The ELT Control System: recent developments

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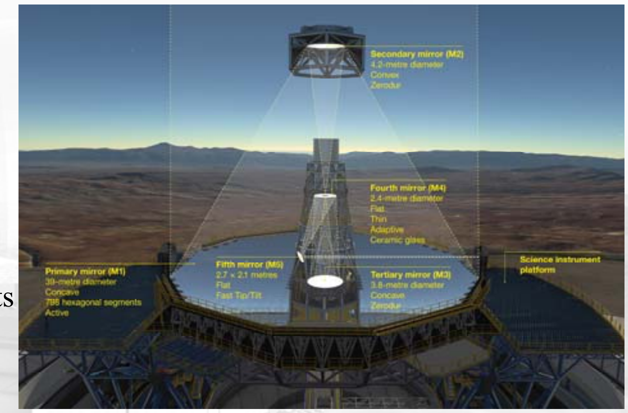
Outline

- The ELT
- The ELT Control Strategy
- Control System Architecture
- Local Control Systems
- Central Control System
- Conclusion

- More on paper and references:
  - RTC and Adaptive Optics, The Minuscule ELT, Common Software Infrastructure

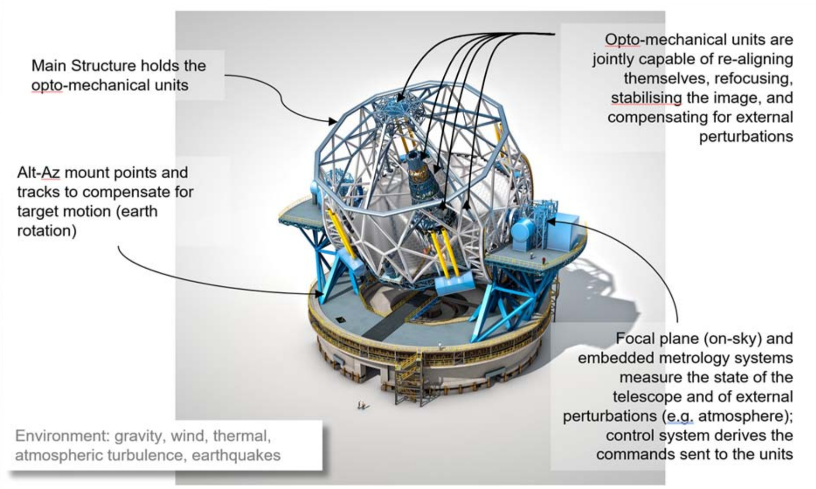
The ELT

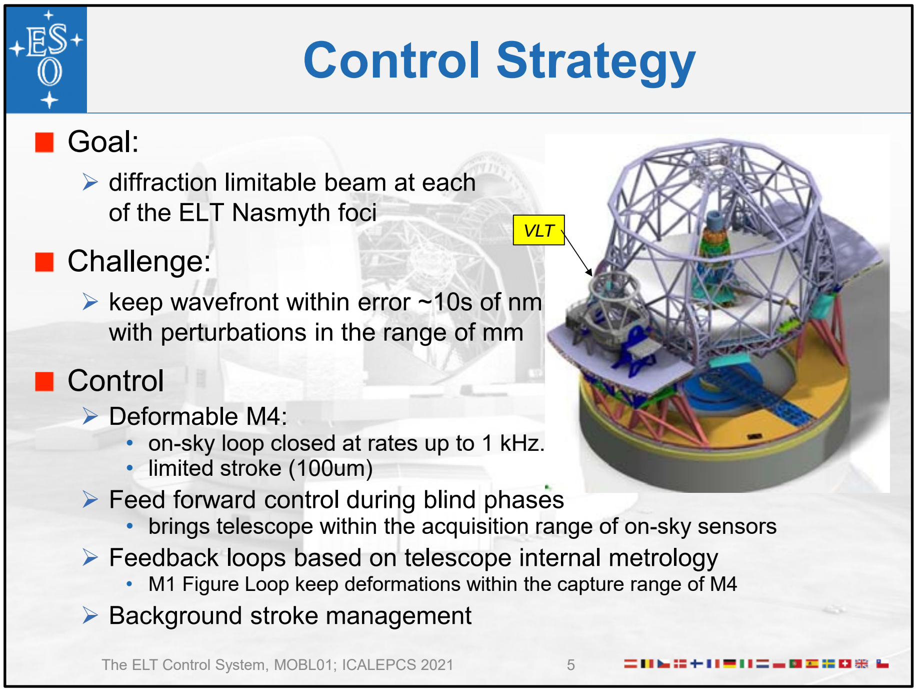
- Large segmented telescope
- 5-mirror scheme
- 10000 tons, 25000 sensors, 15000 actuators
- M1 (39M): 800 1.4M segments
- M4 (2.5M): 5300 actuators
- 6 instruments
- Many distributed control loops: from 0.01Hz to kHz.
- Distributed control requiring synchronization to ms.



