HARMONI: The Extremely Large Telescope first light integral field spectrograph: A novel control architecture to integrate the science instrument control system with that of adaptive optics

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ABSTRACT

HARMONI is the Extremely Large Telescope visible and near infrared integral field spectrograph and will be one of the first light instruments. The instrument supports four operational modes called No Adaptive Optics (NOAO), Single Conjugated Adaptive Optics (SCAO), High Contrast Adaptive Optics (HCAO), and Laser Tomography Adaptive Optics (LTAO). These operational modes are closely related to the wavefront correction topology used to support the performance required for each of the science cases.

By following a novel function model-based systems engineering (FBSE) methodology in conjunction with observing the software computer system golden rule of design; namely having tight cohesion within software modules and loose coupling between modules, a system architecture has emerged.

In this paper, we present the design of the HARMONI Control System (HCS). Although this is not the first time (for example NACO on VLT and NIRC2 on Keck) that the adaptive optics required to correct the atmospheric turbulence is part of a general instrument design, and not tailored for a very specific science case, this will be the first instrument of this size and complexity in the era of extremely large ground-based telescopes. The instrument control design must be compatible with the ELT instrument control system framework while there is also an expectation that the adaptive optics (AO) real-time computer toolkit (RTC-TK) should be used for the realization of the AO real-time control software and hardware.

The HCS is composed of the instrument control electronics (ICE), the Instrument Control System (ICS), and the AO Control Sub-system (AOCS).

The operation concept of the instrument is also novel in that for each mode the instrument creates an instantiation of a virtual system composed of only the system blocks required to provide the selected mode of operation. Therefore, each mode supports a unique system composition in terms of hardware, software, and the sequencing of activities.

Keywords: HARMONI Control System (HCS), instrument control, hard real-time, soft real-time, architecture, behavioural, model-based systems engineering (MBSE), SysML, UML, and operational modes

1. INTRODUCTION

HARMONI is the visible and near infrared, adaptive optics assisted integral field spectrograph (IFS) for the European Southern Observatory's (ESO) Extremely Large Telescope (ELT). Both bright single natural guide star (SCAO) and multiple laser star tomographic AO (LTAO) modes will provide near diffraction limited hyper-spectral imaging over most of the sky. By using a unique high contrast module together with the ability to correct the wavefront using single conjugated adaptive optics algorithms it will be possible to characterize exoplanets. The instrument provides four spaxel scales, and users can select from eleven grating choices with resolving powers ranging from R~3000 to R~17000.

The ELT is an adaptive telescope, with M4 (deformable mirror with over 5000 actuators) and M5 (fast tip-tilt) providing active correction of atmospheric turbulence. The sensing of the wavefront aberrations is done by the HARMONI Laser Guide Star Sensors (LGSS) and the Natural Guide Star Sensors – better rejection of common mode disturbances such as flexure and vibrations is achieved by splitting the wavefront sensing light as close to the science focal plane as possible. The scheme used for wavefront sensing leads to HARMONI's four distinct operating modes: LTAO, SCAO (Single Conjugate AO), HCAO, and NOAO – the latter providing no atmospheric turbulence correction. The instrument will be able to support a wide range of observing programmes.

2. INSTRUMENT DESCRIPTION

An artist impression of the instrument CAD model is showed in Figure 1. The Integral Field Spectrograph (IFS), the primary science instrument, consists of a cryostat (ICR), which houses the optical sub-systems namely: the IFS Pre-Optics (IPO), the Integral Field Unit (IFU) and the four IFS Spectrographs (ISPs). The primary function of the IPO is to provide four spatial scales; the IFU re-arranges the light received from the IPO into four 500 mm pseudo long slits (in a square). Each slit forms an input to one of the spectrographs. Each spectrograph has an infrared camera and a visible camera, which allows an astronomer to observe either in the near infrared or in the visible. Finally, the dispersed spectra from each spectrograph camera will be imaged on its science detector focal plane. Each near-infrared science detector focal plane consists of two 4096 x 4096-pixel HAWAII 4RG arrays.

Light from the telescope is relayed to the instrument by the focal relay sub-system. A user-selectable dichroic in front of the relay separates laser guide star (LGS) light from natural guide star (NGS) and science light to enable LTAO wavefront corrections. All the wavefront sensors used to pick of the laser light are grouped together in a system called Laser Guide Star Sensors (LGSS), while the sensors used to pick of the light from the natural guide stars are group together in the system called Natural Guide Star Sensors (NGSS). The LGSS consists of six laser guide star wavefront sensors. The 120-arcsecond NGS and science field transmitted by the dichroic is relayed to an 'up-looking' focus, which allows a gravity invariant rotating instrument configuration. Calibration light can be fed into the instrument via a deployable up-stream calibration system upstream of the relay.

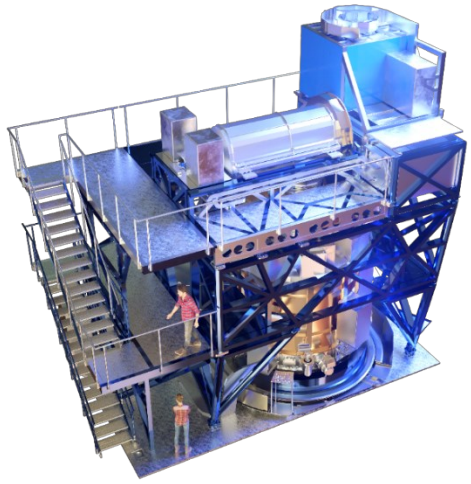


Figure 1: An artist's impression of HARMONI

As described above HARMONI is an adaptive optics (AO) assisted IFS and will be the primary spectrograph for the ELT. The IFS and AO wavefront sensing support systems are being developed concurrently. Due to the addition of the wavefront sensing capability, it should be possible to observe with the instrument in most observing conditions, enabling a broad range of science to be carried out with the instrument.

For simplicity the instrument is separated into two main elements as illustrated in Figure 2, namely: the ***Adaptive Optics***, which is responsible for wavefront sensing and computation of the corrections needed, and the ***Integral Field Spectrograph***, responsible for measuring the spectra of the celestial object of interest. In addition, the instrument support functions are delivered by the HCS, the calibration module, and the HARMONI Science Software (HSS).

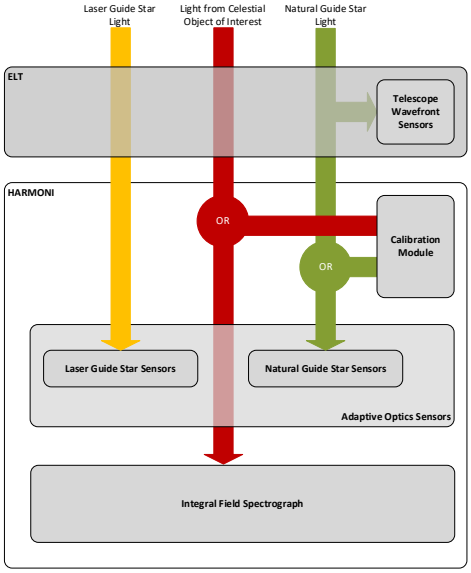


Figure 2: Operational view (includes both the ELT facilities and HARMONI instrument)

2.1 Operational modes

HARMONI will employ multiple wavefront sensors and guide probes to measure the wavefront aberrations using laser and natural guide stars. These wavefront sensors will enable four different ways of wavefront control of the ELT and enhance the images provided:

- Secondary Guiding (or NOAO),
- Laser Tomography Adaptive Optics (LTAO),
- Single Conjugate Adaptive Optics (SCAO), and
- High Contrast Adaptive Optics (HCAO).

For each of the above cases, apart from NOAO, the guiding and wavefront control signals will be calculated by the HARMONI control system and applied to the ELT adaptive mirrors M4 and M5.

The handover of the adaptive optics control to the instrument can be done in two ways:

- **Sequential mode**: the instrument is fully responsible for field stabilization, by producing a control output for tip and tilt of M4.
- **Cascade mode**: in this mode the tip and tilt control output generated by the instrument is not applied directly to M4 but serves as a target reference for the control loop based on metrology coming from the Pre-focal Station (PFS). This mode is useful in case the guide stars in the field of view of the instrument are fainter than the ones in the technical field of the PFS.

The requirements for each of the instrument operational modes are listed in Table 1. The astronomer can select one of four modes: NOAO, SCAO, HCAO and LTAO. Observing templates will have a similar look and feel of existing instruments on the VLT near-IR IFS and will include a variety of sky subtraction strategies such as “offset to blank sky”, “nod-on-IFU” or “stare”, together with the ability to apply small off-sets to work around bad and hot pixels. Mosaicking will also

be supported in the usual way, as will non-sidereal tracking in LTAO and NOAO modes (in SCAO and HCAO mode, the only non-sidereal observation possible is when the AO reference "star" is itself non-sidereal). Near-IR long exposures (typical for spectroscopy of faint targets) will use Sample-Up-The-Ramp (SUTR) readout to minimise read noise, with every non-destructive readout saved in the archive. AO telemetry data, useful for reconstructing the PSF during the exposure, will also be archived.

Table 1: Operational mode requirements

Name	**Wavefront control**	**Dichroic**	**Spaxel size**	**Wavelength range**	**Tracking and guiding**
NOAO	None	NA	All	Full	Telescope in full control/ Sidereal and non-sidereal field tracking; Incremental guiding which is equivalent to the VLT secondary guiding ($f \leq 0.1$ Hz)
LTAO	Laser tomography	LTAO	All	≥ 0.6 µm	Sidereal and non-sidereal field tracking; Fast guiding or tip-tilt free mode. Handover from telescope to instrument will be using **sequential mode**.
SCAO	Single conjugated tomograph	SDic800; SDic1000	All	≥ 0.8 µm; ≥ 1.0 µm	Sidereal field tracking for on- and off-axis guide targets; non-sidereal field tracking for on-axis guide targets; Fast guiding. Handover from telescope to instrument will be using **sequential mode**.
HCAO	Single conjugated tomograph	HCAO	All	≥ 1.25 µm	Handover from telescope to instrument will be using **sequential mode**.

