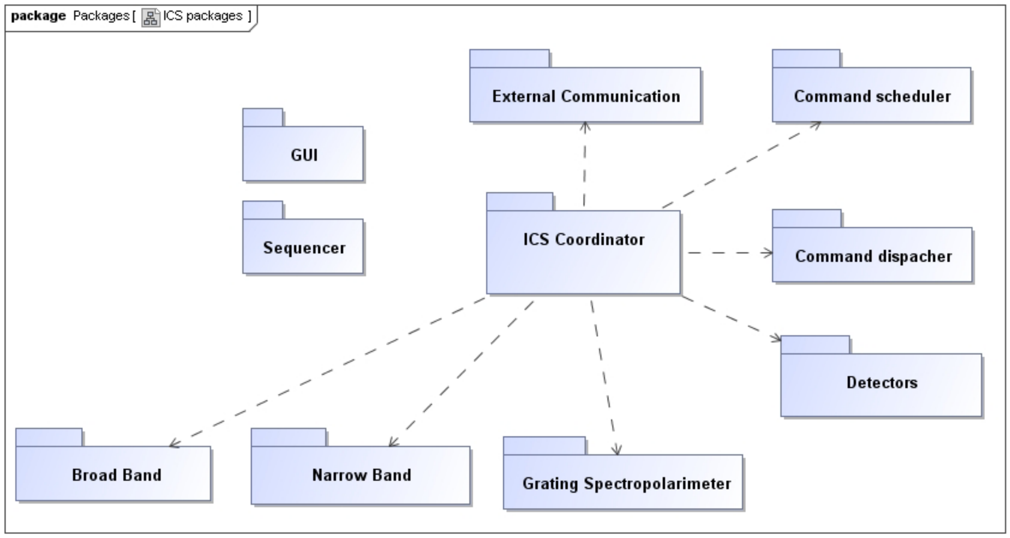

Figure 11. Package diagram for the ICS architecture. For readability only few packages are shown.

As in the case of TCS, an *ICS Coordinator* is responsible of coordinating the communication among all the packages. The communications towards the coordinator is performed through the *sequencer* or via dedicated *GUIs*. This means that two options are available to send a command to ICS: either an already defined configuration, i.e., list of commands and parameters, can be sent to the ICS through the sequencer or a generic user can select a configuration via a GUI. Users can also download a complete configuration and use the GUI to modify some parameters or part of the setup.

Each instrument specific package (*Broad Band*, *Narrow Band* and *Grating Spectropolarimeter*) has been further analyzed both in terms of UML class and sequence diagrams in order to identify all the software entities needed to properly handle the instrument operations. The date rate foreseen by the EST operation is challenging. The required data rates amount to a max. of 82 GB/s for up to 32 detectors (assuming a 4Kx4K format) operating simultaneously at 100 fps (visible) or 30 fps (near IR). The largest contributor will probably be the Narrow Band Tunable Filter, with up to 34 GB/s distributed over 15 detectors. The total translates to 296 TB/hrs and, assuming an exceptional case of a full day of continuous operation, to 3.55 PB/day. At present the handling of such large amount of data is still extreme and will be further studied in the next phases of the project (see[2] for details).

6. CONCLUSIONS

The paper describes the conceptual design for the control software of the EST facility as has been presented at the final (external) review meeting held in June 2011. Several aspects are presented ranging from the high level operations to ultimate instrument and device control. Other aspects like handling of alarms, safety (especially important since EST is a solar telescope), electronic/hardware architecture and interfaces have been instead only briefly addressed. This will be the topic of the next phase of the project, currently waiting for financial approval, where also possible synergies with other ground-based and/or space telescopes will be analyzed and developed.

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