Telescope Control System of the ASTRI SST-2M Prototype

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for the CTA ASTRI Project

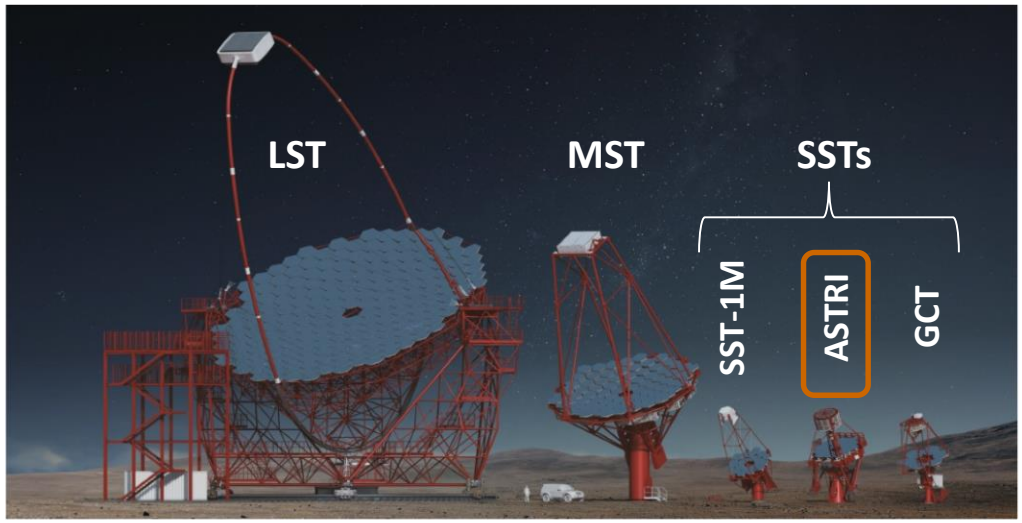
Overview

- ✓ The Cherenkov Telescope Array, CTA
- ✓ ASTRI concept of the Control System and General Architecture
- ✓ Real-Time control systems
  - Technology applied
  - Hardware Architecture and implementation
  - Software Architecture and implementation
- ✓ High level Controllers
- ✓ Summary

CTA, the Cherenkov Telescope Array

The CTA Observatory:

- **Two arrays**, one in **N**orthern one in **S**outhern hemisphere, (**N**, La Palma, Spain; **S**, Paranal, Chile) to provide all-sky coverage;



- **Three classes of IACT telescopes**, Large, Medium and Small Size to cover the very-high-energy gamma-ray range from 20 GeV up to 300 TeV.

	Large Size, LST	Medium Size, MST	Small Size, SST
# of telescopes	N(4), S(4)	N(15), S(25)	N(--), S(70)
Energy range [TeV]	0.02 - 1	0.1 - 10	1 - 300
Field of View [deg]	4.5	8	> 9
Dish diameter [m]	23	12	4

The ASTRI Project

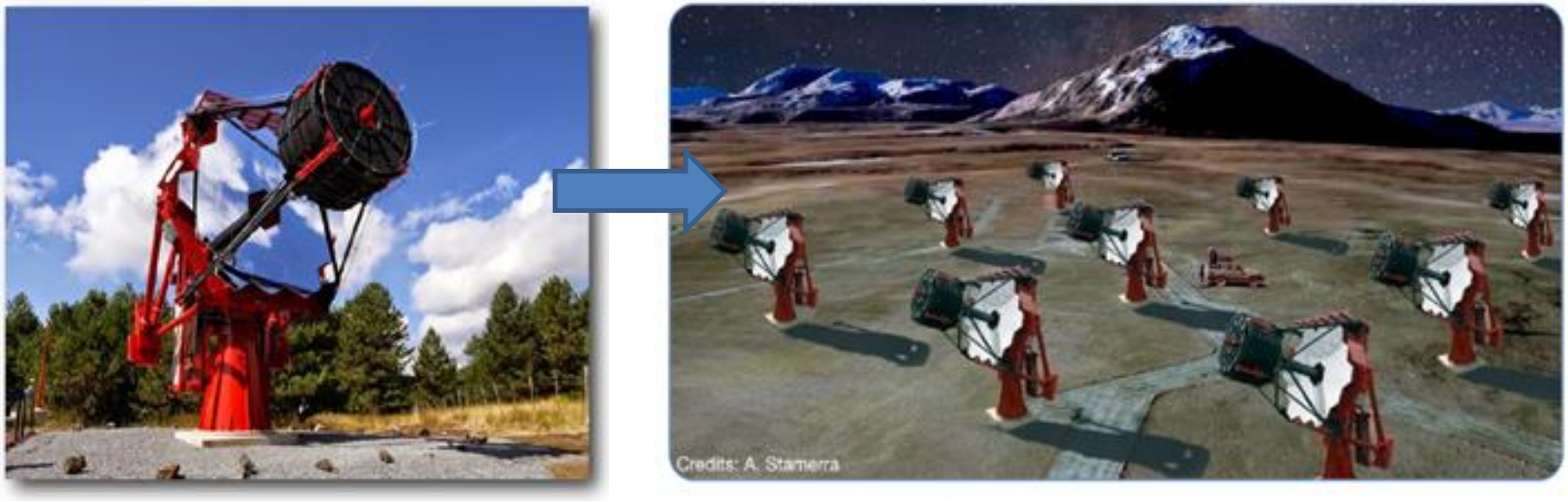
In the framework of CTA, the Italian National Institute for Astrophysics (INAF) leads the ASTRI project and has developed the dual-mirror ASTRI SST-2M end-to-end telescope, prototype for the CTA Small Sized Telescopes.

- **The ASTRI SST-2M prototype is installed at the INAF observing station located at Serra La Nave, on Mt. Etna (Sicily)**
- **It has been inaugurated on September 2014 during the CTA Consortium Meeting in Sicily.**
- **Mechanical commissioning and optical validation stages are successfully done and it is currently undergoing the scientific verification stage.**

Technological prototype, devoted to allow us the measurements of optical and pointing/tracking capabilities, showing the response and reliability of the various subsystems.

ASTRI SST-2M : The Future

A first set of nine ASTRI telescopes (mini-array) is planned to be produced for the early implementation of the southern CTA site.