2.2 Instrument configuration

To prepare the instrument for science operational use the astronomer will need to select on of the four modes defined in Table 1 and also select a valid instrument setting by selecting the spaxel size (4 x 4 mas, 10 x 10 mas, 20 x 20 mas, and 60 x 30 mas), a waveband and spectral resolving power combination. The waveband and spectral resolving combinations are listed in Table 1

Table 2: Instrument waveband and spectral resolving power combinations

Name	**Band**	**λ_{min} [µm]**	**λ_{cen} [µm]**	**λ_{max} [µm]**	**$R_{cen}=\lambda/\Delta\lambda$**
VIS	V+R+I	≤ 0.5	0.65	≥ 0.8	$\gtrsim 3000$
LR1	I+z+J	≤ 0.83	1.09	≥ 1.35	$\gtrsim 3000$
LR2	H+K	≤ 1.45	1.925	≥ 2.40	$\gtrsim 3000$
MR1	I+z	≤ 0.83	0.94	≥ 1.05	$\gtrsim 7000$
MR2	J	≤ 1.05	1.185	≥ 1.32	$\gtrsim 7000$
MR3	H	≤ 1.45	1.625	≥ 1.80	$\gtrsim 7000$
MR4	K	≤ 1.97	2.185	≥ 2.40	$\gtrsim 7000$
HR1	z	≤ 0.828	0.865	≥ 0.902	$\gtrsim 17000$
HR2	H_{high}	≤ 1.538	1.608	≥ 1.678	$\gtrsim 17000$

Name	Band	λ_{min} [µm]	λ_{cen} [µm]	λ_{max} [µm]	$R_{cen}=\lambda/\Delta\lambda$
HR3	K_{short}	≤ 2.017	2.109	≥ 2.201	$\gtrsim 17000$
HR4	K_{long}	≤ 2.199	2.230	≥ 2.400	$\gtrsim 17000$

2.3 Science cases and observation flow

The combination of a diffraction limited imager and an integral field spectrograph represents a powerful combination of instruments, covering a broad range of science cases for the ELT. Nine science cases have been identified in the Top-Level Requirements for the ELT-IFU" (ESO-191883). Use case models for seven of these science cases have been developed and these were captured in the Operational Concept Definition (OCD) for the instrument. For each use case, details regarding the observation preparation, acquisition, observing strategy, calibration requirements, and science data requirements were defined. This information is essential to allow the team to design the instrument architecture and especially the HCS behavioural architecture.

A generic observation flow diagram is presented in Figure 3. The user (astronomer) will prepare an observing proposal in response to an "invitation for observing", this is called the Phase 1 proposal. Once an observing proposal has been accepted the PI prepares the observations using the ESO Phase 2 (P2) tool to define where the telescope should point in terms of coordinates and define the guide stars. At this stage all telescope and instrument guide stars (coordinates, brightness, spectral type, and proper motion) will need to be defined.

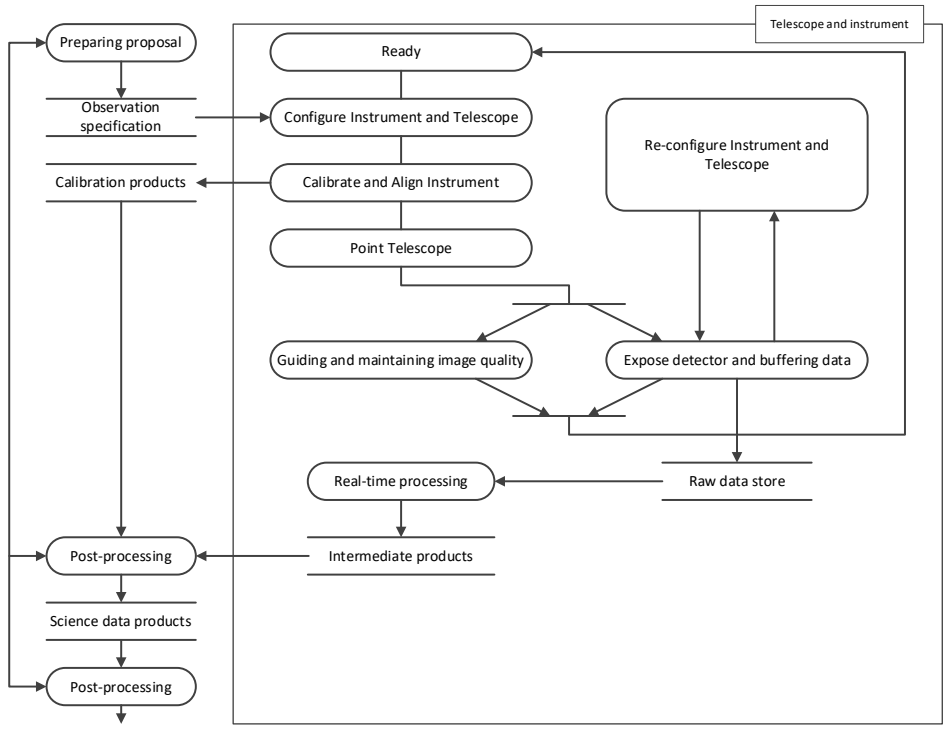


Figure 3: Generic observation flow diagram

ELT observations are prepared and executed via observation blocks (OBs). As for the VLT, one or more templates can be combined into an OB. Typically, the OB is up to one hour long and is formed by templates for pre-set, acquisition, and followed by science exposure templates. For the ELT, ESO has define the so-called quantum bit (QB) to improve the observation efficiency, in that a QB becomes the smallest science unit that can be calibrated, and the data can be reduced and used for science.

The output of the proposal preparation phase 2 is a set of OBs. Each OB consists of a template for acquisition, science exposures, and if required, calibration exposures.

3. SYSTEM ARCHITECURE DEVELOPMENT METHODOLOGY

3.1 Function-based system design methodology

In the International Council on Systems Engineering's (INCOSE) Systems Engineering Handbook (International Council on Systems Engineering (INCOSE), 2015)[1] function-based systems engineering, and model-based systems engineering are described as two distinct methodologies in Chapter 9, called "cross-cutting systems engineering methods". The primary author of this paper disagrees that "modelling and simulation" is a design methodology. In this section of Chapter 9, the authors also discuss SysML™ from the Object Management Group® (OMG®) as an important modelling language and then proceed in Section 9.2 to provides an overview of model-based systems engineering (MBSE). Again, the authors of this paper do not agree. The fact that one can share and exchange information via a model, does not turn a tool into a methodology. The OMG® has formalized a graphical notation, which is based on the Unified Modelling Language (UML) mainly developed and used in software intensive systems. Both SysML and UML make use of a common standardize graphical language. Graphical representation to define systems and sub-systems have been around way-way before we had an abundance of computers, computer power and graphical drawing capabilities available.

As part of my PhD, I investigated the state of the art in terms of software development tools and focused on the Hierarchical Object-Oriented Design (HOOD). At that point in time neither the computing facilities nor the drawing capabilities of any of these tools were sophisticated enough, and the author used standard drawing software such as Harvard Graphics, implementing well known diagram types defined by (Benjamen S. Blanchart, 1990, 1981)[2], (DeMarco, 1978) and (Yourdon, 1988)[3]. Tom DeMarco and Yourdon developed structured analysis in the early nineteen seventies. These diagrams made it into UML and now also called MBSE, while the author believes that these diagram types are very useful as in describing the architecture of a system and can be used to support the development of a system architecture, however one still still needs to define a design framework structure, and that is what was done to ensure that the best possible control system architecture was developed for the HARMONI control system.

The cornerstone of the novel function model-based system engineering (FMBSE) methodology detailed here is driven by the functions required. Identifying all the functions required is achieved by performing a detailed functional analysis (highlighted in Figure 4). This is to ensure that all the functions required to deliver the science data to perform the "as planned" science are identified, described, and implemented. One should not only consider the operational concept of the instrument, and the functional analysis should also be performed for all use cases covering the life-cycle of the instrument. Once the functional analysis has been captured and reviewed, the engineering team can proceed to implement these functions in hardware and software as a first step towards developing the physical and behavioural architecture of the system.

What is unique about this methodology is that it uses the results from the functional analysis to design both the physical and behavioural architecture of the system interactively as described in section 2.1. To communicate the analysis and design work based on this methodology, extensive use is made of graphical models. The graphical models are based on the earlier work done by (Benjamen S. Blanchart, 1990, 1981)[2], (DeMarco, 1978)[3], and (Yourdon, 1988)[4]. These diagrams have been refined and are now incorporated in both UML and SysML.

3.2 Functional analysis

As defined in the NASA SYSTEMS ENGINEERING HANDBOOK, (NASA)[5], "functional analysis is the process of identifying, describing, and relating the functions a system should perform to fulfil its goals and objectives. It is a process that translate stakeholder needs into a sequenced, and traceable functional architecture. The functional analysis should also include the interaction of the hardware and software with all human beings that must interact with the system. The tasks and roles of humans in the system should be clearly defined in terms of inputs, outputs, failure modes, consequence of failure, and interface requirements.

Each user requirement needs to be analyzed and evaluated and the functions required need to be identified and defined. The process is iterative and continues until a function can be implemented with an identifiable product, that either already exists (can be procured) or that can be made utilizing standard industrial manufacturing methods (make). It is common to organize the identified functions into a hierarchical structure. This is especially true for large systems, where the system will transition through several phases in different environments.

The process involves analyzing each system requirement to identify all the functions that need to be performed to meet the requirement. Each function identified is described in terms of inputs, outputs, failure modes, consequence of failure, and interface requirements. Functions are arranged in a logical sequence so that any specified operational usage of the system can be traced in an end-to-end path.

The outcome of a functional analysis becomes the framework for developing the functional and performance requirements and for the development of the physical and behavior architecture of the instrument (system). The results of a functional analysis can be presented in functional flow block diagrams (FFBDs), which are composed of a multi-tier, time-sequenced step-by-step flow diagrams to describe the functional flow of the proposed system. In SysML they have not included a notation to include the traditional functional flow block diagram, however it is possible to use SysML activity diagrams instead, by applying the principles of functional analysis.

