EELT-HIRES the high resolution spectrograph for the E-ELT: software and hardware solutions for its control

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ABSTRACT

The current E-ELT instrumentation plan foresees a High Resolution Spectrograph conventionally indicated as EELT-HIRES whose Phase A study has started in March 2016. Since 2013 however, a preliminary study of a modular E-ELT instrument able to provide high-resolution spectroscopy (R~100,000) in a wide wavelength range (0.37-2.5 μm) has been already conducted by an international consortium (termed "HIRES initiative"). Taking into account the requirements inferred from this preliminary work in terms of both high-level operations as well as low-level control, we will present in this paper possible solutions for HIRES hardware and software architecture. The validity of the proposed architectural and hardware choices will be eventually discussed based also on the experience gained on a real-working instrument, ESPRESSO, the next generation high-stability spectrograph for the VLT and to certain extent the precursor of HIRES.

Keywords: E-ELT instruments, EELT-HIRES control software, COTS, PLC

1. INTRODUCTION

In the framework of the European Extremely Large Telescope (E-ELT) project, since 2008, ESO commissioned a series of studies aimed at clarifying the design options for the first generation of focal and post-focal instruments that could properly address the scientific cases of highest priority. Among the several studies that successfully passed the review phases there were two instrument concepts that included one optical (CODEX[1]) and one near-infrared (SIMPLE[2]) high resolution spectrograph. In this context the Instrumentation and Control Group at INAF-OATs was responsible of carrying out the preliminary architectural design of the software and electronics[3] of CODEX.

After the review phases, following the recommendation of the E-ELT Science Working Group (SWG) and the ESO Scientific Technical Committee (STC), both studies (and consortia) merged to address a new study for one, single, high resolution spectrograph aimed at covering a large simultaneous wavelength range from the visible (ultraviolet) to the infrared. Early in 2013 ten countries (Chile, Denmark, France, Germany, Italy, Portugal, Spain, Sweden, Switzerland and United Kingdom) joined efforts in this initiative termed "HIRES initiative" where EELT-HIRES (High RESolution) has been chosen as a temporary name for the spectrograph (hereafter, for simplicity we will use only HIRES).

In March 2015 ESO issued a Request for Information (RfI) for the development of the conceptual design phase of "*an instrument that will deliver the science case of E-ELT in the area of high (spectral) resolution spectroscopy*" and afterward, in July 2015, the final call for proposal, for the Phase A study of the HIRES for the E-ELT was opened. The consortium, part of the HIRES initiative, successfully answered to both calls and was appointed to conduct the Phase A. Eventually, two more countries (Brazil and Poland) joined the original ten countries to form the final consortium responsible to carry out the study under the PI-ship of prof. A. Marconi (INAF- Italy). The kick-off took place in Firenze in March this year (2016).

In the following we will describe the main results (limited to the control aspects) of the HIRES initiative. The paper is organized as follows: section 2 will present the spectrograph, its functions and science cases, section 3 will describe

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current industrial trends and hardware solutions proposed for HIRES, section 4 will present the software counterpart and section 5 will analyze the (working) case of ESPRESSO, to certain extent a precursor of HIRES, at least for the topic relevant for this paper.

2. INSTRUMENT CONCEPT

A detailed description of the HIRES instrument concept as emerged from the HIRES initiative study and formalized in a *white* book for the science cases and in a *blue* book for the technical concept can be found in[4] and reference therein. Here we just recall its main characteristics relevant in the context of its control:

- high resolution in the range R > 50,000 – 100,000 with the goal of 200,000 for particular science cases (studies of stellar structure and evolution);
- simultaneous wavelength coverage from 0.37 to 2.4 μm;
- moderate multiplexing capability (5-10 objects within a FoV of a few arcmin) with a moderate spectral resolution mode (R ~ 10,000 – 50,000);
- wavelength accuracy of the order of 10 cm/s (goal 2 cm/s for the Sandage test, see below);
- overall stability (over 1 night) of the order of 10 cm/s (goal 2 cm/s for the Sandage test, see below);
- possibility to perform accurate sky subtraction with a precision better than 1%.

All these top level requirements derive from the flagship science cases developed by the Science team (ST) of the HIRES initiative. Taking into account the unique photon collecting area of the E-ELT and the experience gathered by the community in using the suite of VLT high-resolution spectrographs, the ST was able to extract a sub-set of science cases that could have significant impact on hot-topic astronomical research by exploiting a wide wavelength coverage, high resolution spectrograph at the E-ELT.

