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Architecture of the SOXS instrument control software

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ABSTRACT

SOXS (Son Of X-Shooter) is a new spectrograph for the ESO NTT telescope, currently in the final design phase. The main instrument goal is to allow the characterization of transient sources based on alerts. It will cover from near-infrared to visible bands with a spectral resolution of $R \sim 4500$ using two separate, wavelength-optimized spectrographs. A visible camera, primarily intended for target acquisition and secondary guiding, will also provide a scientific “light” imaging mode. In this paper we present the current status of the design of the SOXS instrument control software, which is in charge of controlling all instrument functions and detectors, coordinating the execution of exposures, and implementing all observation, calibration and maintenance procedures. Given the extensive experience of the SOXS consortium in the development of instruments for the VLT, we decided to base the design of the Control System on the same standards, both for hardware and software control. We illustrate the control network, the instrument functions and detectors to be controlled, the overall design of SOXS

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Instrument Software (INS) and its main components. Then, we provide details about the control software for the most SOXS-specific features: control of the COTS-based imaging camera, the flexures compensation system and secondary guiding.

Keywords: SOXS, Instrument Control Software, Software, Spectroscopy, Imaging, Astronomy

1. INTRODUCTION

SOXS, which stands for “Son Of X-Shooter”, is a new instrument¹ being developed for the European Southern Observatory (ESO) New Technologies Telescope (NTT) at the La Silla Observatory, Chile, inspired to the X-Shooter spectrograph² at the Very Large Telescope (VLT). This new, transient-oriented facility will be mainly dedicated to several follow-up programs for the characterization of sources based on alerts. These will come from “traditional” telescope surveys, from high-energy to radio astronomy, and will span to multi-messenger Astronomy, with the inclusion of neutrinos and gravitational wave experiments.³ The instrument covers from near-infrared to visible bands (350 – 2000 nm) and has a spectral resolution of $R \sim 4500$. It features two spectrographs: the first one optimized for the near-infrared wavelengths,⁴ while the second one optimized for the visible wavelength range.⁵ An imaging camera provides a scientific imaging mode,⁶ as well as support for target acquisition and secondary guiding capabilities.

SOXS is composed by several sub-systems, shown in Fig. 1 which here we briefly describe:

Common Path (CP): is in charge for relaying the light from the NTT focal plane to the entrance of the spectrographs. In doing that, the CP selects the wavelength range for the spectrographs (using a dichroic) and changes the focal ratio. A number of devices are present in the CP and have to be controlled by the Instrument Software (INS). The first is the entrance shutter, used to let the telescope beam in or make the instrument light-tight when performing calibrations using internal light sources. A linear motor allows to select the instrument input source: either the lamps of the Calibration Unit or the light coming from the target field on sky. Then, a motorized slide allows to direct all the beam to the Acquisition Camera, for Imaging observation, or to transmit the central part of the beam to the spectrographs, while the periphery is sent to the Acquisition Camera for secondary guiding. Two additional positions are used for calibrations and maintenance. Two separate piezo-electric Tip-Tilt Mirrors are used to compensate for mechanical flexures due to the changing of the gravity vector during observations. The CP also provides an Atmospheric Dispersion Corrector (ADC) for the visible spectrograph, which include two motors, and a linear stage providing adjustment of the focus for the near-infrared spectrograph.

Calibration Unit (CU): includes two sets of lamps for wavelength and flat-field calibration, and an insertable pinhole for alignment.

Acquisition Camera (ACQ): allows to center the source on the selected slit during target acquisition and to perform secondary guiding during observations. It can be used also as light imager in order to perform photometry and flux calibration. It is composed by a commercial *Andor iKon-M 934 Series* Camera, equipped with a deep-depletion CCD and providing a $3.5' \times 3.5'$ Field of View (FoV). ACQ also includes a linear motor for focusing, and an eight positions filter wheel.

Visible spectrograph (VIS): it is based on a new design in which the spectral band is split in narrow sub-bands, thus allowing the use of high efficiency gratings each optimized for a narrow wavelength range. Besides the fixed optics, it comprises an *E2V CCD44-82* $2k \times 4k$ CCD detector, its front-end electronics, the mechanical support and a five position slit exchanger.