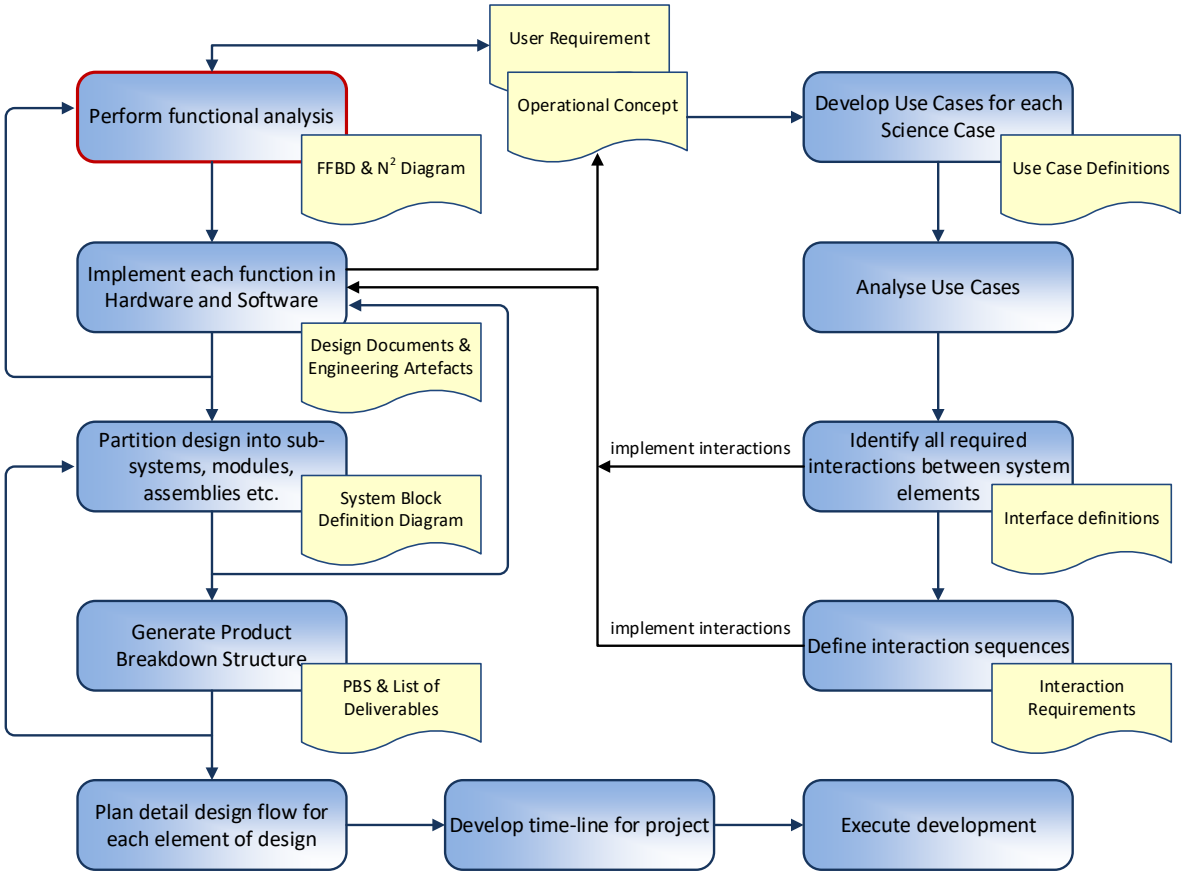


Figure 4: Function model-based systems engineering architecture model development methodology

3.3 Develop system architecture

Once the functional analysis has been completed, the engineering design team start working by providing possible design solutions to implement each of the required functions in hardware and software. The detail of each proposed design concept will vary depending on whether existing modules, assemblies, sub-assemblies, and components can be re-used. It is the systems engineer's responsibility to make sure that all the design elements implementing the system functions work well together and that unintentional negative system properties do not emerge. The next step is to partition the design into sub-systems.

In ground-based optical astronomy, we are interested to characterize the photons received from celestial objects. Therefore, it follows that many functions will be implemented by making use of optical components.

4. HARMONI CONTROL SYSTEM - AN ILLUSTRATIVE EXAMPLE

The unique FMBSE methodology defined in Chapter 4, was used to develop the HCS physical and behavioural architecture. In the rest of this chapter, we will illustrate the methodology by using the development of the HCS as an example.

Based on the project work breakdown structure (WBS) and not on the product breakdown structure (PBS) the HCS is responsible for the control of all devices, except for the science detectors. In addition, the HCS is also responsible for the processing of all the wavefront sensor data and the calculation of correction coefficients, which then will be passed on the ELT Central Control System, so that they can be applied to the ELT adaptive optics mirrors (M4 and M5).

A sub-set of the HARMONI functional block diagrams developed, applicable to the HCS are depicted in Figure 5 to Figure 7. Functions implemented in the HCS in Figure 5 are highlighted in red. In this paper we will focus on the decomposition of "Execute observation" (shown in Figure 6) to illustrate the methodology used to develop the HCS architecture. In Figure 7, the functions implemented as part of the HCS are configure system, adjust configuration (interactive), take exposure, stabilize image, stabilize pupil, and store data as FITS file. Following the functional hierarchy further we focus on "configure system" (Figure 7), and finally focus on configuring the Integral Field Spectrograph (IFS).

The functions to support the configuration of the IFS are shown in Figure 8. As described in section 2.2, the instrument supports four spatial scales (spaxel scales) and eleven waveband and spectral resolving combinations as defined in Table 2. The implementation of functions 3.3.1.2 and 3.3.2.5 resulted in the delivering of this capability. The optical design solution implementing the four spatial scales is depicted in Figure 10 and the complete sub-system block definition diagram is presented in Figure 10 while the optical design to implement the eleven waveband and spectral resolving combinations are depicted in Figure 11, and the equivalent block definition diagram is shown in Figure 12. The third IFS optical system the integral field unit (IFU) is responsible for splitting and slicing the field delivered by the IPO to create the four slits and to deliver these as the inputs to each of the four spectrographs. The input field delivered to the IFU is the same size for all spatial scales, therefore the science fields will vary in both size and orientation. Operationally the IFU has no moving parts and therefore no controls are required.

Although a limited number of functional flow diagrams are shown, an overview of how all the functions have been implemented in hardware is depicted in Figure 13.