Chile, Atacama desert, 3000m
M1: 800 1.4M segments individually controlled in piston, tip, and tilt, several types of sensor data, totalling 24000 I/O points

The ELT Telescope Structure





The goal is to control the telescope enabling the delivery of a diffraction limitable beam at each of the ELT Nasmyth foci, i.e. where the light beam is transferred to the instruments. This means the "spectrum of wavefront aberrations induced by the observatory is below that of the free atmosphere."

The main challenge is to provide a wavefront with an error in the range of 10s of nm in the presence of perturbations that can be in the range of mm (in the case of gravity deformation when changing the telescope pointing)

Most important role in control strategy played by the deformable quaternary mirror (M4). It is controlled in an on-sky loop using stellar light with large temporal and spatial bandwidth. Requires a deformable mirror of unprecedented size (2.5m, 5000 actuators).

M4 on-sky loop closed at rates up to 1 kHz. The limited stroke (100um) of the M4 actuators and the limited capture range of the wavefront sensors exclude that the wavefront can be controlled solely by M4, but requires it to be supported by several additional control systems.

Feed-forward control during the "blind phases" when on-sky loops are open. E.g. a pointing system is used to preset to a new target, with the feed forward model taking into account astrometry and telescope deformations due to gravity and temperature

Feedback loops based on internal metrology control the state of the telescope. E.g. M1 control system moves segments in piston, tip, and tilt (2394 degrees of freedom) to control shape of M1 based on relative displacements using 4524 Edge Sensors. The M1 Figure Loop reduce relative edge displacements to several nm keeps low order deformations within the capture range of M4.

Background Stroke Management redistributes slowly building non-zero-mean components in low order modes of M4 to other degrees of freedom:

- tip and tilt modes are controlled in a collaborative control scheme together with M5 and Telescope Main Axes (Field Stabilization)
- focus and coma are transferred to M2 occasionally, at most every 5 minutes
- higher orders are offloaded to M1 by commanding the low pass filtered modal amplitudes accumulated on M4 to the M1 figure loop control system.

Moving optical surfaces changes the wavefront error measured by the Adaptive Optics system and causes the M4 to desaturate, i.e. saturation management requires a closed on-sky loop.

Unprecedented size of ELT is expected to lead to surprises during commissioning.
Changes in the control strategy are hence expected
The control system is built such that well understood subsystem control is decoupled from less defined high-level (on-sky) control.
The latter one is developed in a way that allows for the flexible adjustment of algorithms during commissioning.