Here it is a list, by no means exhaustive, of key science cases that have been identified:

- detection and characterization of exoplanet atmospheres;
- high resolution spectroscopic mapping of solar system objects;
- study of protoplanetary and proto-stellar disks;
- precise determination of chemical composition and atmospheric parameters of stars beyond the immediate neighborhood of the Sun;
- extension of Galactic archaeology to the Local Group and beyond;
- high resolution spectroscopic observations of the intergalactic medium (IGM) to infer information of reionisation processes and to detect elements synthetized by the first Pop III stars;
- unraveling of the complex roles of stellar and AGN feedback for the supply and retention of the baryonic component of galaxies across the full range of galaxy masses, morphologies and a wide range of redshift, with the help of IGM tomography at high spatial resolution;
- study of extragalactic transients (gamma-ray bursts);
- contributions to fundamental physics through the study of the Universe acceleration in real-time (via Sandage test) and through measurements able to constrain possible variations of the fundamental constants of nature, in particular the fine structure constant $\alpha = e^2/\hbar c$ and the proton-to-electron mass ratio constant μ.

2.1 Technical concept

Opto-mechanically, the design of a high resolution spectrograph for the E-ELT able to cover all the given science requirements, is extremely challenging. The wide spectral coverage requires simultaneous usage of different detector technologies and ability to operate at different temperature environments (in particular cryogenic, moving toward the K band). To reduce optics to a manageable size (so that can be effectively manufactured) a slicing of the pupil is mandatory. A challenge in itself represents also the overall stability needed to reach the required precision. The

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preliminary study showed that a modular fiber-fed cross dispersed echelle spectrograph shall be considered a viable baseline solution for the design of such an instrument.

The overall technical concept is summarized in figure1.

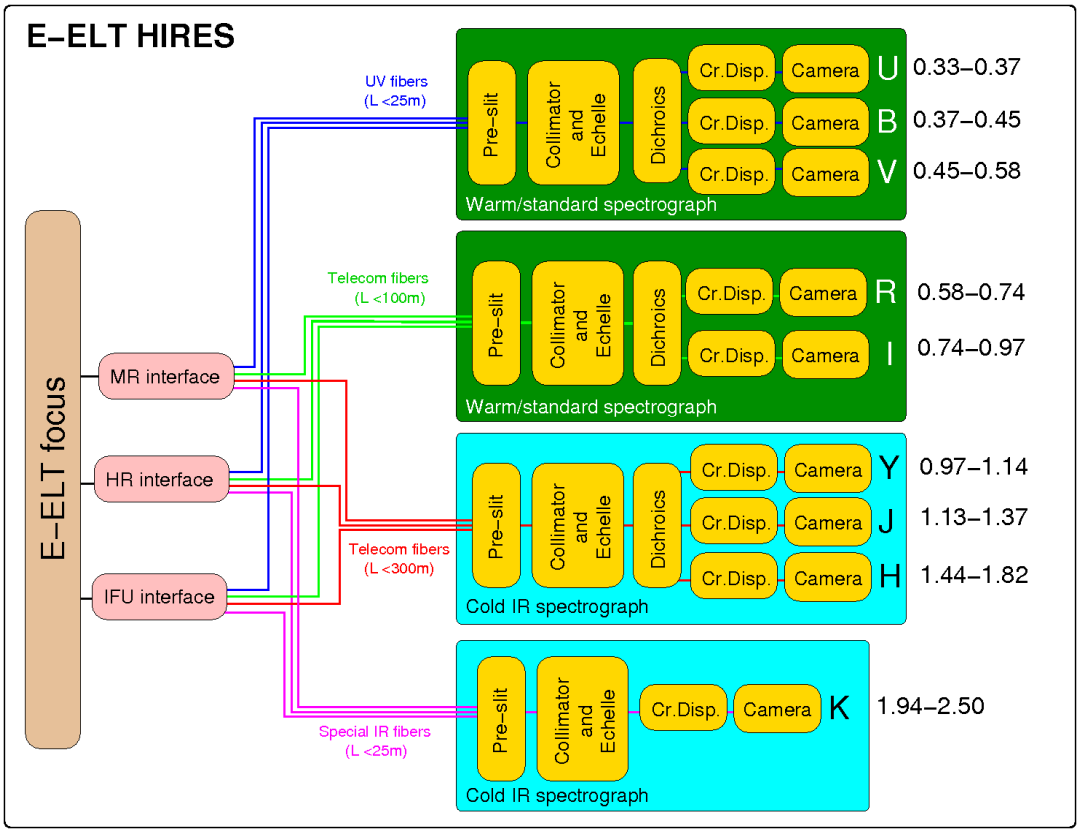


Figure 1. HIRES Instrument concept with four spectrograph modules and the interfaces needed to feed properly the light into them.