Near-infrared spectrograph (NIR): this sub-unit is composed by an echelle-dispersed spectrograph working in the 800–2000 nm wavelength range. It is enclosed in a cryostat supplemented by a Cryo-Vacuum controller. Its detector system comprises a *Teledyne H2RG TM* 2048×2048 pixels hybrid infrared array detector, its front-end electronics and controller. The mechanical support, and a cryogenic, piezo-mechanic slit exchanger, with the same options of the VIS, complete this subsystem.

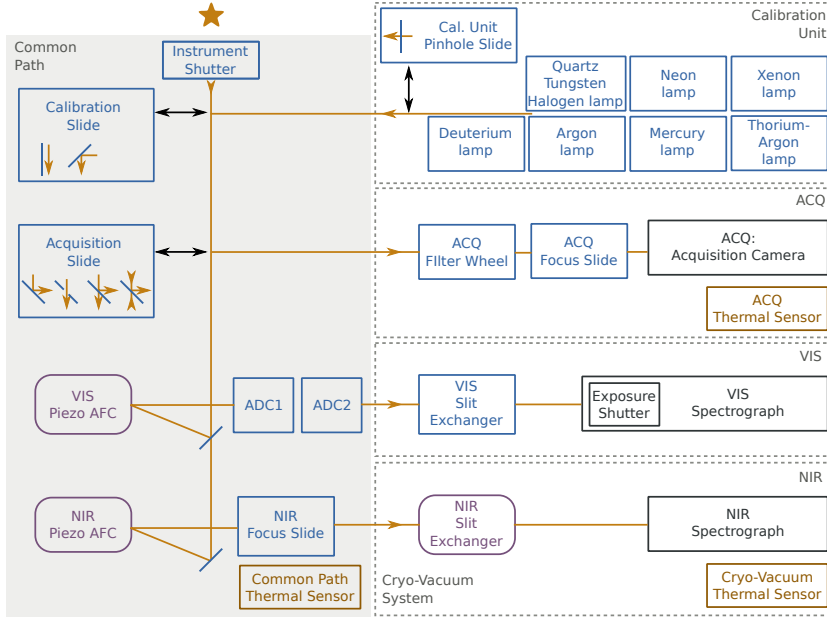


Figure 1. The SOXS instrument from the Instrumentation Software point of view. Boxes represent instrument devices, sensors and detectors. Rounded boxes represent non-VLT standard devices. The path of the light is also indicated for clarity.

Cryo-Vacuum Control Sub-system (CVS): consists of all the hardware and the electronics related to control and monitoring of the cryogenic functions for the two cryostats (enclosing the UV-VIS detector and the whole NIR spectrograph, respectively).

The SOXS project went through the Preliminary Design Review (PDR) in July 2017 and is currently approaching the Final Design Review (FDR), scheduled for July 2018. In this paper we present the current status of the Instrument Software (INS). This paper is part of a series of contributions⁴⁻¹³ describing the SOXS design and properties after the instrument PDR.

The control network architecture is presented in Sect. 2, and the overall design of the Instrument Software is described in Sect. 3. Then, we give some more details about the design of the ACQ camera software (Sect. 3.1), the flexure control system (Sect. 3.2), and the secondary guiding software (Sect. 4). The development status is treated in Sect. 5, and conclusions are presented in Sect. 6.

2. NETWORK ARCHITECTURE

The control network of SOXS is illustrated in the deployment diagram in the left panel of Fig. 2. The architecture is the typical one for control system of VLT Instruments: a number of local controllers are connected to a supervising Instrument Workstation (IWS) through an Instrument LAN, based on Gb Ethernet. Following the recently-introduced VLT standard,¹⁴ all instrument functions are controlled by a single *Beckhoff* Programmable Logic Controller (PLC). A separate *Siemens* S7 PLC is responsible for the CVS functions and sensors control. The CVS is an autonomous system, SOXS INS is not in charge of controlling but only monitoring it.

The detector controllers for the VIS and NIR channels are instances of the ESO New General Detector Controller (NGC). The respective Linux Local Control Units (LLCUs) are connected to the IWS via the Instrument LAN.