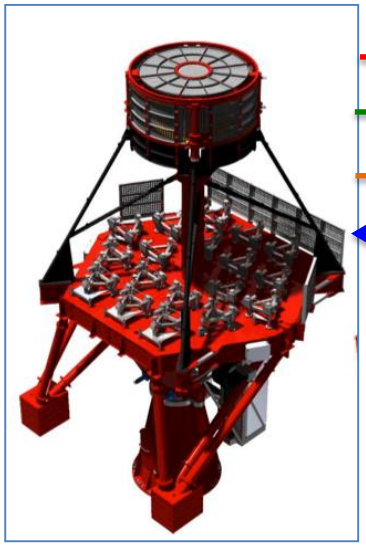


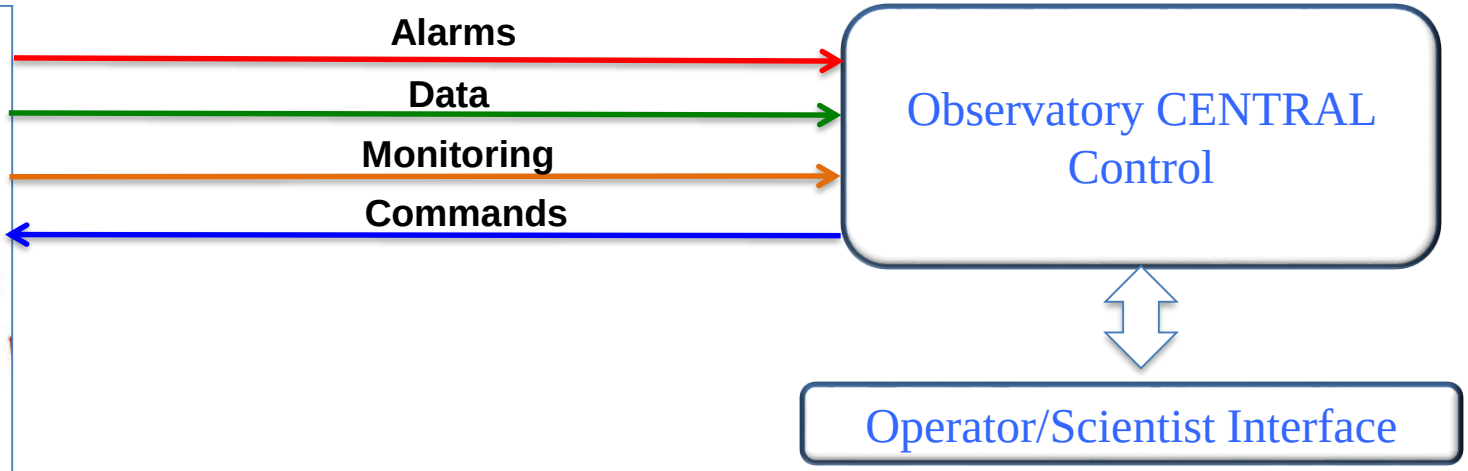
The ASTRI SST-2M Telescope Control System serves as a prototype for the Control System of the future ASTRI mini-array.

ASTRI SST-2M Control: The Main Concept

- **Stand-alone, intelligent and active machine, able to efficiently perform all the required engineering and operative functionalities, to receive commands, to transmit monitoring data and eventually recover errors.**

- **Easy to be integrated in an array configuration.**



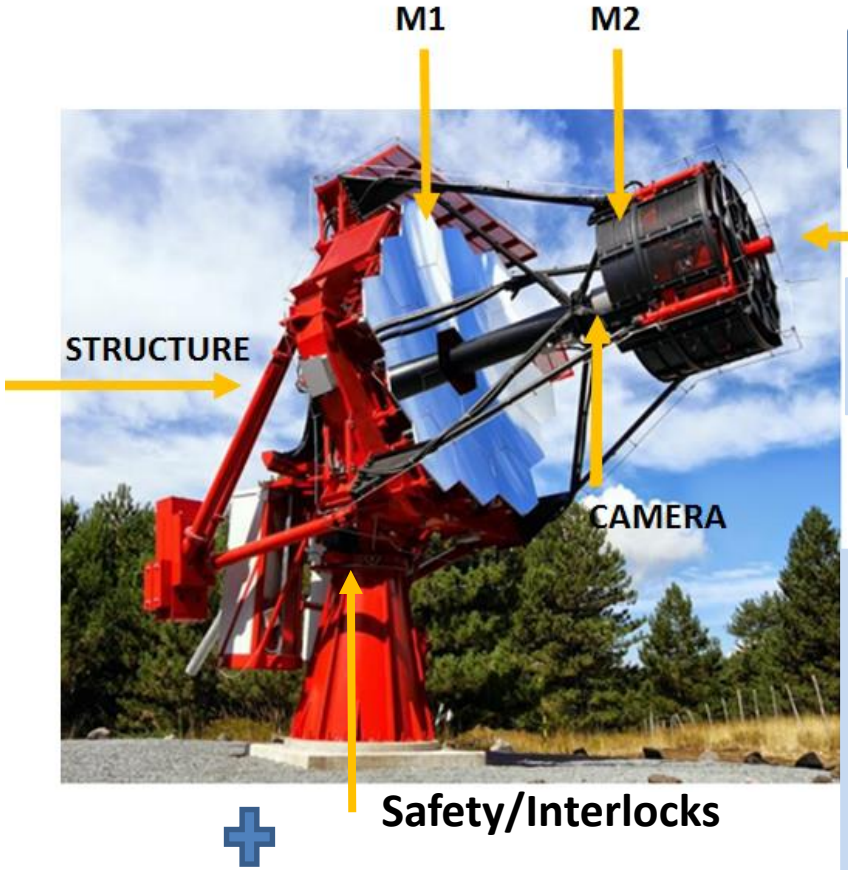


FUNDAMENTALS

Appropriate Synergy between the Telescope hardware (Mechanical structure, optical system…) and Control System (Hardware & Software).

ASTRI SST-2M Control: The Main Concept

The ASTRI SST-2M is composed of a complex set of devices and the control systems are responsible for running them correctly executing commands received from the external controllers (Telescope Control System and Graphical User Interfaces), whose task is the coordination of the various subsystems.



Auxiliaries

- **Weather Station**
- **UVScope (NSB Calibration)**

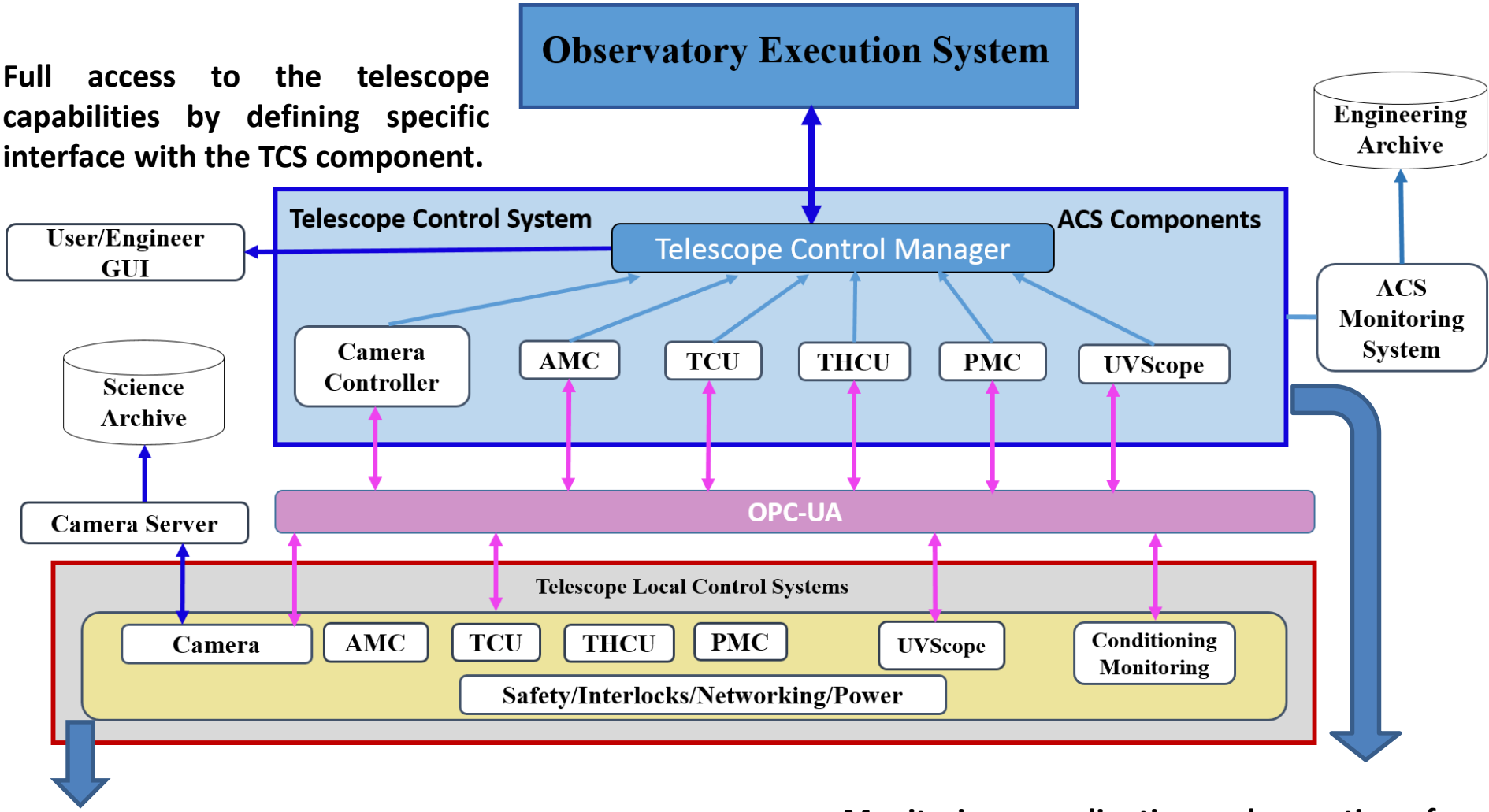
ASTRI SST-2M is designed to be a stand-alone active telescope