The light from the telescope is split through dichroics into *N* wavelength channels; four have been taken into account during the design phase of the HIRES initiative: (U)BV, RI, YJH and K (the inclusion of the U band is provisional and depends of the E-ELT efficiency in the 0.33 – 0.36 μm wavelength range). Each wavelength channel includes several telescope optical interfaces that feed, through groups of fibers, a dedicated spectrograph module. All spectrometer modules have a fixed configuration, i.e. no moving parts. They include a series of parallel entrance slits, each linked to a separate set of fibers that, in turn, determines the observing mode. Based on the inferred scientific requirements three observing modes have been implemented: high-resolution (HR, with R > 100,000), medium resolution (MR, with R ~ 14,000) and integral field (IFU, with R ~ 100,000).

The detailed description of the interfaces and the modules is outside the scope of the present paper and could be found in[4]. Here we want just to recall that the overall design follows the philosophy of the next generation, high resolution, ultra-stable spectrograph, ESPRESSO[5] that will be installed at the VLT in 2017. As in case of ESPRESSO, also HIRES front-end modules are responsible to dispatch the light into each fiber bundle towards the spectrograph. Their main functionality is to provide the necessary pupil and field stability, observing mode selection, calibration source injection and (possible) atmospheric dispersion correction. The spectrograph modules, which as a starting point follows the ESPRESSO opto-mechanical design, as stated, do not host any movable function, but require a continuous monitoring (especially considering possible cryogenic environments) to ensure full instrument operability and safety.

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3. HIRES CONTROL SOLUTIONS

Taking into account the HIRES top level requirements both in terms of high-level operations as well as low level control, the baseline design for the control architecture follows an approach similar to the one typical of the current state-of-the art astronomical focal plane instruments. The proposed overall control architecture could be seen logically split in several sub-systems each dedicated to a specific task (see figure 2):

- A low-level control package responsible to handle the vital part of the instrument (motorized devices, lamps, sensors, piezo systems etc.); it will interface with the electronic part;
- A high-level control package responsible for the coordination of activities of the detector, the low level part and the telescope. It will interface with the E-ELT data flow, in particular it will execute the next observation recipe, acquire the technical/scientific frames and send them to the archive, which will store the results of each observation;
- A Detector Control Software (DCS), responsible to control/handle all scientific detectors.