On the other hand, the ACQ camera is based on a Commercial, Off-The Shelf (COTS) component, providing an integrated controller and a USB interface. In the baseline design it is foreseen to route the USB connection to the IWS through the Observatory LAN by means of a commercial USB extender.

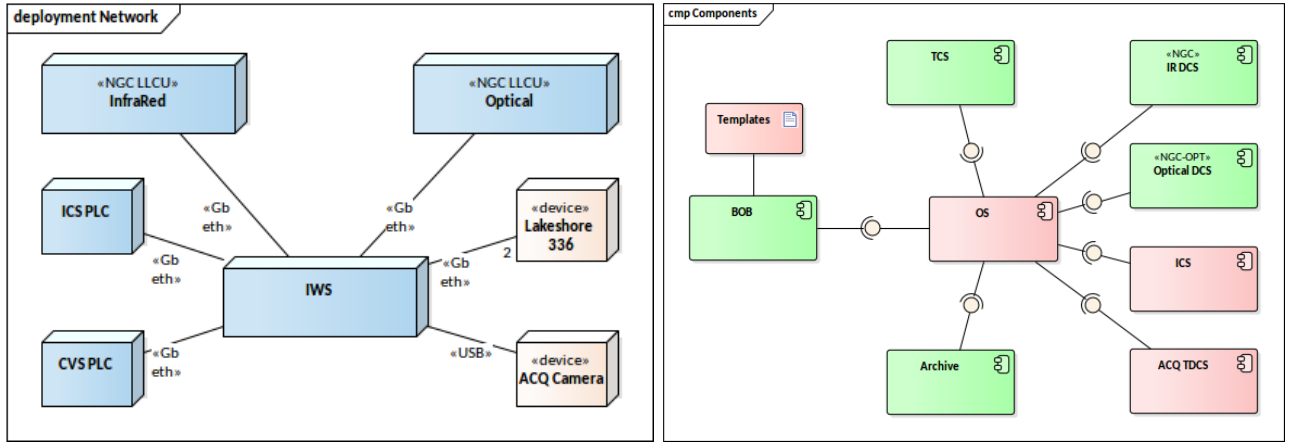


Figure 2. Left: Network control architecture of SOXS. Right: Components of the SOXS software; red boxes represent software to be configured or developed, while green boxes represent VLTSW components that will be used without modifications.

Finally, NIR and VIS detectors temperatures are controlled by means of two *Lakeshore 336* controllers, which are directly connected to the IWS through Gigabit Ethernet.

3. SOFTWARE ARCHITECTURE

The SOXS Instrument Software is in charge of the control of all instrument functions and monitoring of all sensors. It shall also manage external interfaces: with the High-level Observation Software (HOS), the Telescope Control Software (TCS), and the Archive. INS also implements all procedures relative to observation, calibration and maintenance operations, in the form of templates.

SOXS is an instrument for the NTT, and therefore it is not mandatory that it complies with VLT standards. However, given the large experience in our group in the development of control software for VLT instruments, it has been decided to adopt the VLT standards also for SOXS INS.

Therefore, the SOXS INS architecture follows the standard partitioning of VLT Instrument Software applications. All instrument functions except detectors are controlled by an Instrument Control Software (ICS), science detectors are controlled by instances of Detector Control Software (DCS), which, in this case, are based on NGC software. On the other hand, since the Andor camera is not a standard VLT component, its control software is an application based on the Technical DCS Software Development Kit (SDK) which is part of the VLTSW2016 release we are using.¹⁵

The ICS provided by VLTSW supports a number of “standard devices”, like linear stages, shutters, lamps, etc., for which no code development is necessary, but it is enough to provide configuration information (location and type of signals, motor control parameters, etc.) For non-standard devices, some development is required to properly interface them with ICS. In SOXS control system, two devices are non-standard: the piezo-actuated tip-tilt mirrors used for flexure compensation and the cryogenic piezo-mechanic stage used for slit positioning in the NIR spectrograph.