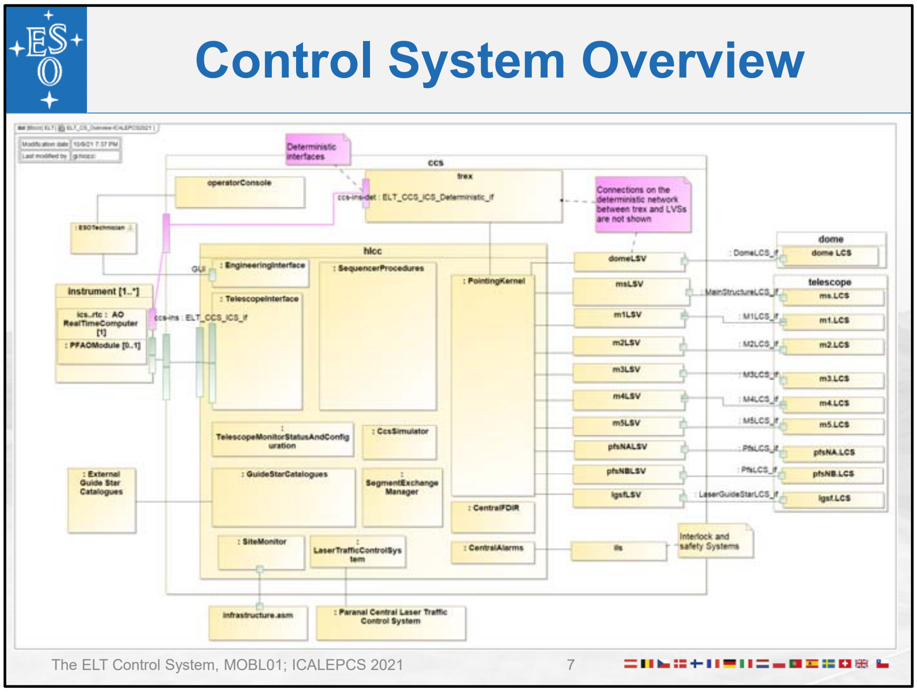
ELT CS architecture drivers

Architecture drivers:

- Subsystems contracted to industry.
- Instruments developed by consortia.
- De-coupling of subsystems
- Flexible at AIV/Commissioning
- Obsolescence management

Foundation's status, June 2021

Industry -> LCSs (organizational boundary) -> strong ICDs, Ethernet
ESO CCS -> LSVs + high level coordination
De-coupling -> anonymous pub-sub
Always capable of reconstruct state from measurements
Look at paper and references for more details



Here you can see a simplified view of the control system, with the main components.

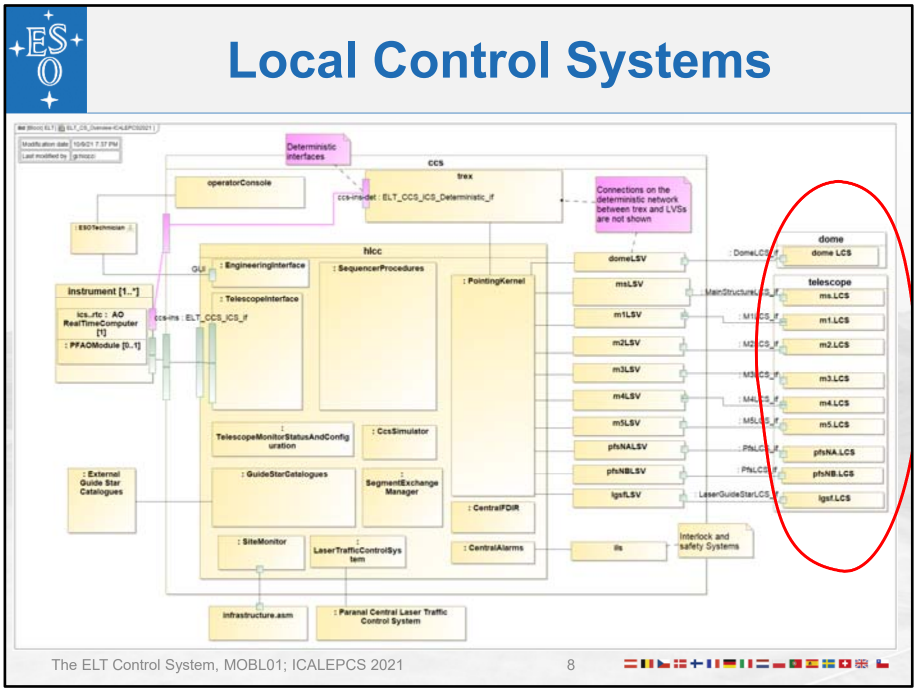
The architecture enforces a distinction between a telescope device (*the System Under Control - SUC*, e.g. the M2 unit) and the component controlling that device (*the Control System - CS*).