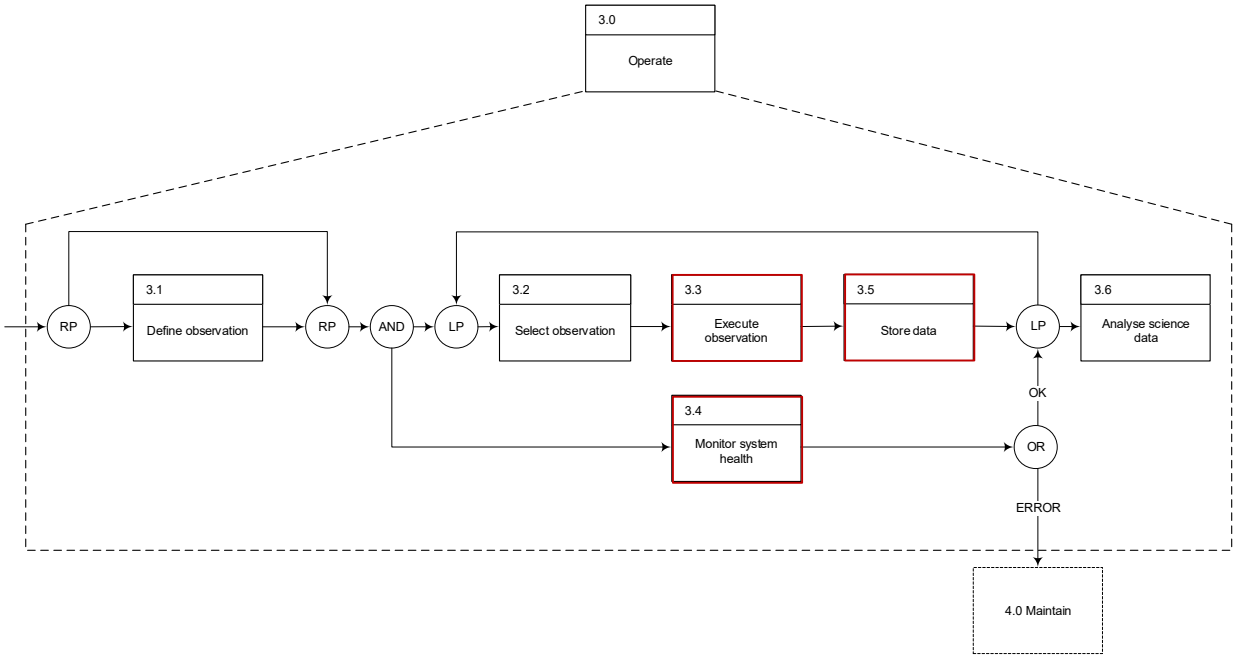


Figure 5: Functional block diagram – operate

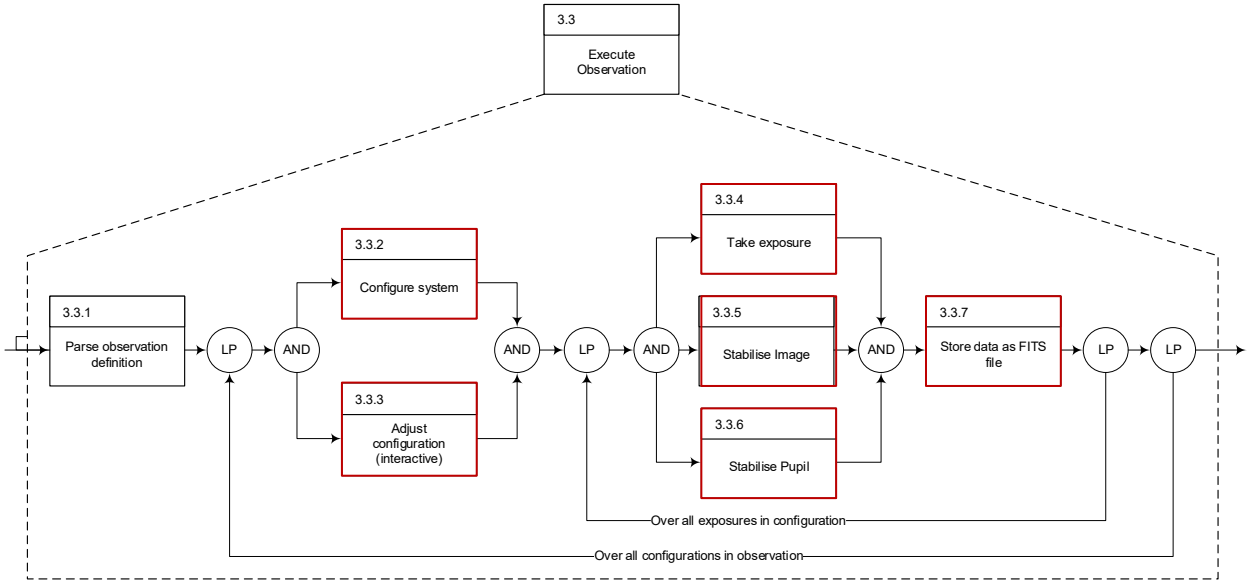


Figure 6: Functional block diagram – execute observation

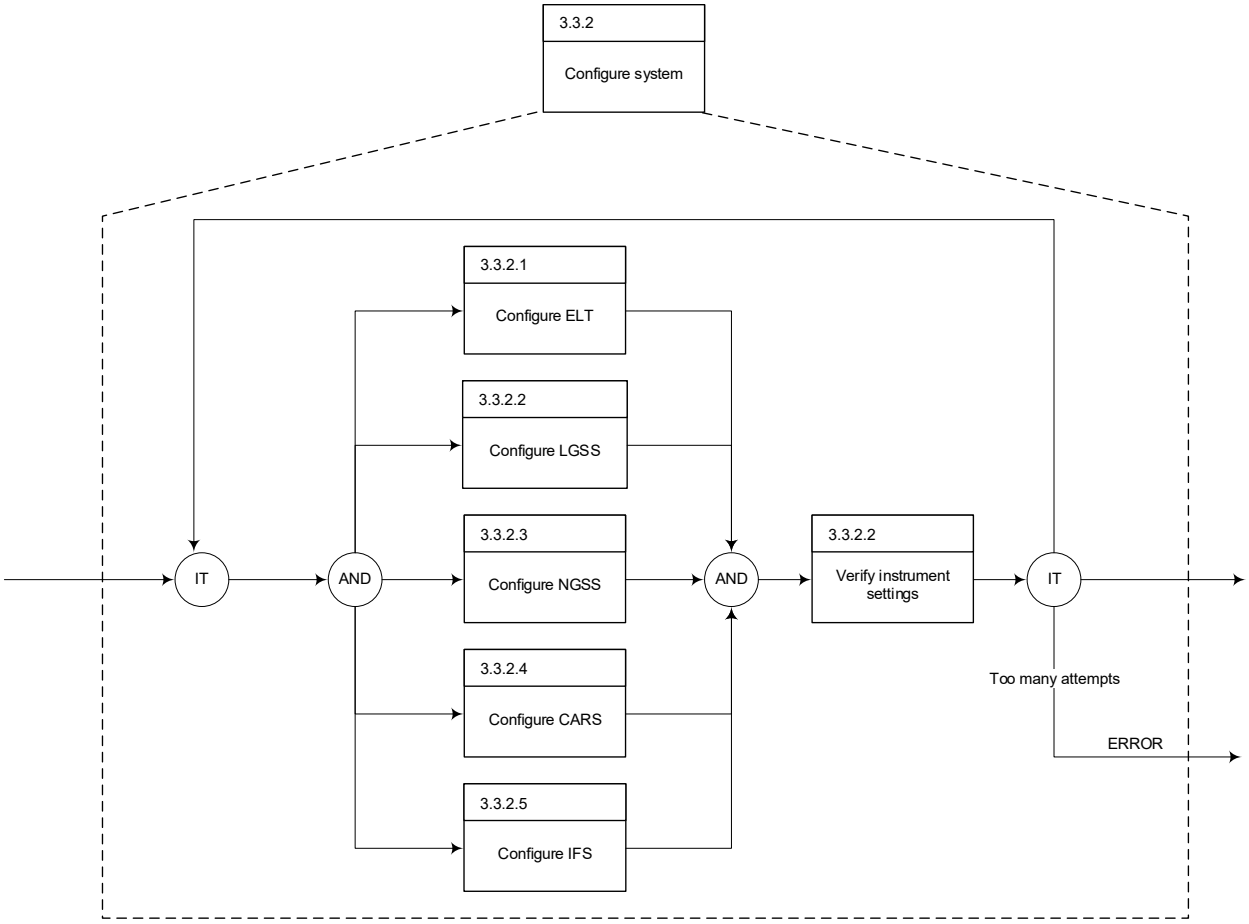


Figure 7: Functional block diagram - configure system

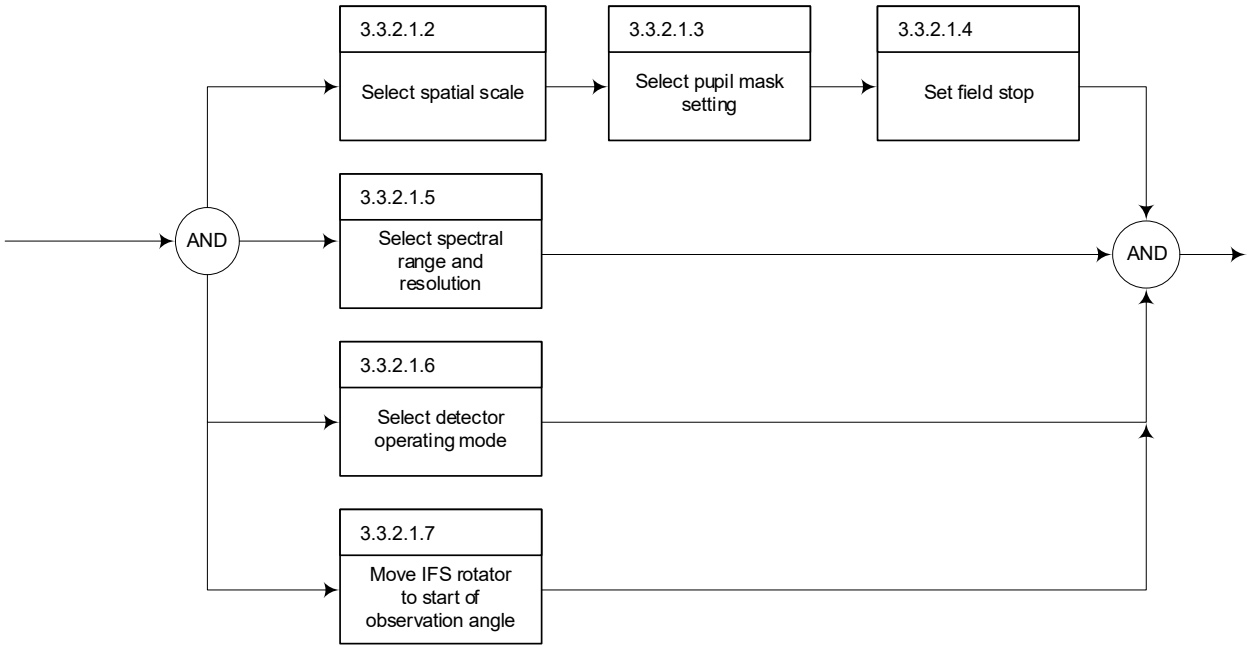


Figure 8: Functional block diagram - configure IFS

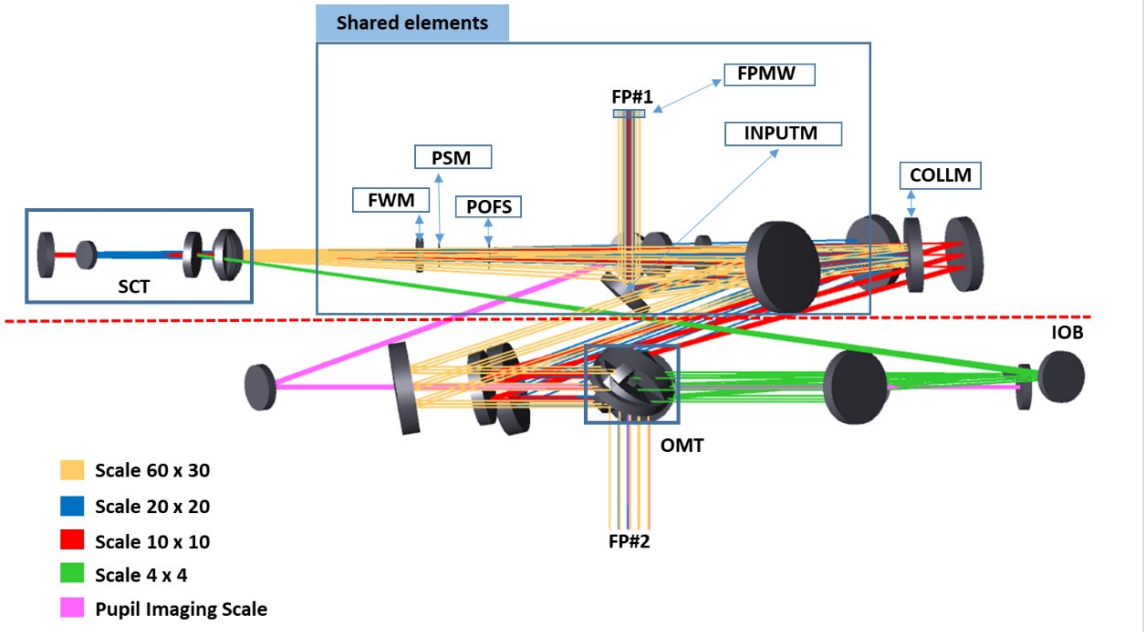


Figure 9 IFS Pre-Optics (IPO) design implementing the four spatial scales

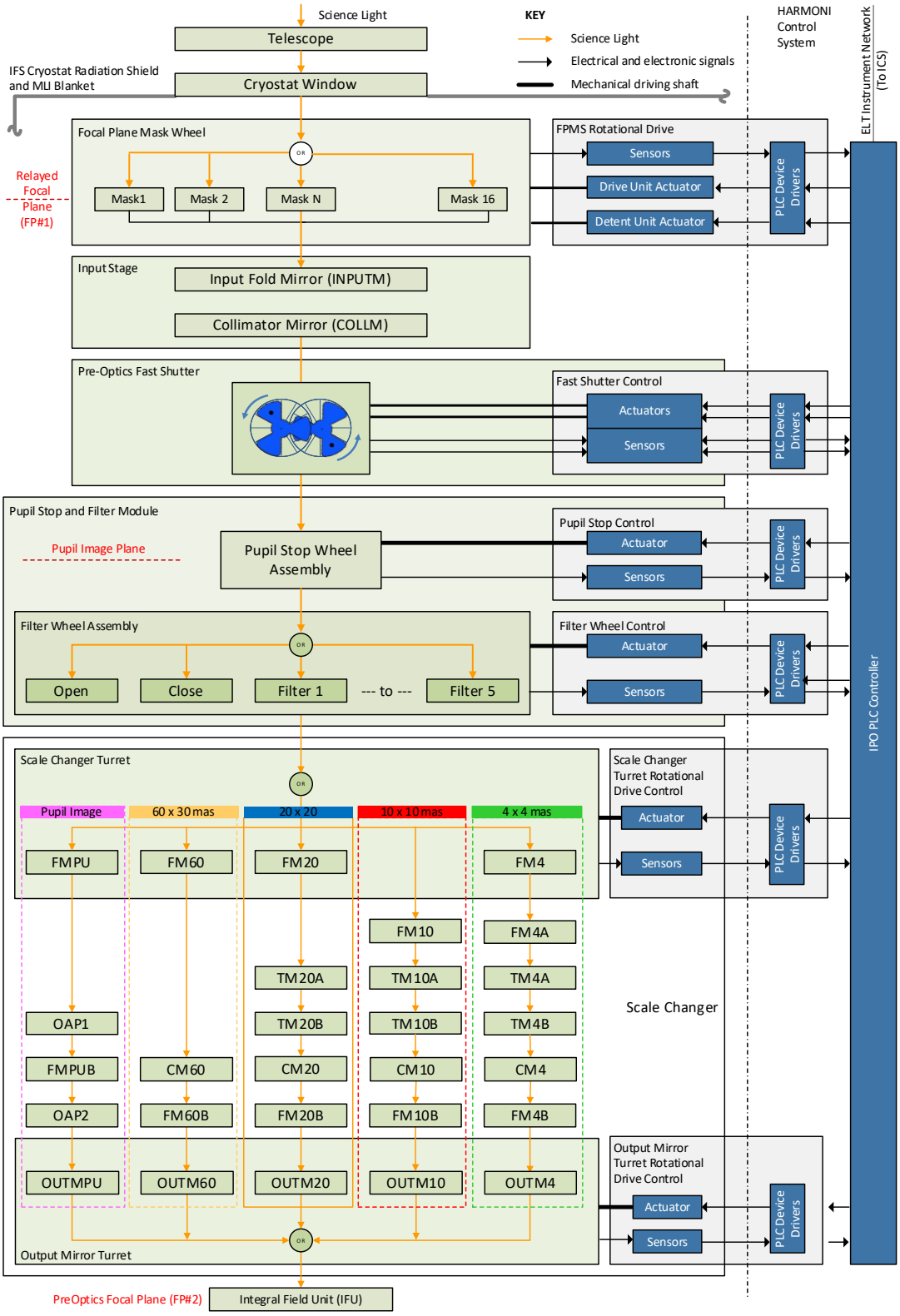


Figure 10: IPO block definition diagram

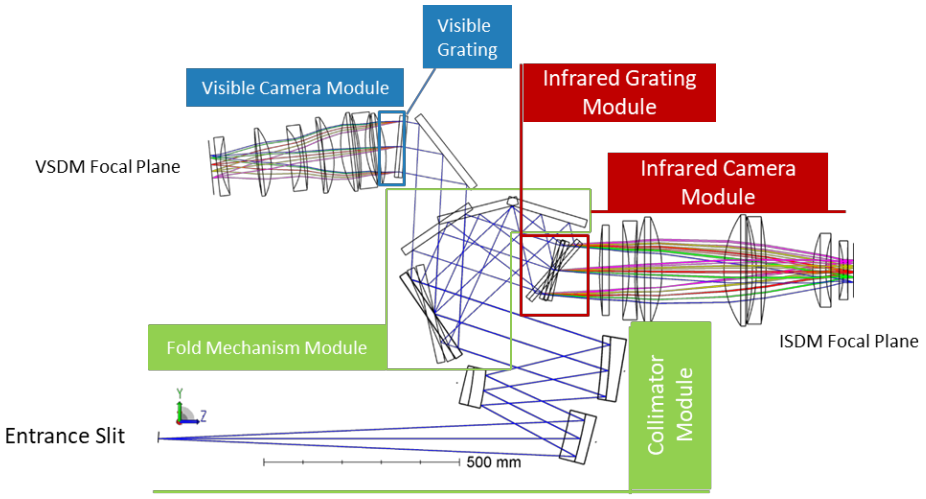


Figure 11: IFS Spectrograph (ISP) optical design implementation to deliver the eleven waveband and spectral resolving combinations

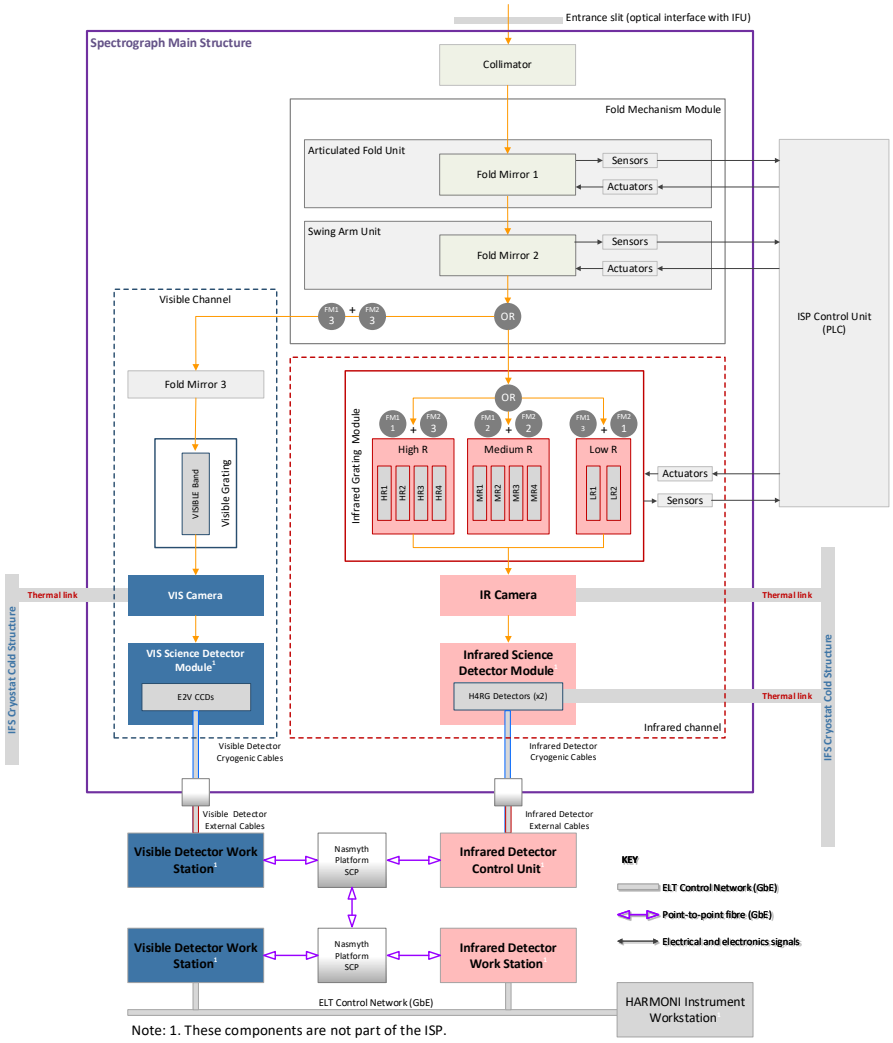


Figure 12: ISP block definition diagram

Partitioning is the process whereby the system architect divides the first order conceptual design into system blocks such as sub-systems, modules, and assemblies based on the chosen system hierarchy. Whilst experienced systems engineers will draw upon their previous experience, it is possible to sum up this in the following guidelines:

a. Simplify the number and types of interfaces between system elements (i.e., systems, sub-systems, modules, etc.)

b. Ensure high cohesion between functions within each system element.

c. Make sure that the couplings between system elements are weak.

In numerous publications this step is normally incorrectly referred to as the allocation of functions to hardware and software elements, while in fact the functions delivered by each system or sub-system element have been inherited by the partitioning of the various hardware and software elements within a system hierarchy. The partitioned instrument solution is depicted in Figure 13 where the functions are implemented primarily using opto-mechatronics components, and then partitioned into four systems, namely the LGSS, NGSS, Calibration and Focal Plane Relay System (CARS), and the IFS.