On the other hand, since the Andor camera is not a standard VLT component, its control software is an application based on the Technical DCS Software Development Kit (SDK) which is part of the VLTSW2016 release we are using.¹⁵

Operations are coordinated by a central component, the Observation Software (OS), which is also in charge of managing external interfaces. All observation, calibration and maintenance procedures are implemented as templates, which are executed by the Broker of Observation Blocks (BOB) through commands sent to the OS.

These SOXS INS components are displayed in the right panel of Fig. 2.

As already mentioned, the ACQ camera and the Active Flexure Compensation system are special components of the SOXS instrument (i.e. not directly supported by the VLT Instrument Software framework). Therefore we briefly describe them in the following subsections.

3.1 Acquisition Camera control

The imaging and secondary guiding camera of SOXS is a Commercial Off-the-Shelf (COTS) component, provided with a USB 2.0 interface for external connection. Since the SOXS IWS will be located about 3 km from the ACQ, while USB cable connections are limited to a few meters, we decided to use a commercial, switchable USB extender (*Icron 2304GE-LAN*¹⁶) to route the connection through the La Silla LAN and then to the IWS. This solution, however, has not been validated on the field, and tests are underway at the Observatory to verify its feasibility.

Therefore, a fall-back design is being considered in which an intermediate computer will be located aboard the instrument, close to the camera and directly connected to it via USB, and will act as a “software gateway” towards the IWS.

In either case, the ACQ camera control will be based on TDCS¹⁵ SDK, and its core will consist in a class providing the “communication interface” with the camera. The main difference will be that in the baseline, this class will directly interface with the Andor camera via USB, directly calling the vendor-supplied driver functions, while in the fall-back design, the communication will happen through the Instrument LAN with the mediator computer, which will then talk to the camera through its driver.

3.2 Active Flexure Compensation

Since SOXS will be installed at the Nasmyth focus of the NTT, during an observation it will change its orientation with respect to the gravity vector. This will result in some flexures which might move the target with respect to the spectrographs slit. For this reason, two piezo-actuated tip-tilt mirrors (TTM) are located in the common path and will be used to correct for this effect.

The TTMs will be commanded by INS through the instrument PLC via analog signals (one per axis). Since the TTMs are not a VLT standard actuator, a “special device” will be developed. During observations, this component will operate as a “tracking axis”, updating in a loop the position of the TTM depending on the rotator angle, via a look-up table. Since the expected loop frequency is about 1 Hz, timing constraints are not tight, so it has been decided to implement this tracking loop entirely in the IWS.

4. SECONDARY GUIDING

NTT is provided with a guide probe for automatic guiding. In order to compensate for possible differential auto-guiding errors, the option of performing secondary guiding was explored.

As a first step, we investigated the probability of finding suitable secondary guiding stars in a typical SOXS observation. To this end, we simulated images of stars of several magnitudes (from $m_r = 16.5$ to 19.8) by using the Advanced Exposure Time Calculator (AETC).¹⁷ Simulations were repeated 100 times per magnitude bin, using two different seeing values (0.8, typical value expected at La Silla,¹⁸ and 1.6 arcsec, a bad seeing scenario) and as they were observed with no filter or with the SDSS r filter. The integration time was set to one second, in order to simulate a secondary guiding loop with a frequency of 1 Hz. All other values used in the simulation (telescope and instrument transmission, atmospheric extinction, efficiency of the detector, etc.) are consistent with the NTT, the La Silla Observatory, and the ACQ parameters. Then, simulated star positions were fitted with a 2D Gaussian function, and the error and the Root Mean Square (RMS) between the expected and retrieved position of the centroid were calculated. Results show that, by using the ACQ camera in SOXS at the NTT, it is possible to measure the center of a star brighter than $m_r = 19$ with an RMS of less than 0.1 arcsec, which is the specification for target stability on SOXS spectrographs slit.

Furthermore, we simulated 10 000 random telescope pointings on the sky observable from the NTT. For each pointing we counted the number of stars brighter than $m_R = 19.0$ in the ACQ FoV, available in the General Star Catalog II (GSC2).¹⁹ Our results indicate that in more than > 95% of pointing, at least one suitable guide star can be found in the GSC2.