As a system of systems, the ELT contains layers of controllers. A lower level component comprising a CS and SUC appears as a SUC to a higher-level CS.
For example, the primary mirror segment position actuators (PACT) with embedded position controller and course and fine stage actuators appear as components of the SUC to the M1 CS responsible for figure control.

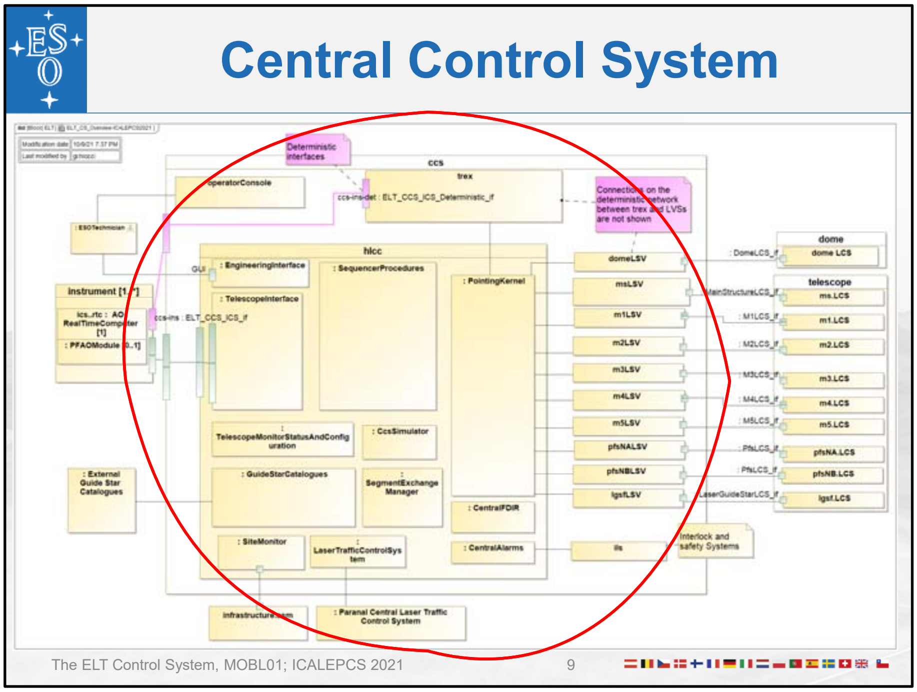
First breakdown

- Local Control Systems (LCSs): individual control systems associated with Telescope subsystems -> contracted to industry
- Central Control System (CCS): single system that integrates these -> ESO development, scientific domain and integration
- Instruments Control System: consortia using ESO provided framework