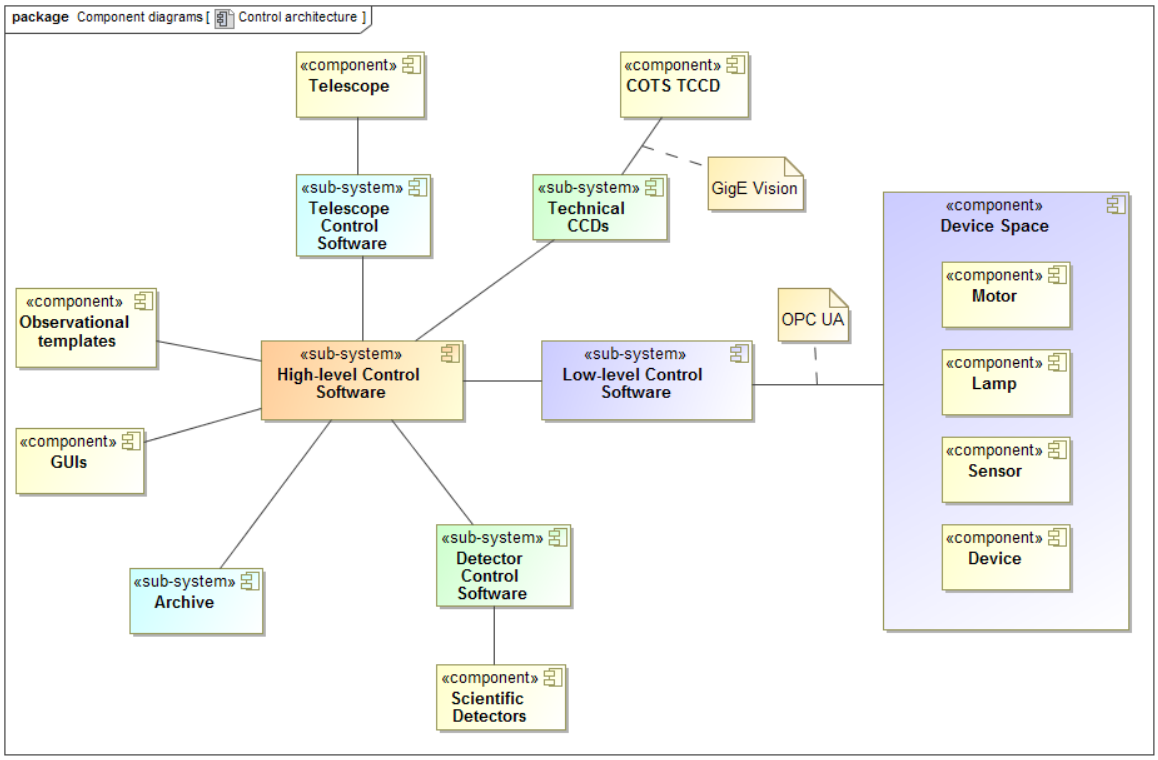


Figure 2. HIRES control architecture with communication I/f; group of same colors represent common sub-systems: violet - low-level packages, orange - high-level packages, green - DCS. It is assumed that TCS and Archive (blue color) are part of the E-ELT infrastructure.

In the past, due to limited industrial solutions that could fit astronomical requirements in terms of device control, there was no other choice as to develop, ad-hoc, custom solutions for most of the hardware/software control related aspects. In the literature a lot of examples could be found related to this (the ESO VLT control system is a typical case). Clearly, this approach has inherently several drawbacks: custom solutions are expensive both to develop and implement as well as to maintain (especially on a long term). Engineers that contribute to the initial development not always remain in the

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same working place and over time the "painful" process of know-how transfer could become an issue. Moreover, for more hardware related aspects, it is well known that technology is advancing very fast, and the core components chosen in the early design days may soon become obsolete yielding problems for system maintainability. The proposed HIRES control architecture has been developed keeping in mind these considerations trying to mitigate as much as possible the impact on the hardware procurement, maintainability and long term operability.

3.1 Industrial trends and adopted control solutions

Considering the time plan for the E-ELT and HIRES in particular (at least 10 years from now for the HIRES first light followed by 20 – 30 years of operations), components/devices obsolescence become one of the major issue to guarantee proper instrument operability and scientific productivity (e.g. the Sandage test requires a long term overall stability of the order of 2 cm/s for decades). A definitive solution to this problem does not exist, but a key factor in mitigating obsolescence is the level of "*industrial standardization*" (of course, where applicable). By selecting commercial off the-shelf components (COTS) adhering to wide spread accepted industrial standard (possibly, IEEE certified) guarantees (in principle, full) interchangeability and interoperability thus minimizing obsolescence. Products, even of different vendors, with standardized interfaces could be almost flawlessly interchanged leaving the existing high level control layer and similarly, high level layer could evolve maintaining existing hardware unchanged. Based on this, the proposed control of the future HIRES spectrograph follows *standard* industrial trends (where applicable) in the following areas:

- fieldbus distribution;
- time synchronization;
- high performance camera communication;
- unified architecture for software-device connectivity;
- device control.

3.2 Fieldbus distribution

Current trends in the control paradigm especially in case of complex, large system follow a distributed approach: centralized control units are substituted with several agile, intelligent nodes (like Programmable Logic Controllers – PLCs) interconnected by a network. "*Fieldbus*" is the name of a family of protocols used for real-time distributed control. The interconnection network could be a dedicated one, with proprietary protocols running on it, but also solutions with proprietary protocols running on standard Ethernet infrastructure exist. The latter are particularly appealing for the E-ELT/HIRES case since this will allow to fully reuse Ethernet-based network infrastructure that will be certainly available at the E-ELT not imposing additional requirements to the E-ELT infrastructure itself. Example of real-time protocols that could run on such Ethernet-based fieldbus systems are EtherCAT (standardized in IEC 61158) invented (and used by COTS provided) by Beckhoff Automation or PROFINET used by Siemens.

3.3 Time synchronization

In the field of astronomical instrumentation the precise time synchronization and time distribution (for certain scientific cases even at the level below microsecond) is a strong requirement and HIRES is not an exception. Even though at the time of writing this paper no definitive solutions are imposed by E-ELT to external consortia, exhaustive tests at VLT points to the adoption of the Precision Time Protocol (PTP, standardized as IEEE 1588) as the standard E-ELT protocol for time synchronization. Several vendors nowadays offer COTS components based on this protocol (e.g. Beckhoff, Siemens etc.) which guarantees interoperability also looking ahead towards E-ELT instruments.