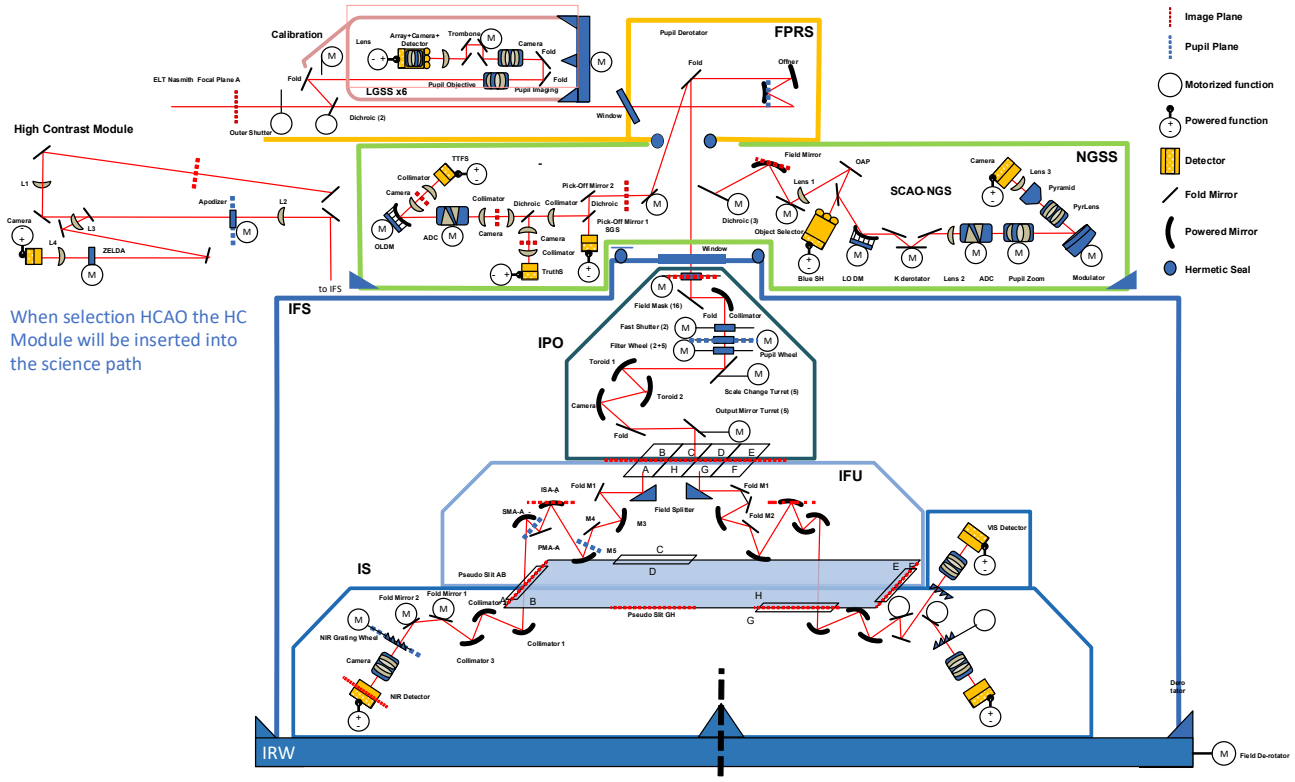


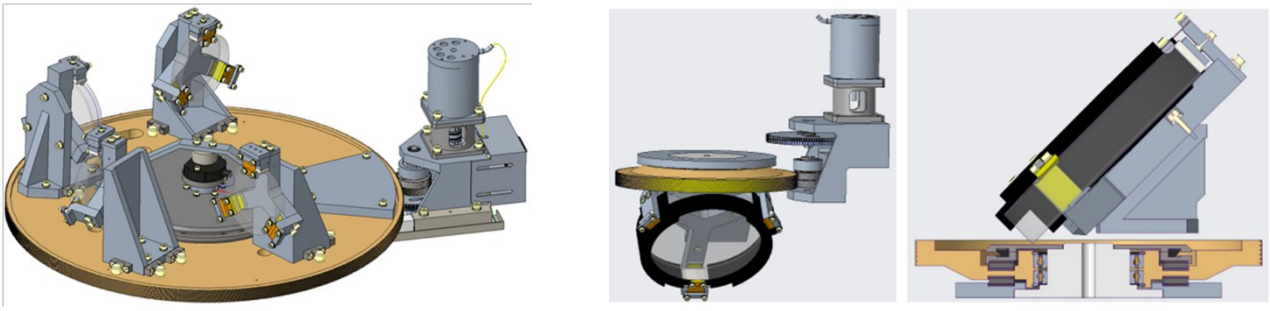
Figure 13: Implementation and partitioning of functions into systems

For the keen observer it should be clear that the instrument block definition diagram in Figure 13 is incomplete, in that there is no indication of how all the controllable devices will be controlled. If the control electronics and software in the HARMONI instrument were associated with the four systems shown in Figure 13, then the conceptual design process would have been completed. In astronomical instrumentation projects, there is a tendency to group the development of the instrument control system elements into a work breakdown structure (WBS) based on the engineering disciplines required rather than to base it on the instrument architecture, and HARMONI is no exception.

The next step in the design process therefore was to design the control solutions for each of the controllable devices identified to ensure that the various system elements will work well together as a system hence an overarching control element will be required. The functional and performance characteristics for each of the devices have been defined and captured in a device control design and analysis document.

Following on from the need to observe using the spatial scale selected by the astronomer (one of the four spatial scales), this function is implemented by selecting the correct spatial scale optical path.

This is done with a scale changer turret (SCT) housing four, fold-mirrors, one for each scale that will be used to direct the light to follow the selected scale's optical path. To complete the implementation there is also an output mirror turret (OMT), consisting of a single output mirror. The OMT rotates such that it directs the optical beam for each scale to the IFU. The performance requirements are listed in Table 3 and the motion profile of the turrets based on a counting full-steps is depicted in Figure 15.



Scale changer turret (SCT) Output mirror turret

Figure 14: Implementation solution for the function - select spatial scale

Table 3: SCT and OMT motion control characteristics

Performance Parameter	**Requirement**
Motion type	Rotary movement (clockwise)
Motion profile	Depicted in Figure 15
Range	Multi-turn
Reference set point	Homing based on micro-switch
Hard stop limits	NA
Soft stop limits	Based on motor full-steps count, micro-switches, & temperature sensor.
Resolution = Minimum step size	0.055-0.060mm
Repeatability	± 7 µm
Size of payload	Diameter 439mm; thickness 15mm
Weight of payload	11.2 kg
Life-time	≥ 10 years
Operating environment	High Vacuum and cryogenic environment (T= 130K)

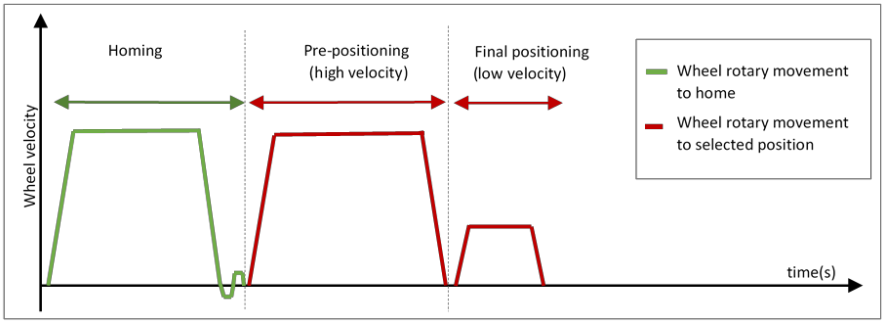


Figure 15: STC and OMT motion profile

Three different motion types are defined in the SCT control strategy:

Homing: After mechanism initialization, when an error is detected or before any movement to a new target, position the platform is rotated by the drive unit it reaches the global home position (detected by the home micro-switch). To refine the home position, once the switch is activated, the drive is reversed until the home switch is cleared and then driven back into the home switch at a very low speed.

Scale selection, high velocity: In this stage, the turret shall be driven to a pre-calibrated position before the selected mirror based on motor full-step counting. Once the position is reached, the motor shall be de-energized.

Scale selection, low velocity: In this stage, the turret shall be driven to the target scale position based on step counts. This movement is performed at low angular velocity and during this stage the turret activates a position switch used to validate that no steps are lost until this point. Once the final position is reached, the drive unit motor shall be de-energized.

Additionally, the control system monitors the temperature of the mechanism based on the measurements received from the SCT temperature sensors. Temperature alarms will also be implemented, and the instrument operator shall be able to stop the movement when required.

The control strategy design includes redundancy in terms of the sensors, so that anomalies within the system can be detected. The position switch activation will be used to validate the drive unit step counts at pre-calibrated locations near the final target position. If the position at the switch activation instant is not coherent with the pre-calibrated value, an alarm should be raised. Additionally, the position switch used with the absolute encoder mounted on the wheel axis, provides a redundant home in case of failure of the original home-switch element. The control implementation design requirements for the IPO are summarised in Table 4, the electronic devices are listed in

Table 5 and depicted in Figure 16.