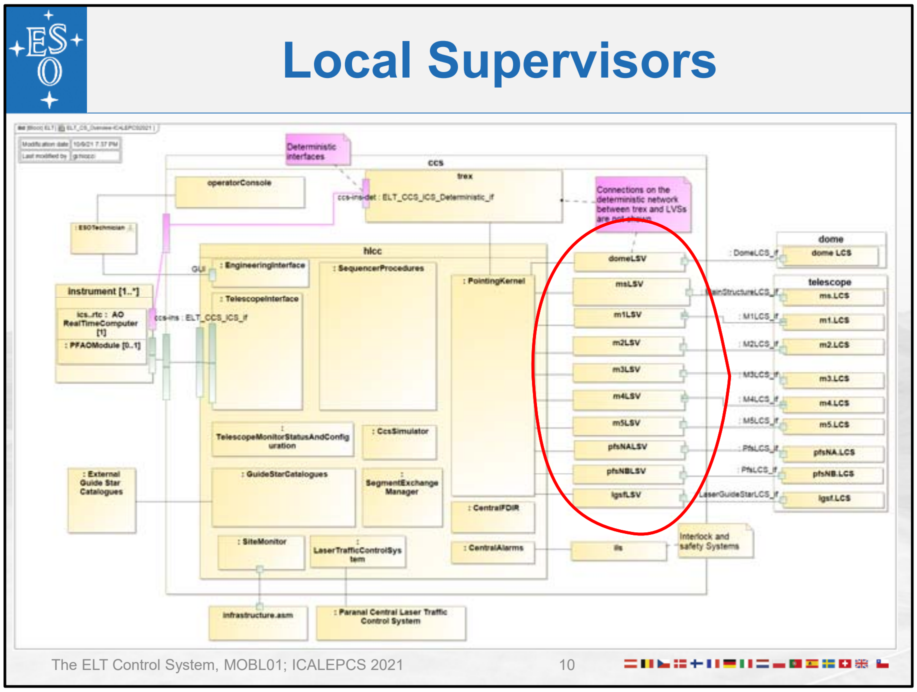
Strict interface management



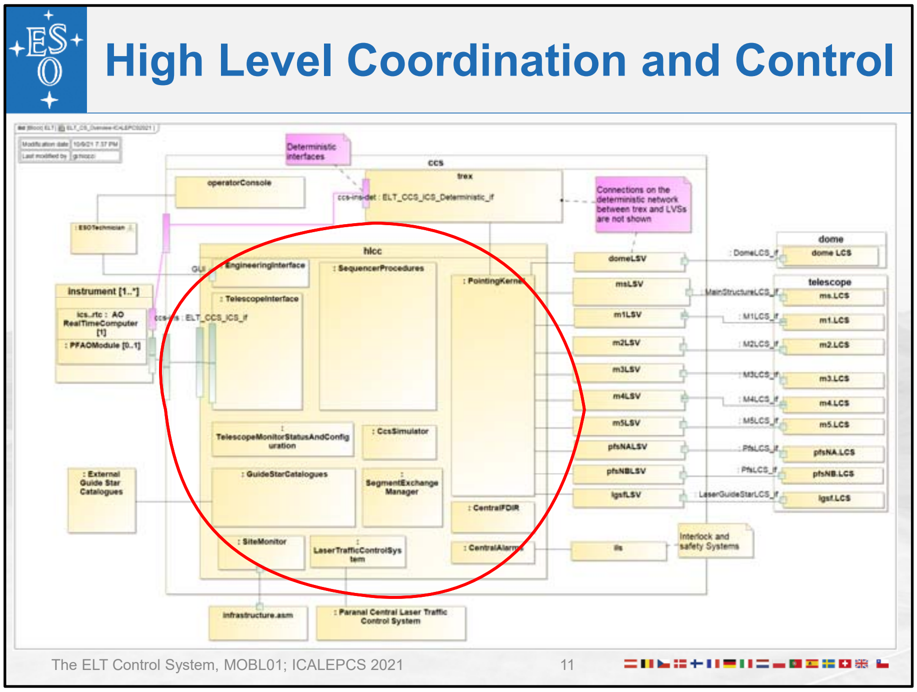
- Talk to the hardware
- Control and Safety
- No assumptions about the nature of the subsystem use in the context of the telescope control
- Individual and independent control of subsystem devices and functions
- Contracted to industry together with HW (Exceptions: M1 and LGSs). Their can use their technological expertise.
- ESO follow up
- Definition of ICDs critical
- Design done, HW being produced, CS being implemented