3.4 High performance camera communication

Triggered by the ESPRESSO project, ESO together with INAF-OATs conducted a market survey with the aim to analyze current trends in industrial COTS CCD cameras market to foster interoperability, lowering procurement and maintenance costs (see[6] and reference therein). Among the very wide palette of products found, this market survey eventually lead to a selection of cameras supporting the GigE Vision® protocol introduced in 2006 by (and supported by) the European Machine Vision Association. The reasons are exactly as discussed above: gigabit-Ethernet based communication overcomes limits in cabling schema (e.g. imposed by USB or Camera Link) and allows full reuse of existing network infrastructure; standardized high level communication protocol (GigE Vision® coupled with

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GenICam™ generic programming interface) allows to cope with high performance communication needs, guaranteeing at the same time, interoperability and interchangeability.

3.5 Unified architecture

OPC Unified architecture (OPC UA) is an industrial (standard) communication protocol developed by the OPC foundation aimed to connect various kinds of systems and devices over TCP networks. The interoperability is achieved through a server-client approach: the server is (usually) supplied by the hardware manufacturer and represents the interface between internal proprietary protocols and OPC UA standard. Through the "server", control nodes are exposed to outside world in a standardized way which could be accessed by dedicated "clients". The client implements the OPC UA communication by means of APIs and allows the user application to access the exposed nodes. Additional information could be found in[3]. It is important to stress that by properly separating the client logic from the communication protocol this approach guarantees full hardware/software interoperability and its validity have been proven at Paranal by several instruments (and in particular ESPRESSO) that have adopted it as a standard control communication protocol.

3.6 Device control

The core technology proposed for HIRES devices control (i.e. motorized functions, piezo's, lamps, sensors) is PLC-based. PLCs are wide spread devices used by industry since decades in automation technology. They are essentially hard real-time systems where outputs are produced based in response of input conditions. The way outputs are done is fully programmable and this offers a huge flexibility allowing with the same PLC to control almost any functionality the system will require. PLC programming languages are standardized in IEC61131-3 open international standard; their usage coupled with the PLCOpen motion control standard specifications allows to write efficient and flexible PLC code that is vendor and product-independent as has been proved in ESPRESSO case[5].

4. HIRES SOFTWARE SOLUTION

Following the experience of VLT and ALMA projects, ESO is investigating also for the E-ELT the possibility to offer to external consortia a common software infrastructure for the control of E-ELT instruments (actually, at the time of writing, this seems the final confirmed decision). Therefore we can assume the existence of a framework that will offer all standard services typical of modern control system (like error and alarm handling, common communication infrastructure etc.).

Beside the framework itself, also the typical operational flow scenario will follow the successful VLT data flow scheme:

- the high-level software translates the "commands" coming from outside (e.g. observational recipes, dedicated GUIs etc.) into further "commands" to be sent to the detector, electronics and telescope;
- detector software, the instrument low-level software and the telescope control software then take care of instructing the respective hardware;
- as a result, and as a positive acknowledgement, final FITS image(s) is(are) produced and archived.

The word "commands" is written in quote on purpose. In the VLT framework, each command is really "a command" composed by a string made up of one or more keywords and parameters, chained together. Each keyword specifies the subsystem and device the message is addressed to. But different paradigm could exist to convey the information from one system to the other. In the ATST (Advanced Technology Solar Telescope) middleware for example, a parameter-based methodology is used[7]; the main data type is a configuration, which contains a header and a body. Yet, a different approach would be to base the interaction on a completely different, publisher-subscriber, paradigm. At this level of the project anyway a detailed design of the communication infrastructure is not relevant. It will anyhow depend on the winning software technologies that will be adopted in the E-ELT case.

The initial proposal as developed during the HIRES initiative is to implement the various software packages listed above not as a set of stand-alone interacting processes (i.e. following the VLT software concepts), but to consider them as a distributed system composed of several collaborating/communicating objects (components) that lives inside a runtime environment (container). This philosophy is not new and is at the heart of the ALMA Common Software (ACS), which is based on the so called Component/Container model. This allows to separate, with proven benefits in terms of

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application deployment and execution, the functional behavior of components from the service aspects required to implement and manage them.

Being HIRES in the current design composed by several spectrographs (they could be seen as individual stand-alone instruments) that shall and will work in parallel, this paradigm appears quite effective. At the top there is a so called Supervisor Component (see figure 3), which is the only entity that dialogues with the high-level E-ELT parts and the Archive; its main responsibility is to coordinate the activity of instrument specific Coordination Components (hereby with the word "instruments" we mean the individual spectrographs). Their task is to manage and coordinate their respective low-level electronic and low-level detector software parts.