Table 4: IPO control implementation definition

		BASIC			CONTROL PARAMETERS								ACTUATOR	SENSORS	
		THERMAL DOMAIN	ROTATION DOMAIN	CONTROL MASTER	CONTROL MAG [DOF]	No. STATES [LIMITED]	RANGE	ACCURACY	PRECISION REPEATABILITY	OPERATION REGIME	OPERATIONS PER DAY	EXTERNAL SYNC	ACTUATORS	SENSORS [FUNC] (DISCRETE)	SENSORS [FUNC] (CONTINUOUS)
1	IFS.PREO.FPMW	CY1	F	PL	AP1	16U	360°	±0.5mm	±2.5um	SS	10	.	1 STM	2 SWT DE	1 MEN MO
2	IFS.PREO.CPSM	CY1	F	PL	AP1	8U	360°	±23um	±2.5um	SS	10	.	1 STM	2 SWT HM	1 MEN MO
3	IFS.PREO.FWM	CY1	F	PL	AP1	8U	360°	±0.5mm	±0.5mm	SS	10	.	1 STM	2 SWT HM	1 MEN MO
4	IFS.PREO.FSM	CY1	F	PL	AP1	2U	20ms - TBC s	±0.5ms	.	SS	10	Y	1 STM	.	1 MEN MO
5	IFS.PREO.SCM	CY1	F	PL	AP1	5U	360°	±0.5°	±2.5um	SS	10	.	1 STM	2 SWT HM	1 MEN MO
6	IFS.PREO.OFMM	CY1	F	PL	AP1	5U	<330°	±0.5°	±2.5um	SS	10	.	1 STM	2 SWT HM 2 SWT LM	1 MEN MO
7	IFS.PREO.THC	CY1	F	PL	T	.	77-300K	±0.5K	.	C	C	.	.	.	15 TES MO

Table 5: Electronics design – controlling IPO devices

Description and part number	No. off	DIN rail position
Control Power Supply 24V, 1.5A, for logic and sensors power supply	1	1
Application Power Supply 24V, 7.5A, for motors power supply	1	2
EtherCAT coupler (Beckhoff EK1100), to communicate with EtherCAT network	1	90
Stepper motor terminal, 24V, 1.5A max, 2 digital inputs (Beckhoff EL7031)	6	10 - 15
8-channel digital input terminal (Beckhoff EL1008), for additional limits inputs	1	21

Description and part number	No. off	DIN rail position
4-channel analog input terminal (Beckhoff EL3154/64), for magnetic encoders	2	30-31
2-channel RTD sensor terminal (Beckhoff EL3202)	6	40-45
4-channel RTD sensor terminal (Beckhoff EL3214), for 6 IFS.IFU temperature sensors	2	46-47
Connection panel with	1	NA
MIL-26482 circular connectors for stepper motor and limit switches	6	NA
MIL-26482 circular connector for analog encoders and temperature sensors	6	NA
Connector RJ45 for EtherCAT connection	2	NA
Connector IEC C16 for mains power supply.	1	NA

The low-level software that will run on the instrument control PLCs must comply with the PLC instrument control framework, and it is based on the TwinCAT software library developed by ESO. It is important to note that the controllable device hardware elements (motors, sensors etc.) belongs to each of the systems (LGSS, NGSS, CARS, and IFS) as defined in Figure 13.

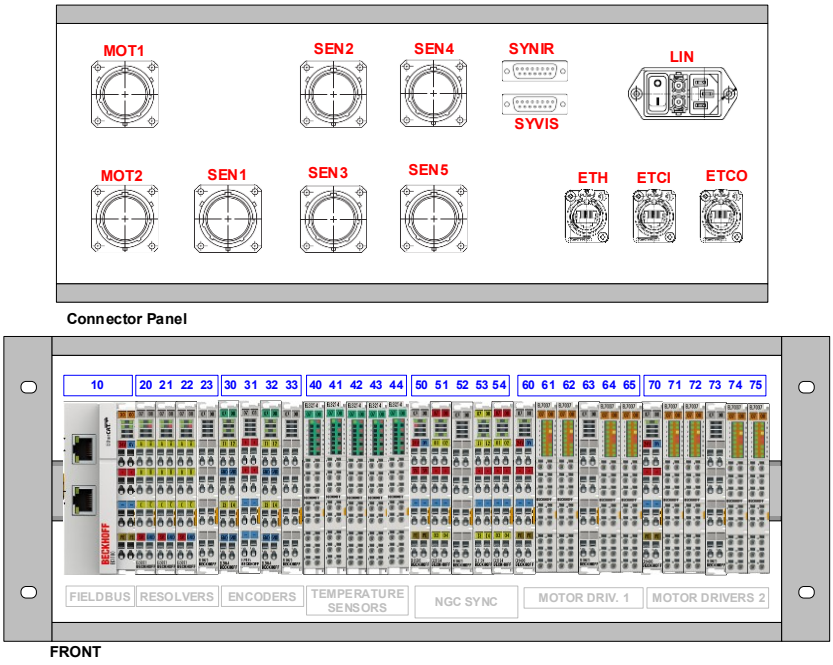


Figure 16: IPO Local control unit

This process was repeated for all the controllable devices shown in Figure 13 and the as derived architecture for the instrument control electronics (ICE) is depicted in the block definition view in Figure 17. ICE will also provide cabinets to house the electronics for all the instrument subsystems as well as auxiliary services like cabinet thermal control, mains power supply, communications, internal cabinet cabling and the interconnecting cables up to the boundary of a system.

Based on the work package allocations the team was forced to partition the control solution into electronics hardware and instrument control software. The two work packages were allocated to two consortium partners. The partitioning was purely driven by the WBS which is not ideal.

The final part of the puzzle to complete the HCS architecture is to consider the sequencing of the various functions. The key to unlock this essential part of the architecture is the design choice made to base the instrument's operational modes (see section 2.1) on the astronomer's selection of which wavefront correction topology to use. The mode selection flow diagram is shown in Figure 18. In Figure 19, you can also see which sensors will be used for measurements.

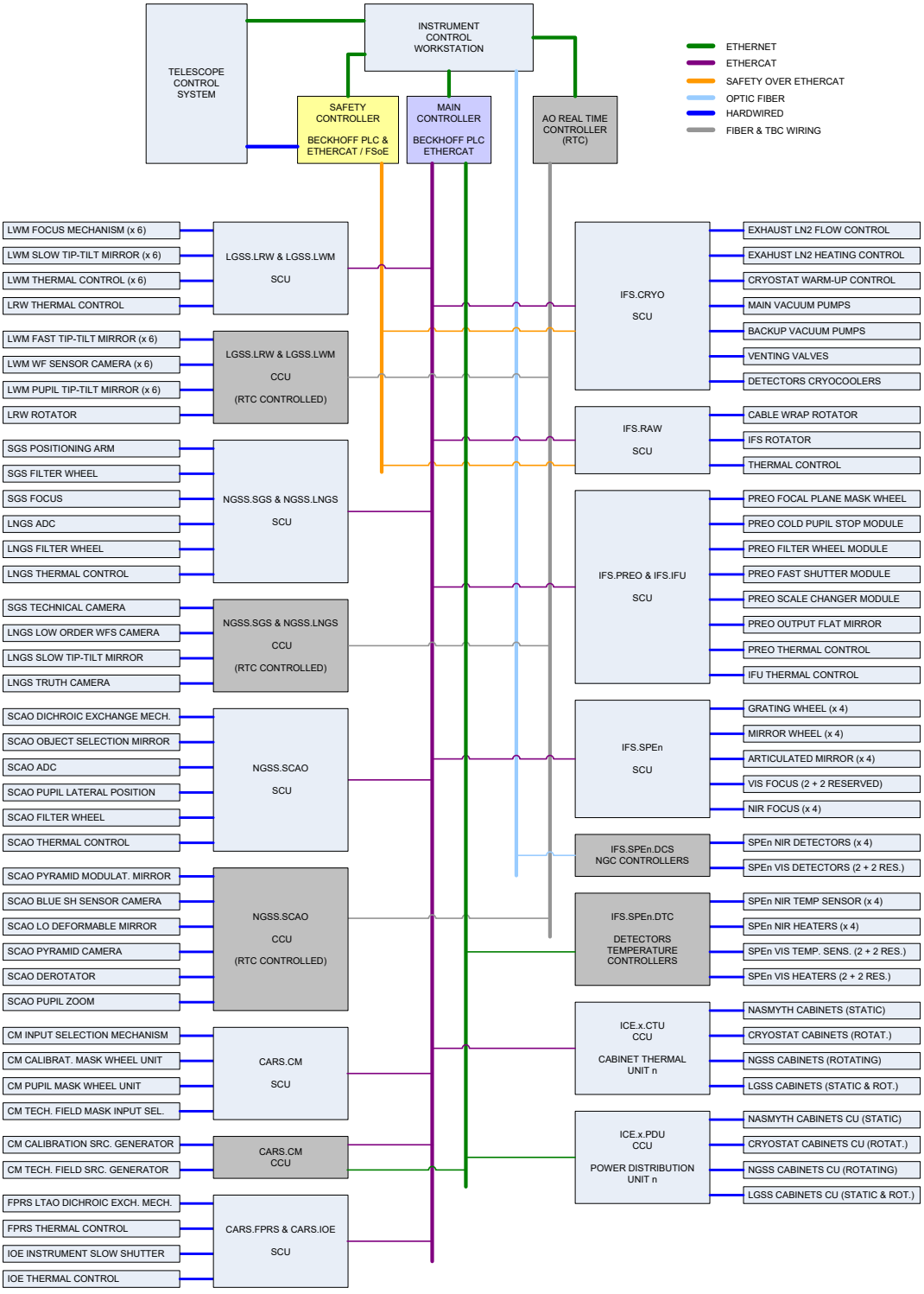


Figure 17: ICE architecture

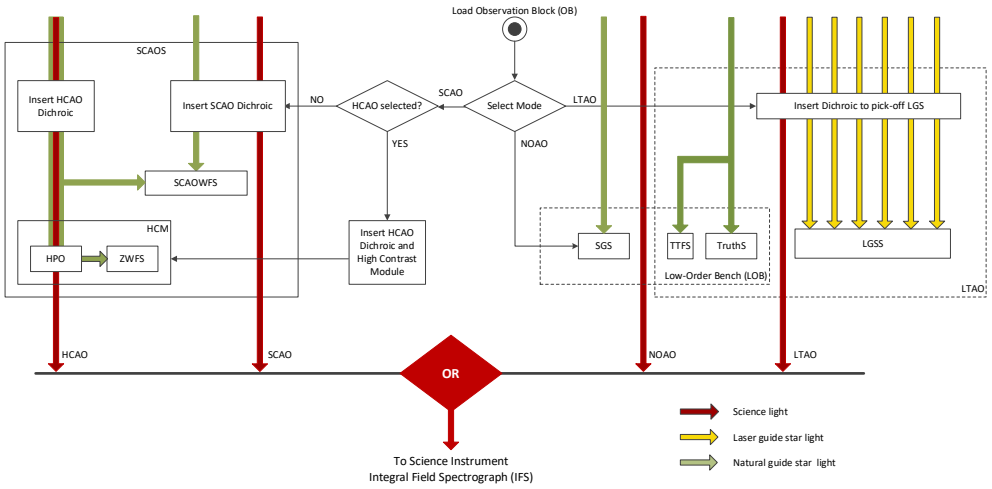


Figure 18: Mode selection diagram

Not only is the HCS responsible for implementing the modes but it is also responsible to provide all the computer hardware and software required to calculate the corrections required to guide the telescope, stabilize the image (F3.3.5) and pupil (F3.3.6). These corrections will be used by the telescope to ensure that the science field is tracked, and the image and pupil are stabilized during an observation. These functions were partitioned into what we call the adaptive optics control system (AOCS). It is a requirement that all adaptive optics control software and hardware must comply with the ESO Real Time Control Software standards and use the real time RTC toolkit. The resulting AOCS architecture is depicted in Figure 19 and the hard real time controller instantiation when observing in LTAO mode is shown in Figure 20.