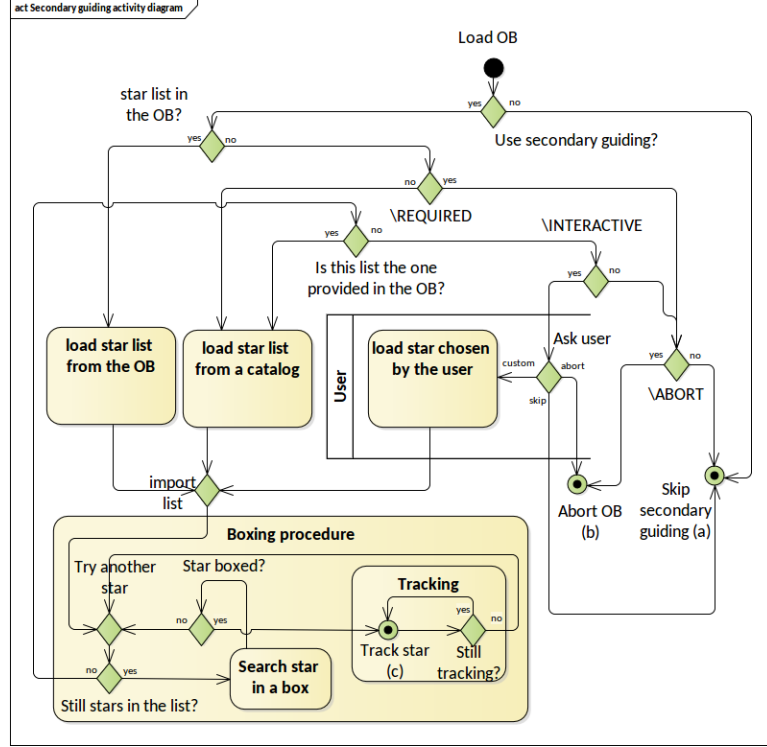


Figure 3. SOXS Secondary Guiding (SG) sequence diagram. Possible scenarios include running the Observation Block (OB) without the use of secondary guiding (a), aborting of the OB (b), or successfully track a star (c). Fallbacks are controlled by a series of flags in the OB: “REQUIRED” determines if the guiding star must be provided in the OB; “ABORT” determines whether to skip SG or abort the observation; “INTERACTIVE” determines if a user interaction is foreseen.

From this analysis, we can conclude that secondary guiding in SOXS is feasible for the majority of observations.

During spectroscopic observations, the central 15'' (diameter) of the observed field will be transmitted to the spectrographs, while the rest will be visible in the ACQ imager. A reference star will be selected in the ACQ field and used to check for guiding errors. A secondary loop will run in SOXS IWS, at a lower frequency with respect to the telescope auto-guiding, and will use the reference star to measure error vectors and compute corrections, which will be sent to the telescope as offsets.

Since SOXS is expected to perform observations of transients it is desirable that its operations are as automatic as possible, with little user interaction. This has been taken into account in designing the secondary guiding star acquisition procedure shown in Fig. 3.

If the observation foresees secondary guiding, a list of information about suitable guiding stars in the target field (expected position, expected brightness) may then be provided in the OB, and this requirement can be either mandatory or not. In a positive case, a boxing procedure is called. This procedure consists of a series of operations to select a guiding star candidate from a list, search it in a box, and track it. If the guiding star list is not required nor available in the OB, or the list provided in the OB does not help to successfully find an object to track, then another star list from a catalog will be loaded. The boxing procedure will then be called on this catalog list. In case of failure of the boxing procedure, the user intervention may be asked to skip the guiding, to abort the observation, or to pick manually a star in the Acquisition Camera FoV, in order to repeat the procedure.

5. DEVELOPMENT STATUS

The Software Development Process, mandated by ESO for a VLT Instrument Software, foresees that no code is written until the Final Design Review has been successfully granted.