One could argue that the disadvantage of such a design is the added complexity to the design (especially in terms of collaborating objects), but the parallelism, internal complexity and the possibility to handle each spectrograph independently is naturally achieved.

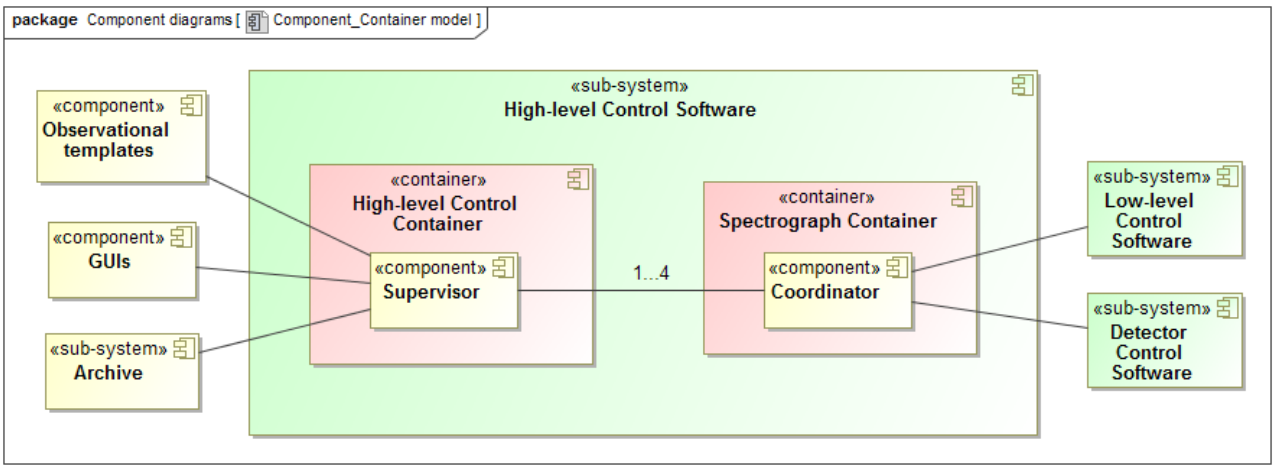


Figure 3: HIRES high-level software architecture illustrating the supervisor concept.

According to the Component/Container paradigm, also the low-level software is designed as a collection of Components which "live" in one or more Containers. There is one (or more) Component(s), acting as a supervisor, which exposes a well-defined interface to the high-level software and manages the communication with the devices, simulation levels and/or the engineering mode. The Components linked to the physical devices are in charge of forwarding the appropriate commands to the hardware.

5. FROM ESPRESSO TO HIRES

The proposed technological solutions are not only "paperwork", but are currently being applied (for the first time at the VLT for a permanent instrument) to the ESPRESSO[5] instrument control case. ESPRESSO is a fiber-fed, cross-dispersed echelle spectrograph that will be commissioned in the Combined-Coudé Laboratory (CCL) of the VLT in the Paranal Observatory in Chile starting from Q1 2017. In several aspects ESPRESSO could be seen as a precursor of HIRES; apart from the location (which is under discussion in case of HIRES) and the number of involved spectrograph modules, the main science cases, top level requirements as well as the opto-mechanical design are very similar. For example, likewise HIRES, also ESPRESSO has a front-end unit (actually four) whose purpose is to collect light from the telescope(s), stabilize it and feed it into the spectrograph; the spectrograph itself has no movable parts and is placed in a vacuum, temperature controlled chamber and resembles therefore one of the HIRES spectrograph module. Also, the way of operating the instrument is quite similar, in particular the ability of ESPRESSO to operate in different resolution regime ranging from medium up to very high resolution.

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For the case of ESPRESSO, the advantage in adopting the control solution highlighted in section 3 could be easily understood from figure 4. ESPRESSO, similarly to future HIRES instrument, is not only logically but also physically distributed on a relative big area. There are four front-ends each receiving light from the respective Coudé train (CT); each CT has its own motorized functions (mainly stages) that must be positioned correctly in order to direct light towards the CCL. The CT CPUs controlling them are moreover placed at big distance (~ 50 m) from the CCL which makes the whole ESPRESSO system complex. Since preliminary design phases, it became therefore evident that relying on the existing VLT control standard based on the concept of VME-based Local Control Unit (LCU) would have posed serious problems due to the complexity in building several LCUs (which in turn would have implied very high, almost not affordable, costs and maintenance efforts).