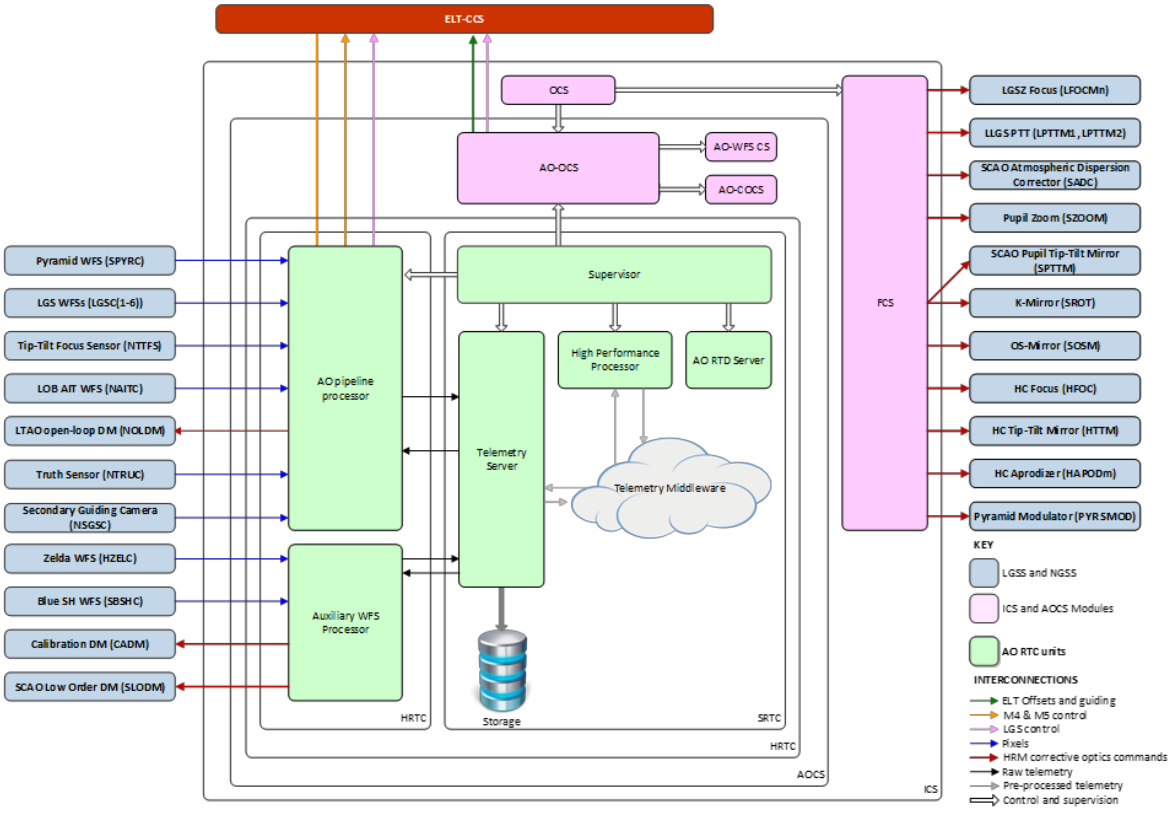


Figure 19: Adaptive Optics Control Software

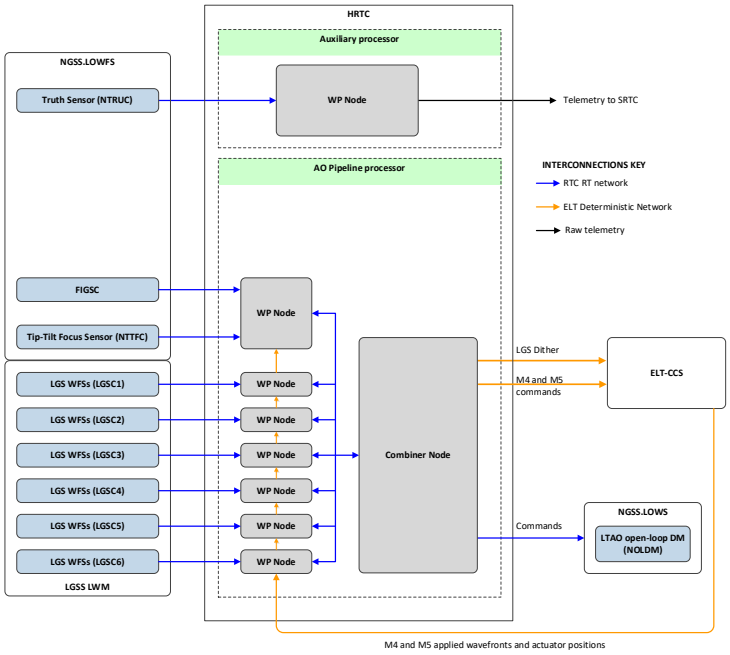


Figure 20: Hard-real-time controller operating in LTAO mode

Finally, the HCS architecture is defined in bock definition diagram is defined in Figure 21. From a hardware perspective the HCS consist mainly of PLCs and device drivers housed in electronics cabinets for the control of the various devices, while for the implementation of the AOCS high performance computers are used and the most interesting part is the software implementation to process the wavefront sensor camera pixel data and the various AO topologies.

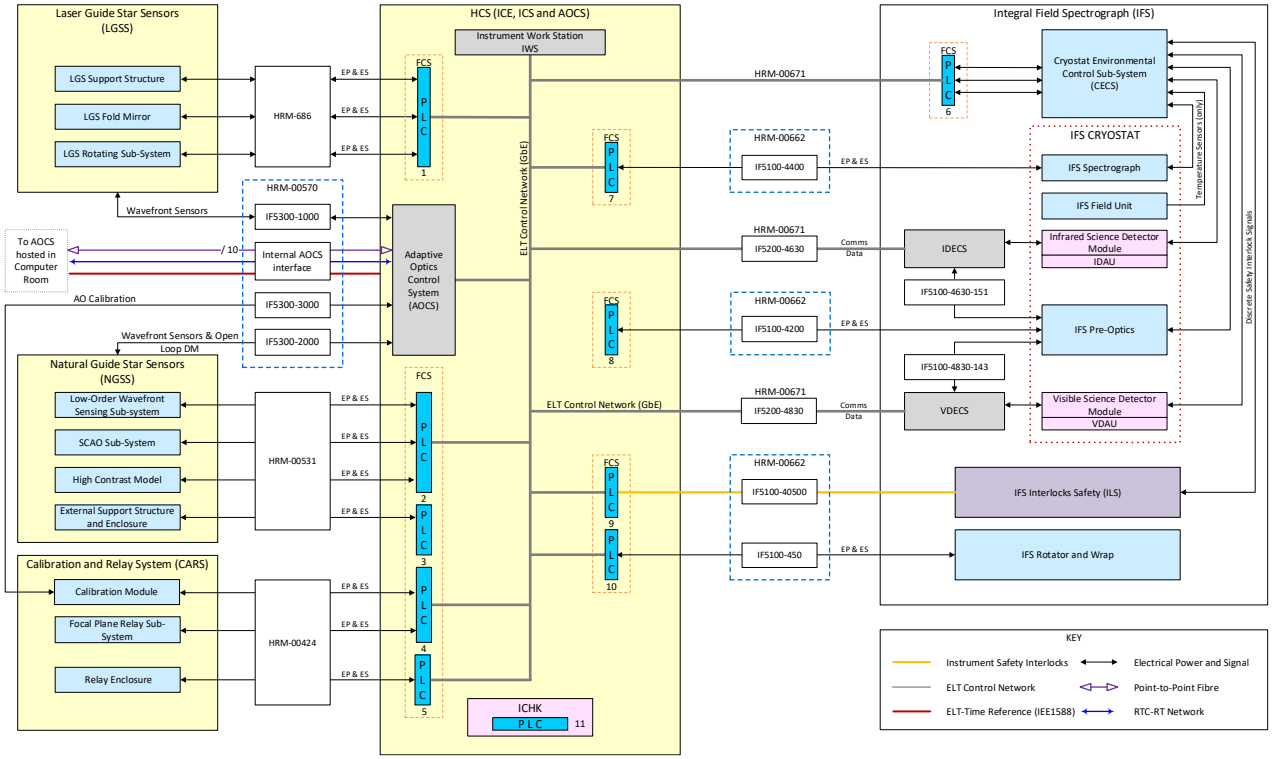


Figure 21: HARMONI control system physical architecture

5. CONCLUSIONS

The development of the HARMONI Control System (HCS) has been spread among three research organizations, to provide the control needs for the science instrument (IFS), the Calibration Module, the Focal Plane Relay Sub-System, the LGSS and the NGSS. A consequence of this work allocation made the task of developing the control architecture much more difficult. Despite that, the team showed that with a well-developed structured approach based methodology such as the function-based systems engineering it is possible to develop an elegant system architecture.

Without such a structured methodology it will be impossible to keep control of the number of interfaces and interactions required between the various team members from the numerous organizations involved.

There is a lot more material to show and illustrate the work done by the team, unfortunately this would not be possible within a single paper.

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