All the components have to be managed by specific controllers to perform the required functionalities

- **Pointing and tracking (Structure)**
- **Pointing/tracking Calibration (PMC)**
- **Position, tilt and Mirror Control (M1 and M2)**
- **Camera detection**
- **Health and switching on-off the sub-devices**
- **Maintenance, test and Calibration activities**
- **Safety procedures**

Telescope Control : General Architecture

Full access to the telescope capabilities by defining specific interface with the TCS component.

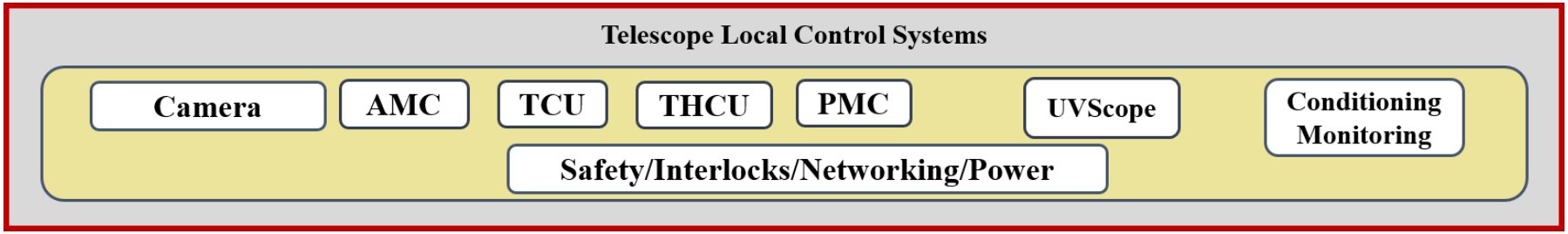


- Telescope Hardware and auxiliaries controllers.
- Auto consistent real-time functions development.

- Monitoring, coordination and execution of the hardware functionalities.
- No direct hardware control
- No responsibility for time-critical operations.

Real-Time Control : Local Control System

Real-Time Local Control includes the control of the Mount structure, the controllers dedicated to the health and safety systems of the telescope and the control of the Active Optics.



Active Mirror Control (AMC)

Position and tilt of Primary and Secondary mirrors

Safety PLC

Execute Safety procedures and actions based on Interlocks signal and logic chain.

Telescope Control Unit (TCU)

- Motion of the Mechanical structure
- Start-up/Shut Down procedures
- Pointing/tracking
- Procedures needed for the maintenance, testing and calibration activities.

Telescope Health Control Unit (THCU)

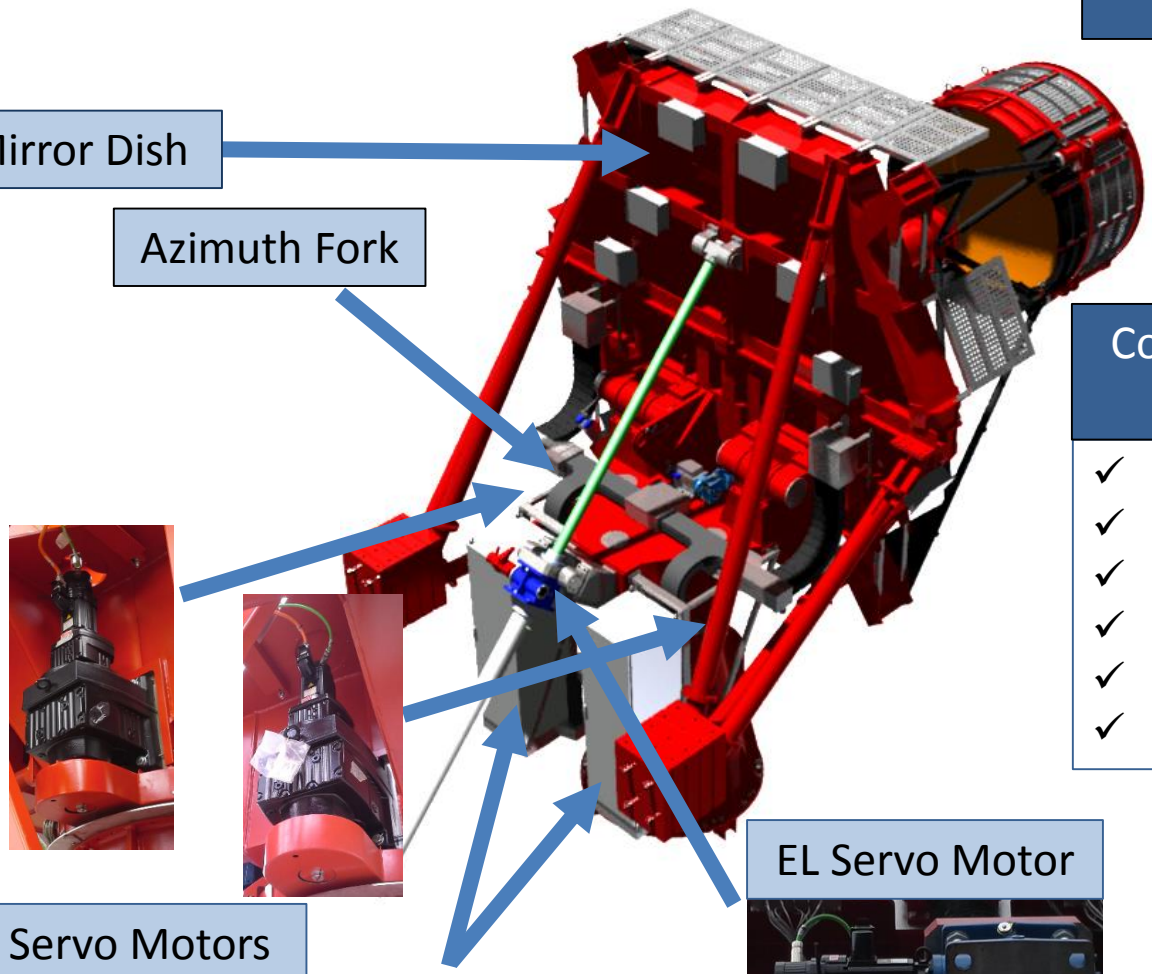
- Handling I/O signals (Interlocks)
- Health monitoring of the telescope
- Power Consumption monitoring
- Switching on/off the telescope components (e.g. camera, actuators).

- **PC-Based Programmable Logical Controller Technology (PLC).**
- **Each component has is own PC in which the related PLC is running independently**

The Mount Structure

Mechanical structure and components designed to allow for accurate pointing and tracking.