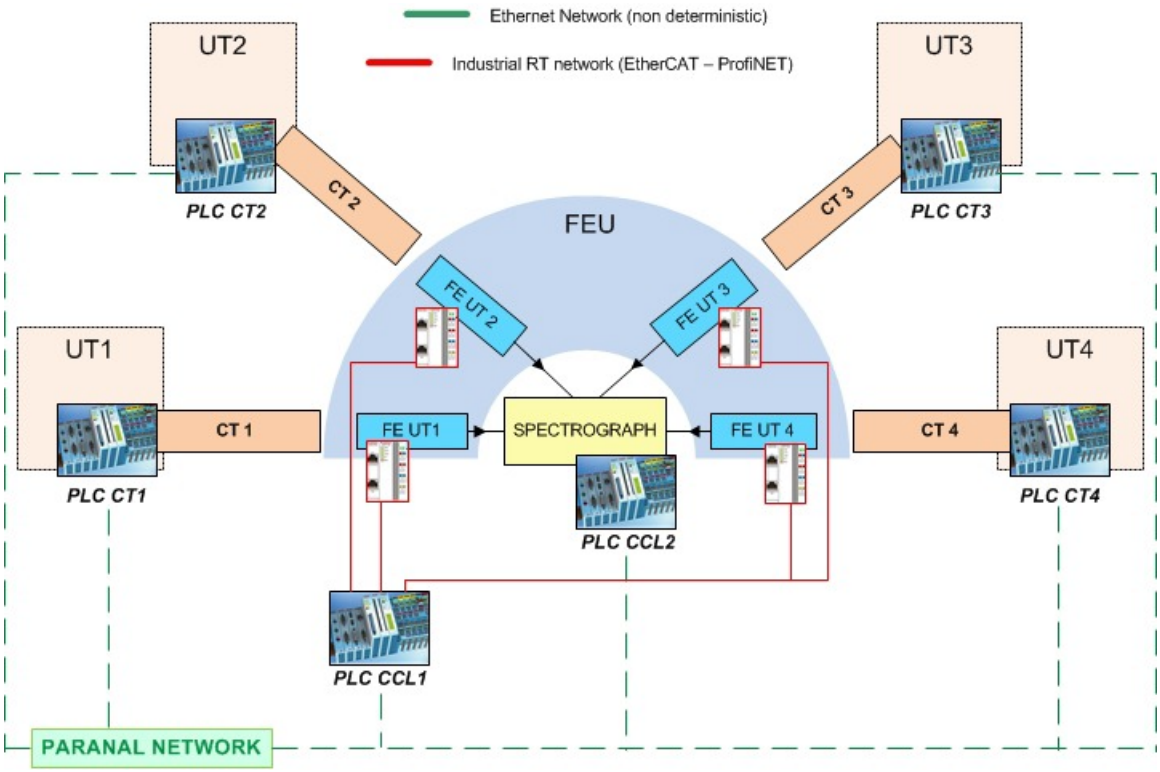


Figure 4: field-bus distribution in case of ESPRESSO instrument.

The adoption of the fieldbus technology interconnecting PLCs (of Beckhoff brand for the control of functions and of Siemens brand for the handling of the cryogenic systems) solves in an elegant way most of the issues related with the previous technology. The cost in building such a system is not comparable with the VME-based LCUs, moreover the usage of the OPC UA allows seamlessly to connect PLCs of different brands to the existing VLTSW without any performance penalties. ESPRESSO has still not been delivered in Paranal and definitive results especially looking at long term maintainability could not be inferred. However the current integration phase shows all the benefits in using the described technology in terms of robustness and ease of system integration.

Some final considerations should be deserved also to the technical CCDs (TCCDs). As described in previous section, due to ESPRESSO's distributed nature (i.e. its installation on all 4 UTs) and due to its stringent scientific requirements in terms of final stability, nine TCCDs are required to stabilize the incoming light. Out of these nine TCCDs particular demanding in terms of requirements are the four devoted to the field stabilization whose purpose is to maintain an astronomical object centered on the fiber (by driving accordingly a mirror cemented on a piezo system) during the whole duration of the scientific exposure with a stability requirement of 0.06 arcsec on the sky.