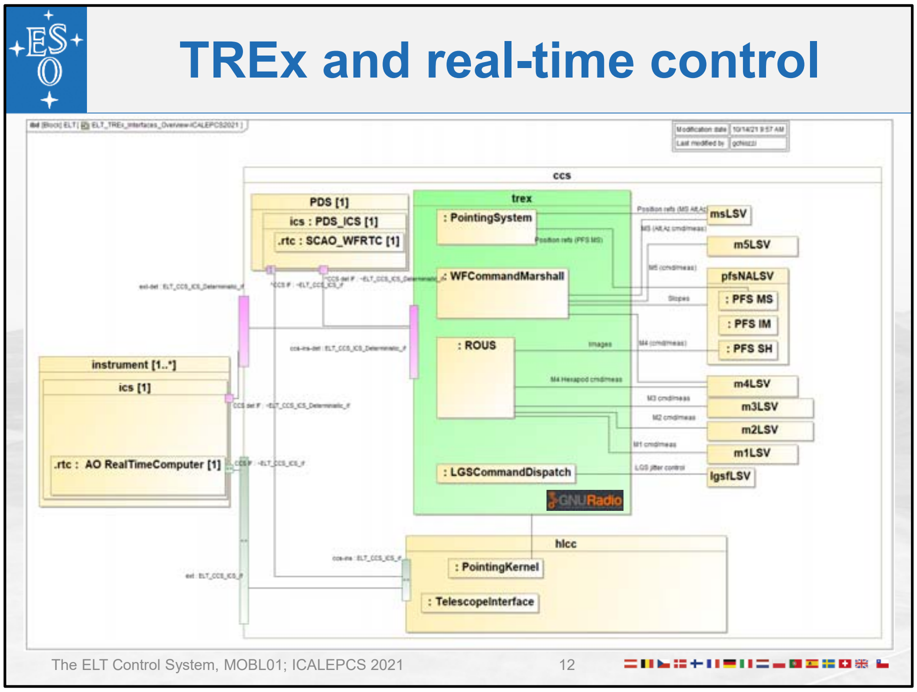
- integrates the Local Control Systems into a single system
  - implementing the coordinated control, system level safety, monitoring and user interfaces required to operate
- provides monitoring, logging and archiving for long term trending and configuration control
- Developed at ESO -> scientific domain knowledge
- Common SW infrastructure:
  - communication: zmq, dds
  - services: configuration, online database, central logging…
  - application framework:
    - state machines interpreter engine (SCXML)
    - state variable pattern
    - *Estimator-Controller-Adapter* pattern (JPL state analysis)
      - Adapter -> communicated with SUC
      - Estimator -> receive via adapter measures from SUC and extimates SVs
      - Controller -> commands SUC via adapter
  - decoupling by anonymous pub/sub and shared online DB



- 1-to-1 LSV-LCS
- implement subsystem telescope domain logic and translate the telescope concepts into the device domain
  For example,
  - M1 LSV is responsible for controlling and maintaining a certain optical quality of the whole telescope primary mirror surface
  - M1 LCS is managing the actuators and sensors installed on each segment of the mirror
- Independent and decoupled subsystem functions
- Prototypes and design mostly completed; implementation started



- Single interface of the whole telescope toward operators and instruments control software
- Coordination of telescope functions
- Challenge: flexible system to be extended/modified during AIV/commissioning
- Our strategy: design/implement by Features:
    - independent supervisory applications designed to perform a complete operational function/use case of value to the users of the system.
    - Sequencer Procedures (initially) in interpreted Python, accessible to the commissioning team (not necessarily SW developers)
- Prototypes being developed, under detailed design