Altitude – Azimuthal Design



Compliant with CTA requirement for the Small Size Telescopes

- ✓ AZ Range : ± 270°
- ✓ EL Range : -1° to 90°
- ✓ Max AZ speed : 4.5°/s
- ✓ Max EL speed : 2°/s
- ✓ Positioning accuracy : < 12 arcsec
- ✓ Tracking accuracy : < 6 arcmin

The Security System

Interlock chain : In order to guarantee the maximum safeguard for the human operator during maintenance and commissioning activities and for protecting the mechanical structure during normal operations.

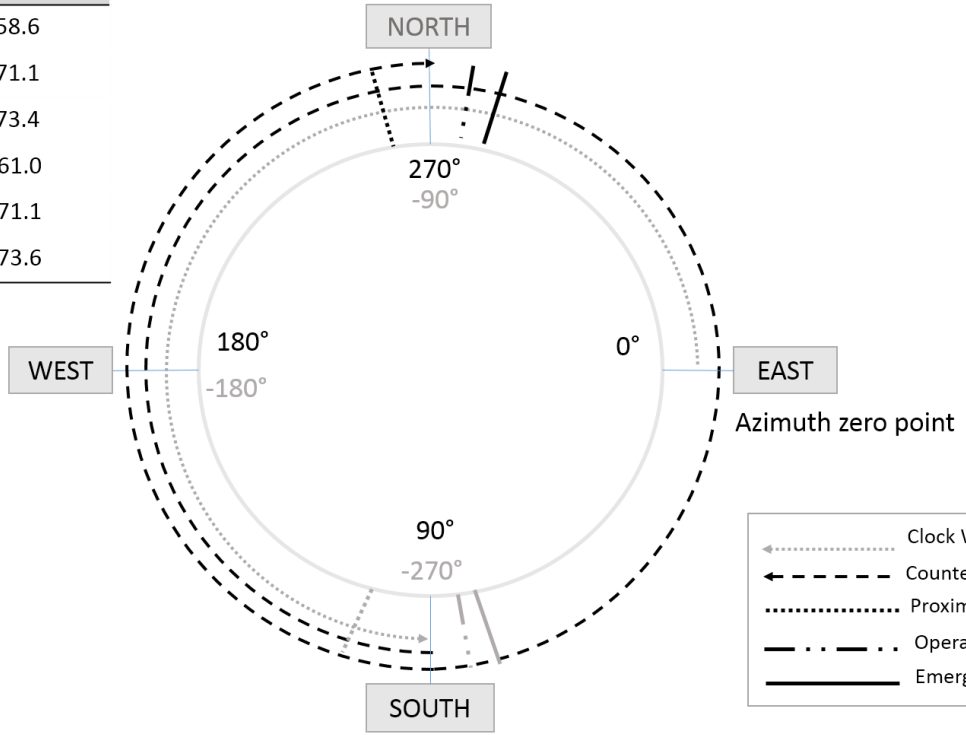
Compliant with CTA requirement and IEC 61800 standards directive for safety

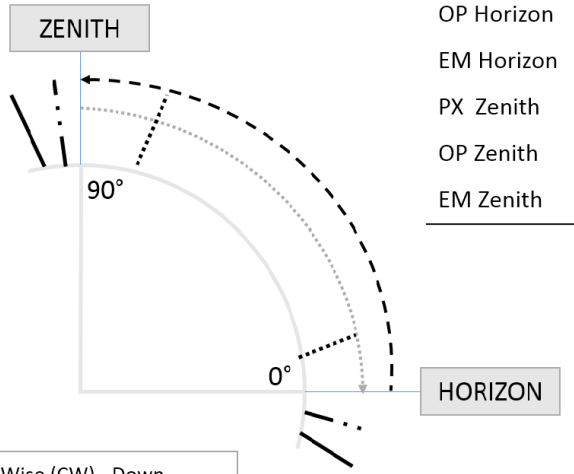
- Emergency Limit Switches (EM)
- Operational Limit Switches (OP)
- Proximity Inductive Switches (PX)

- 3 Emergency Stop buttons
- Base and Cabinets doors opening switches

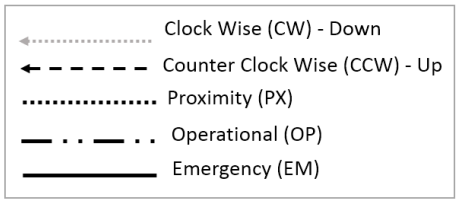
- Az and EL Stow pins insertion/Extraction systems

Switch	Position [°]
PX CW	258.6
OP CW	271.1
EM CW	273.4
PX CCW	-261.0
OP CCW	-271.1
EM CCW	-273.6



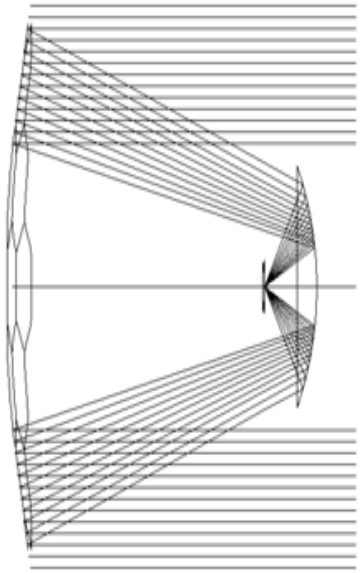


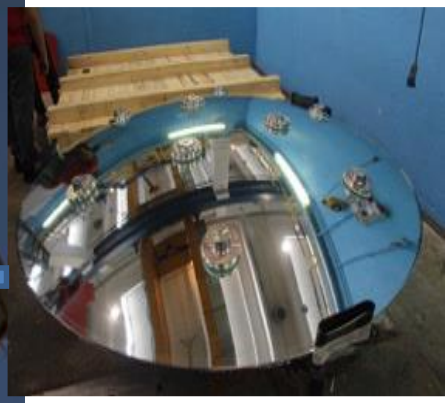
Switch	Position [°]
PX Horizon	3.8
OP Horizon	-0.6
EM Horizon	-1.3
PX Zenith	87.1
OP Zenith	91.2
EM Zenith	92.2