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Figure 5 shows the internal disposition of functions in one of the ESPRESSO front-end. On the lower left two cylinders can be seen which host two, glycol-cooled, AVT (Allied Vision Technologies) BigEye G-132B Cool, TCCDs. The picture shows immediately the advantage of using COTS products also for the engineering camera case. Old ESO standard based on the e2v detectors integrated in ESO custom made camera heads need, in order to be used, specific DSPs deployed on PCI bus bridged to Motorola PowerPC VME boards. This is not only an order of magnitude more costly than the similar (in terms of performance) COTS product, but requires bulky electronics and custom-made, dedicated software, to control them.

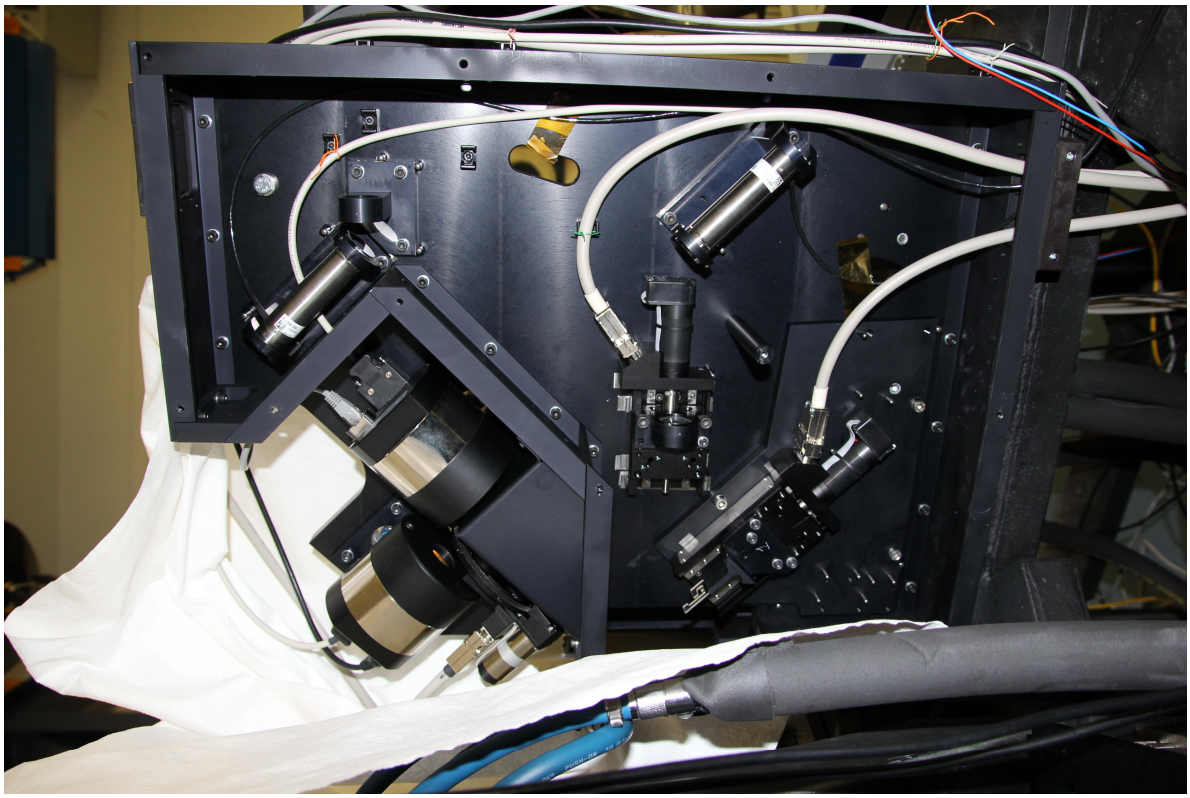


Figure 5: Detail of one of the ESPRESSO front-ends showing the two COTS AVT TCCDs on the lower left used for field and pupil stabilization.

COTS solution, as the one selected in ESPRESSO project, have instead all the electronics already mounted in the camera head that coupled with GigE standard ensures that they can be easily exchanged and replaced in future, a mandatory requirements considering the long life-time foreseen for HIRES.

6. CONCLUSIONS

In this paper we have presented the main ideas developed for the hardware and software control of the HIRES instrument for the E-ELT as emerged at the end of the "HIRES initiative" study. Particularly, we have focused on solutions that could ensure long term maintenance and interoperability, but without losing in performance or in limiting the ability to operate in harsh environmental conditions. This appears really critical for new astronomical instruments in general, and for HIRES in particular. It is important to remark that all the technologies presented are already a reality in ESPRESSO for the VLT which could not only be seen as a HIRES precursor, but also as a full-fledged test-bed for its control technology.

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