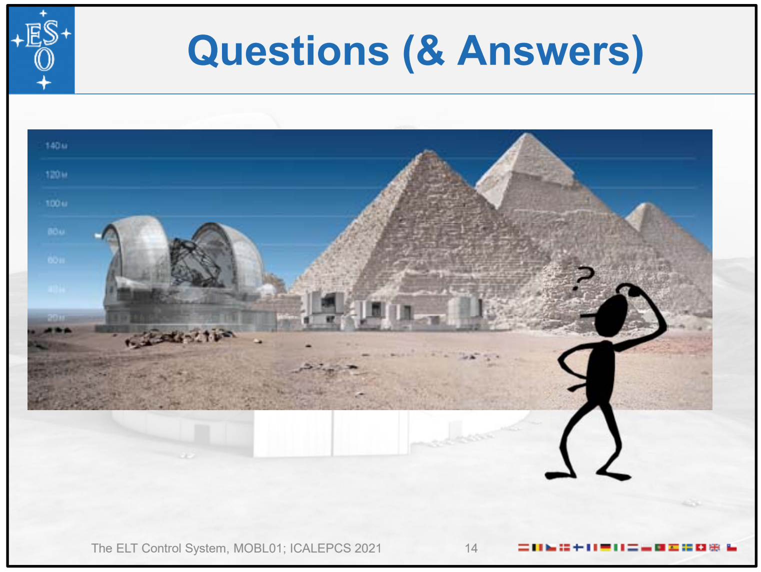


- Real-time control loops are allocated to the Telescope Real-time Executor (TREx)
  - communicates directly with instruments, LSVs and LCSs using, when necessary, the deterministic network
  - is commanded and monitored by HLCC
- Under requirements analysis
  - flexible software framework for real-time control applications
  - must be suitable for use by control engineers
  - visual programming environment, comprising a palette of data analysis and algorithmic building blocks, is foreseen
  - should not require detailed knowledge of SW real-time systems when mapping the application to the underlying hardware resources.
- Demonstration prototype implemented in 2019 based on GNU Radio and used in MELT
  - free open-source development toolkit to implement signal processing tasks
  - GUI usable by non SW engineers
  - good C++ and Python integration
  - 1kHz loop rates are reliably achievable

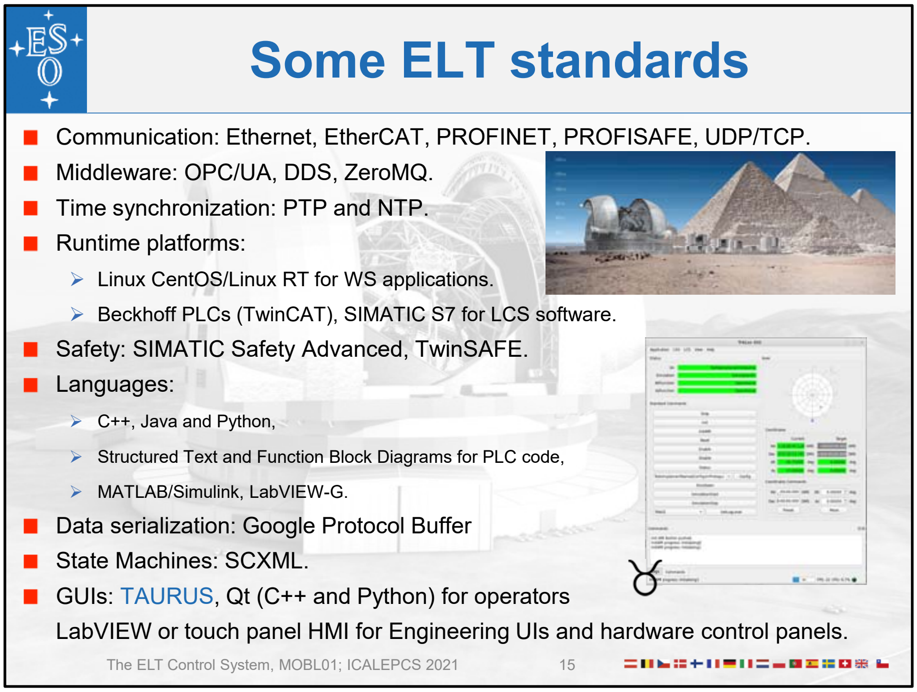
- 2kHz loop rates may be possible.

Conclusions

- Reqs, architecture, design carried on in the past years.
- Most subsystems (LCSs) contracted out and in production.
- Technical infrastructure and prototypes have been developed.
- We are now moving to serial development of system components (HLCC, LSVs, RTC, AO).
- Requirements for TREx real time components are being collected and design will follow.
- Validation test benches (MELT) are operational
- Scientific First Light is foreseen for end 2027



Here you can see an artistic impression of the ELT side by side with the piramids and the VLT telesco
While you think about questions, I will leave you with a “casual” list of tools and standards we have



Ensure consistent level of quality
Standards collected in set of documents, applicable to any ELT control system development
Alternative solutions for well justified particular purpose not excluded, but subject to approval