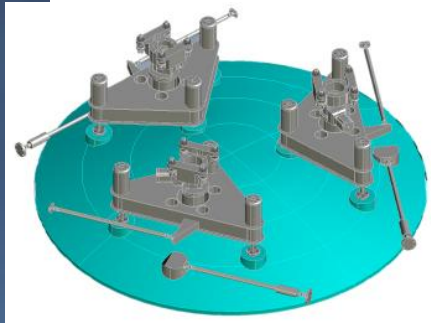
The Optical System

Dual-mirror Schwarzschild-Couder (SC) configuration

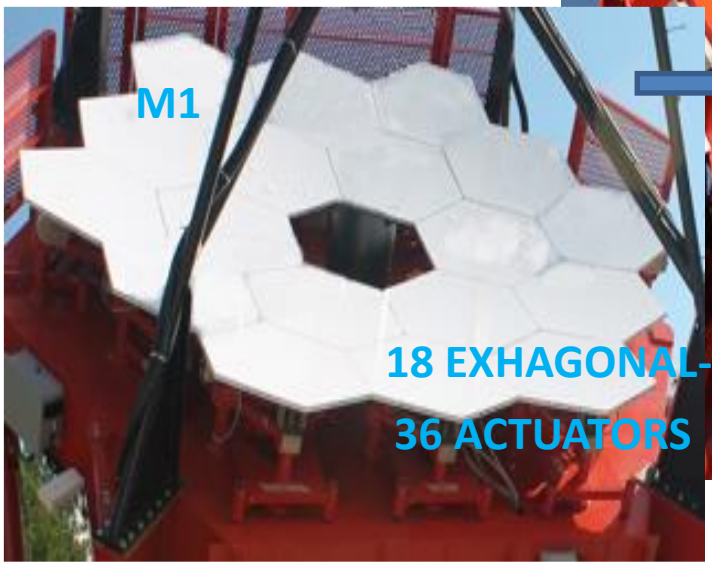




M2 Monolithic

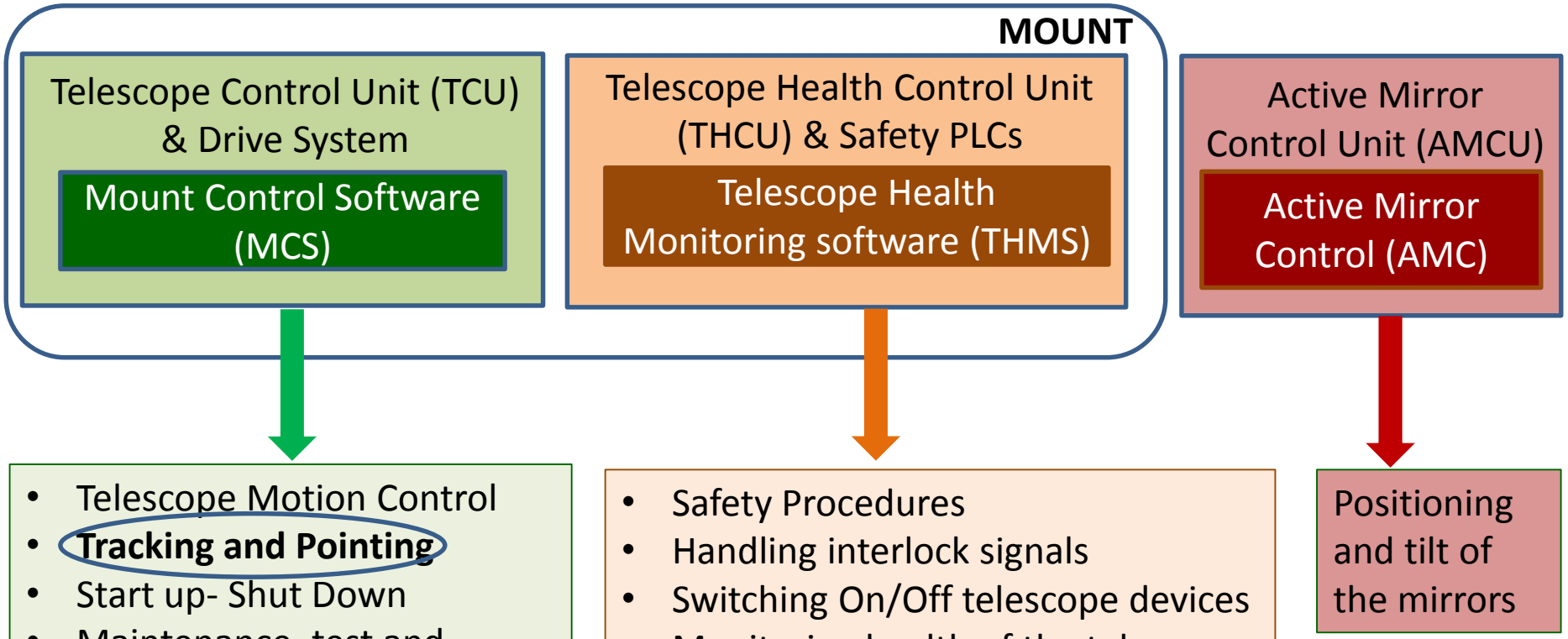


3 ACTUATORS



Real-Time Control : Local Control System

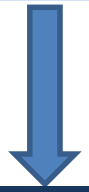
Separate sets of dedicated electronics and software packages



Performance of the control system is a critical point

In particular the pointing and tracking performances depend on the choice of the drive system, on the control electronics, and on the software controllers

- **Compactness ->** PCs and I/O modules are small and fully integrated in the electronics cabinets attached to the telescope.
- **Software Depenability ->** PLCs are programmed in a set of domain-specific languages (standardized as IEC61131-3) and PLC run-time system ensures reliable execution of the code in real-time.
- **All-in-one solution ->** the PLC executes the control logic in real-time and offers the remaining CPU time to the operating system, the Human Machine Interface (HMI) application, and an OPC Unified Architecture (UA) communication server.
- **Extensive development environment ->** The development environment comprises a set of features able to facilitate the implementation of the code, the debugging and possibly HMI applications.



High real-time performance in a very compact assembly

Real-Time Local Control : Hardware Development

PC-Based control technology : **Beckhoff** industrial PC and software Programmable Logical Controllers (PLCs) based on **TwinCAT 3** environment as development platform

BECKHOFF

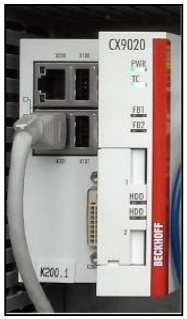
Beckhoff Industrial PCs for control cabinet installation

TCU

- 4-core Industrial PC C6930-0040
- Windows 7 64 bit system
- 3rd Generation Intel Core i7 processor with 8 GB RAM

AMCU

- 2-core Industrial PC C6930-0040
- Windows 7 64 bit system
- 3rd Generation Intel Core i5 processor with 8 GB RAM



THCU

- Compact PC CX9020
- Windows Embedded Compact 7 operating system
- 1 GHz ARM CortexTM-A8 CPU