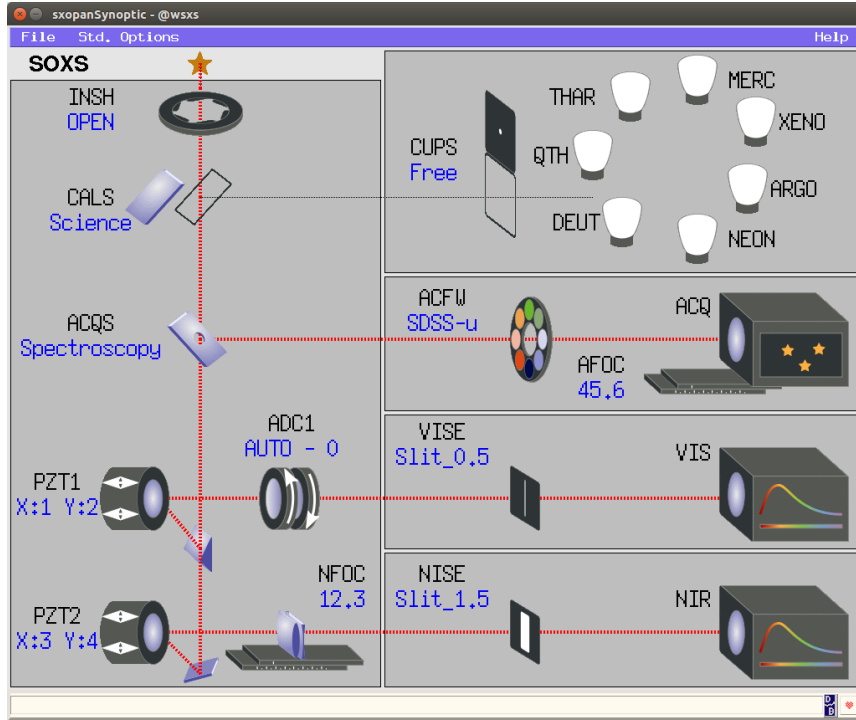


Figure 4. SOXS Synoptic panel, showing a configuration in which light is directed to the acquisition camera.

In the SOXS case, however, we decided to proceed differently. First, because we were not bound to closely follow the VLT “rules”, but also because SOXS, being similar in design to X-Shooter, shares many operational procedures with it, and so we could take the existing X-Shooter INS as guidance.

Thus, during the design phase, we adapted the template Instrument Software, provided by the VLTSW, to the SOXS case, and started configuring standard (software) devices. Dummy configurations were prepared for the two science detectors (because the real ones are not available yet). The template TDCS implementation was used for the technical camera. This allowed us to run SOXS INS in full software simulation and to start implementing and testing templates. Procedures for starting-up and shutting-down the software have been written, and a few user interfaces have been implemented. Figure 4 shows the current implementation of the Synoptic panel, which is intended to provide a quick graphical representation of the current instrument setup.

Automatic tests have also been implemented, which exercise software build from scratch, testing of the instrument functions, the detector control software, the observation software and, finally, all templates. Currently, roughly the 50% of observing templates, mainly concerning calibration procedures, and the 20% of maintenance templates have been completed.

6. CONCLUSION

We presented the general software architecture of the SOXS instrument for the NTT, a double spectrograph with an imaging and guiding camera, and its peculiar features in terms of hardware (guiding camera and camera connection) and software solutions (special devices, secondary guiding).

The instrument software is based on the VLT Common Software for the management of standard devices, which have already been configured in simulation, and on custom software for the management of special devices, i.e. the piezo-electric actuators for flexure compensation and the piezo-mechanic slit exchanger for the near-infrared spectrograph.

Spectrograph detectors are managed using ESO NGC controllers, while the COTS imaging camera is managed through a custom component based on TDCS. We also presented a default (USB extender) and a fallback (single-board computer) scenario for the connection of the imaging camera to the instrument workstation.

Observation and Maintenance software have been completed mainly for what concerns calibration (Dome Flats, Bias, Lamps, Motor tests), and we estimate that about 40% of SOXS templates are completed, while development is ongoing for remaining templates.

Imaging camera is also responsible for secondary guiding. We presented a sequence of operations that minimize user intervention, and we calculate that the probability to find at least two tracking star candidates in the Field of View of the camera is $> 95\%$.

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