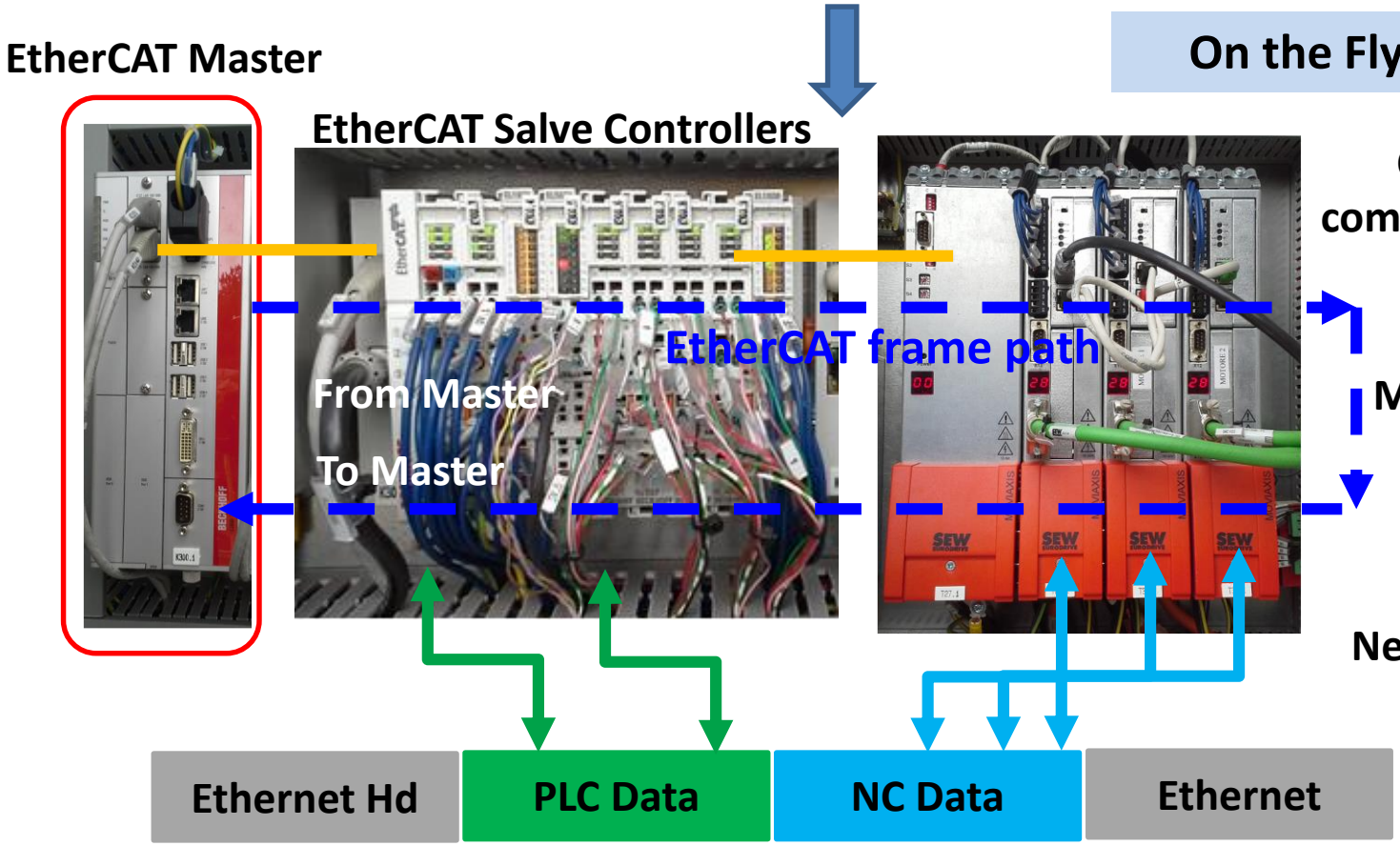
Safety PLC

- Safety Standard DIN EN ISO 13849-1:2008 and IEC 61508:2010 (SIL 3)
- Cycle Time 500 µs – 25 ms

Real-Time Local Control : Communication Protocol

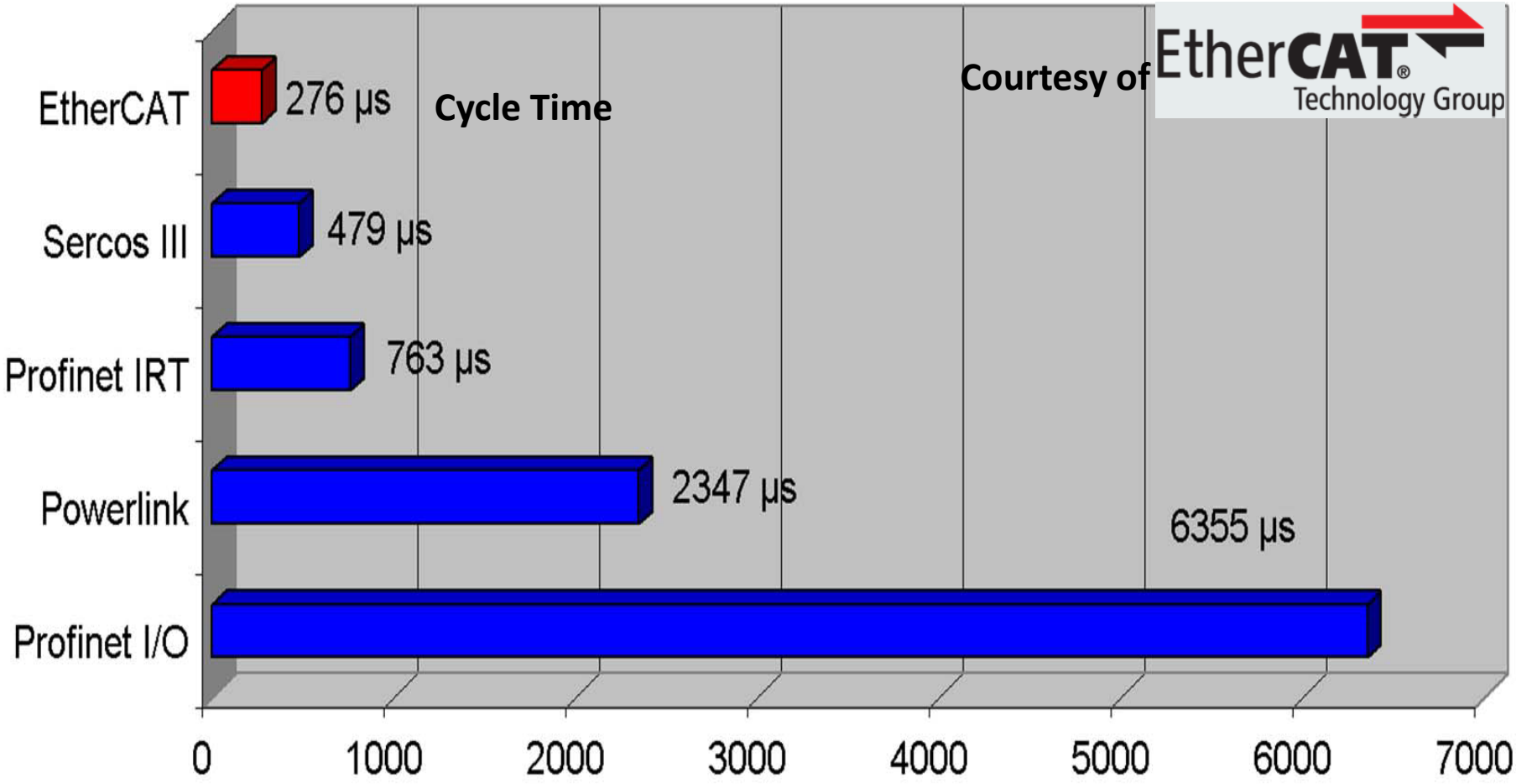
Internal communication Protocol : Ethernet Control Automation Technology (EtherCAT)

- Ethernet network protocol developed by Beckhoff for real-time requirements in automation technology (standardized in IEC 61158)



EtherCAT Performance Example

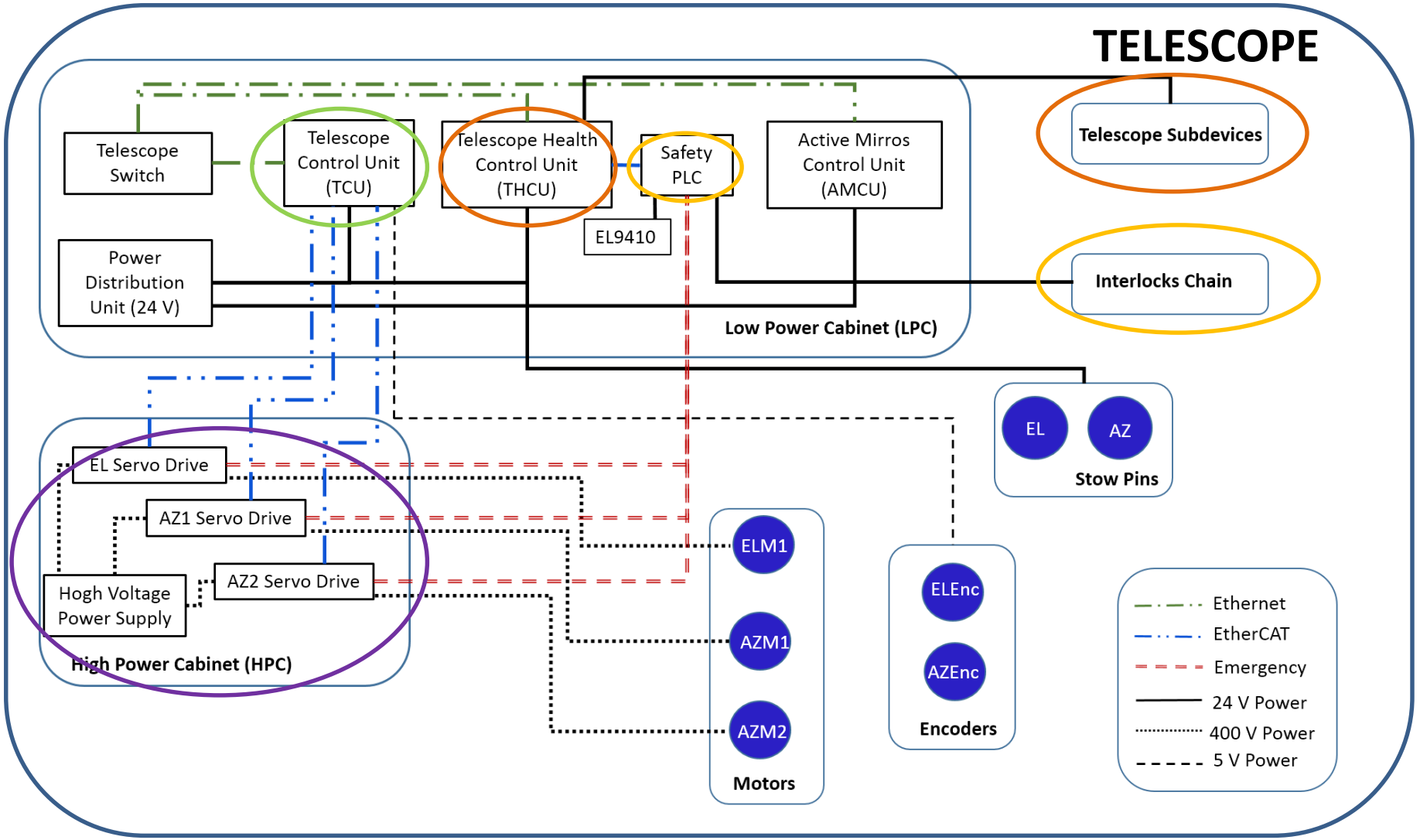
- 40 Axis (Each 20 Byte Input/Output Data)
- 50 I/O stations (560 EtherCAT bus Terminals)



https://www.ethercat.org/download/documents/Industrial_Ethernet_Technologies.pdf

The Real-Time Local Control Hardware Architecture

Electronics and hardware parts needed to drive the telescope to any accessible sky position and to operate safely the telescope during the commissioning, testing and observing phases .



The Telescope Control Unit : Hardware Architecture

Homogeneity and compatibility of real-time communication

Power Connections
EtherCAT
Ethernet

Telescope Switch

TCU

HPC

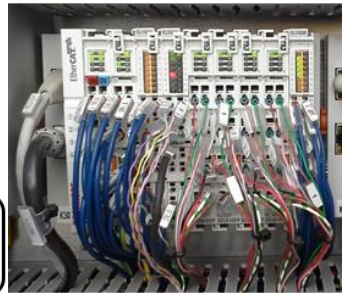
AZ Servo Drivers

EL Servo Driver

EL1808 Input Terminals

EL5032 EnDat Encoder

EL5021 Sin/Cos Encoder



START
STOP
ELEVATION UP
ELEVATION DOWN
AZIMUTH CW
AZIMUTH CCW
OP MODE SELECTION

Mobile Push button

AZY0
AZLCW0
AZLCCW0
ELPHIGH
ELPLOW
AZSTOPRE
ELESTOPRE

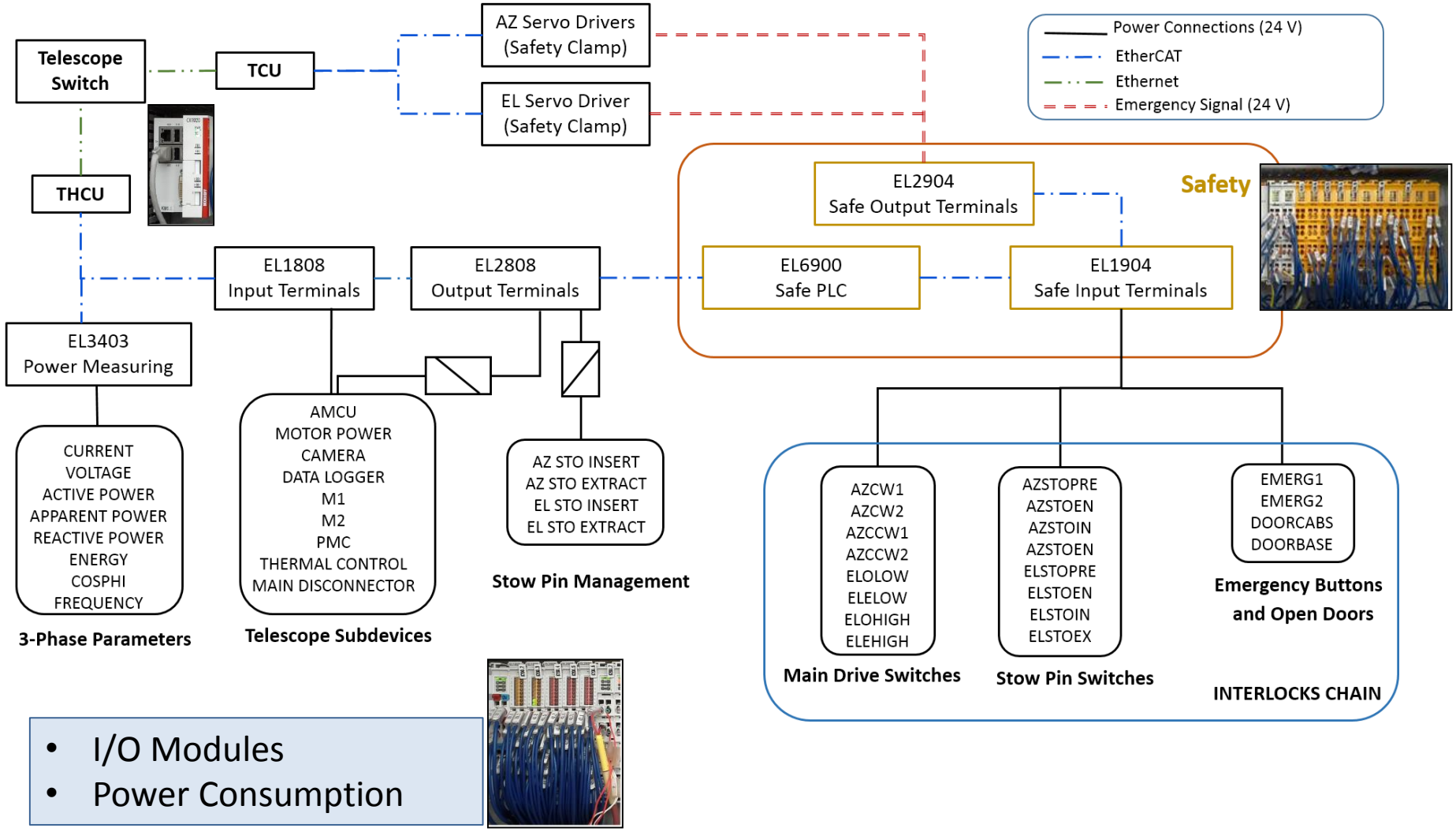
Pre Limit Switches

Elevation Absolute Encoder

Azimuth Incremental Encoders

Encoders

- Input Terminals and Encoder Interfaces
- Servo Drives



- I/O Modules
- Power Consumption

Real-Time Local Control : Software Development

Local Control Package is implemented through Programmable Logical Controller (PLC) Beckhoff TwinCAT 3 environment using Structured Text (ST) IEC61131-3 language

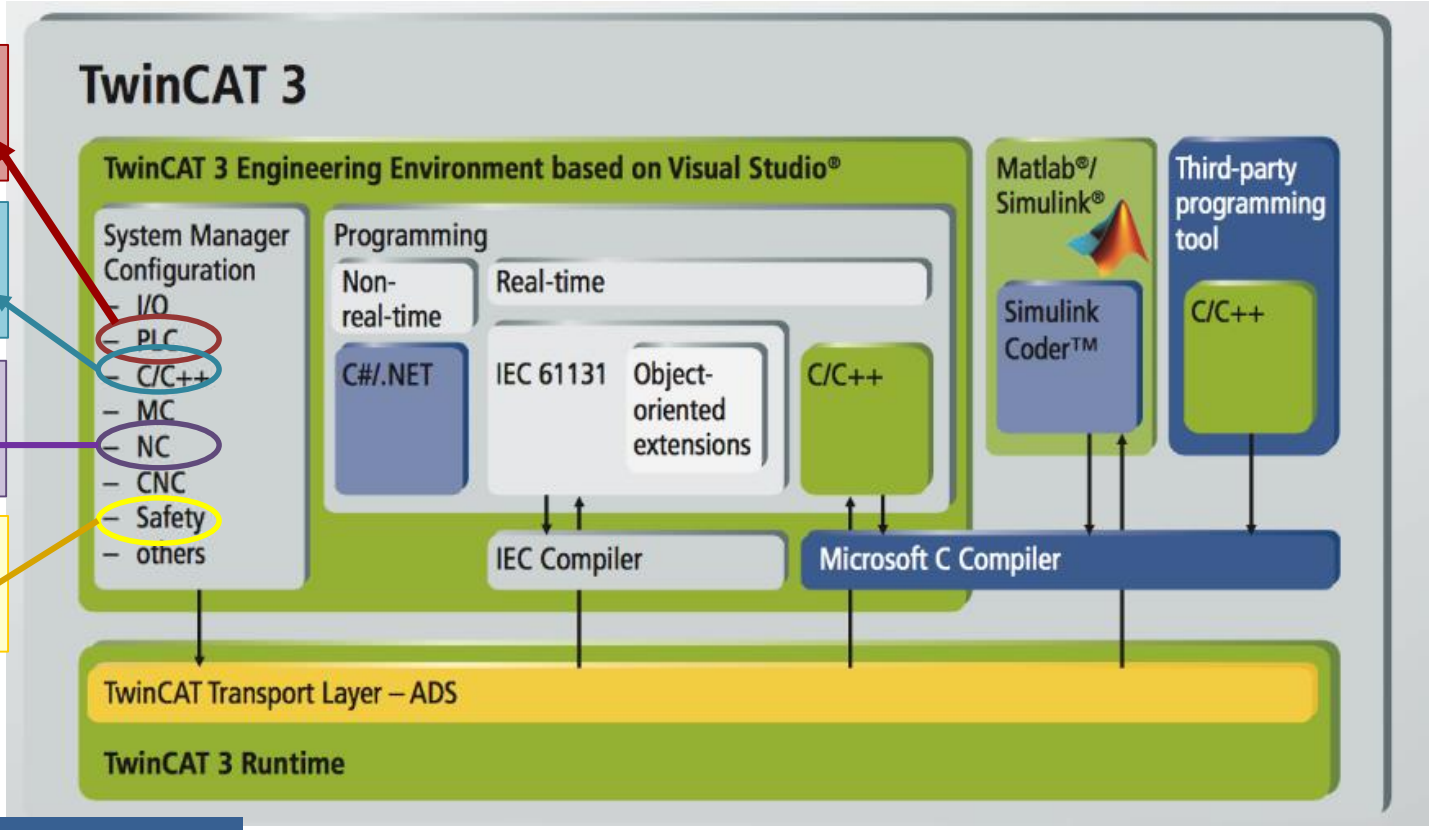
Modular and flexible software framework with integrated motion functionalities

Motion Control and functionalities

C/C++ Real Time application

Axes positioning Control

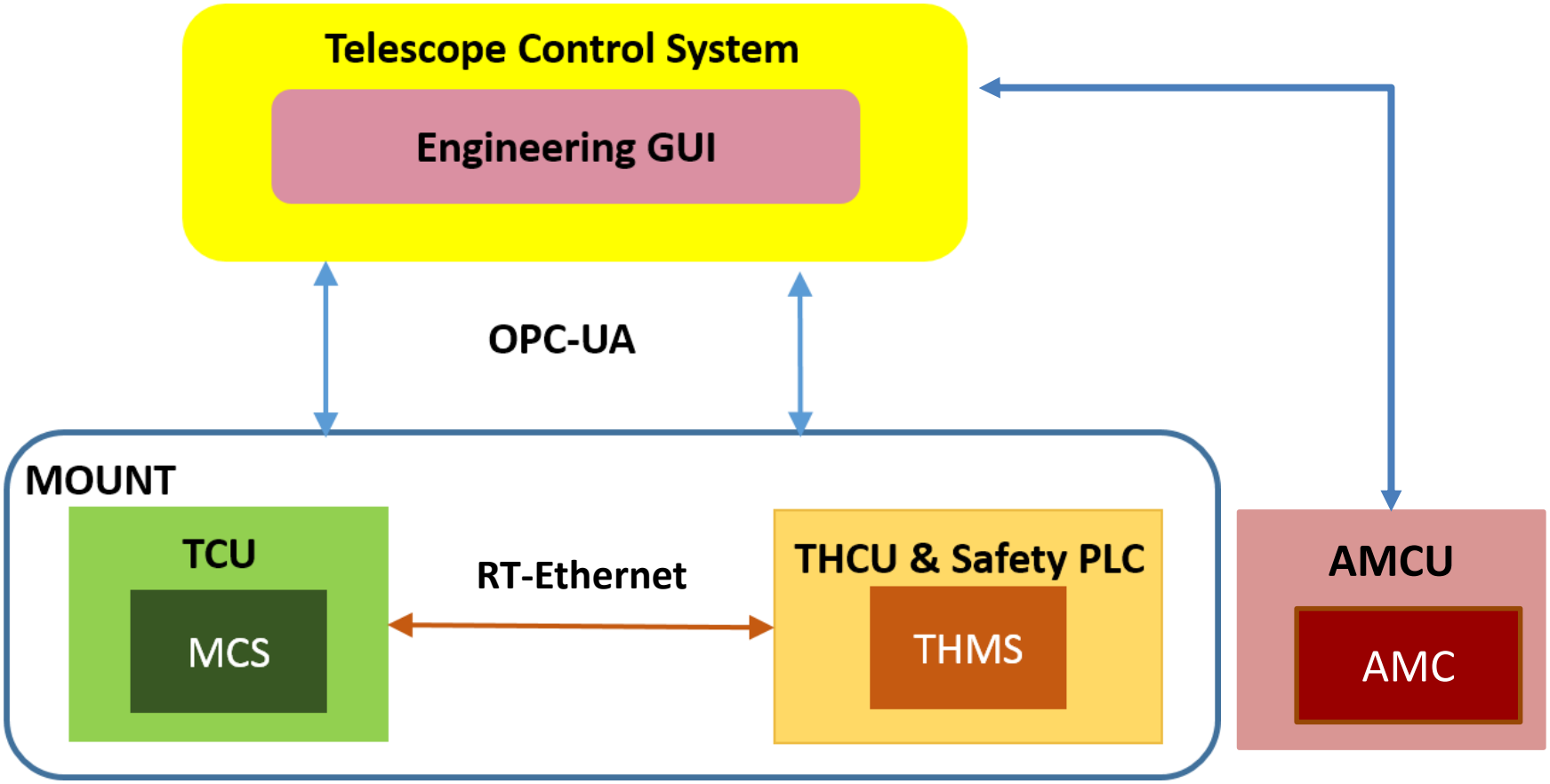
Safety-Related applications



Simplification and effort reduction of the development of real-time control and safety applications

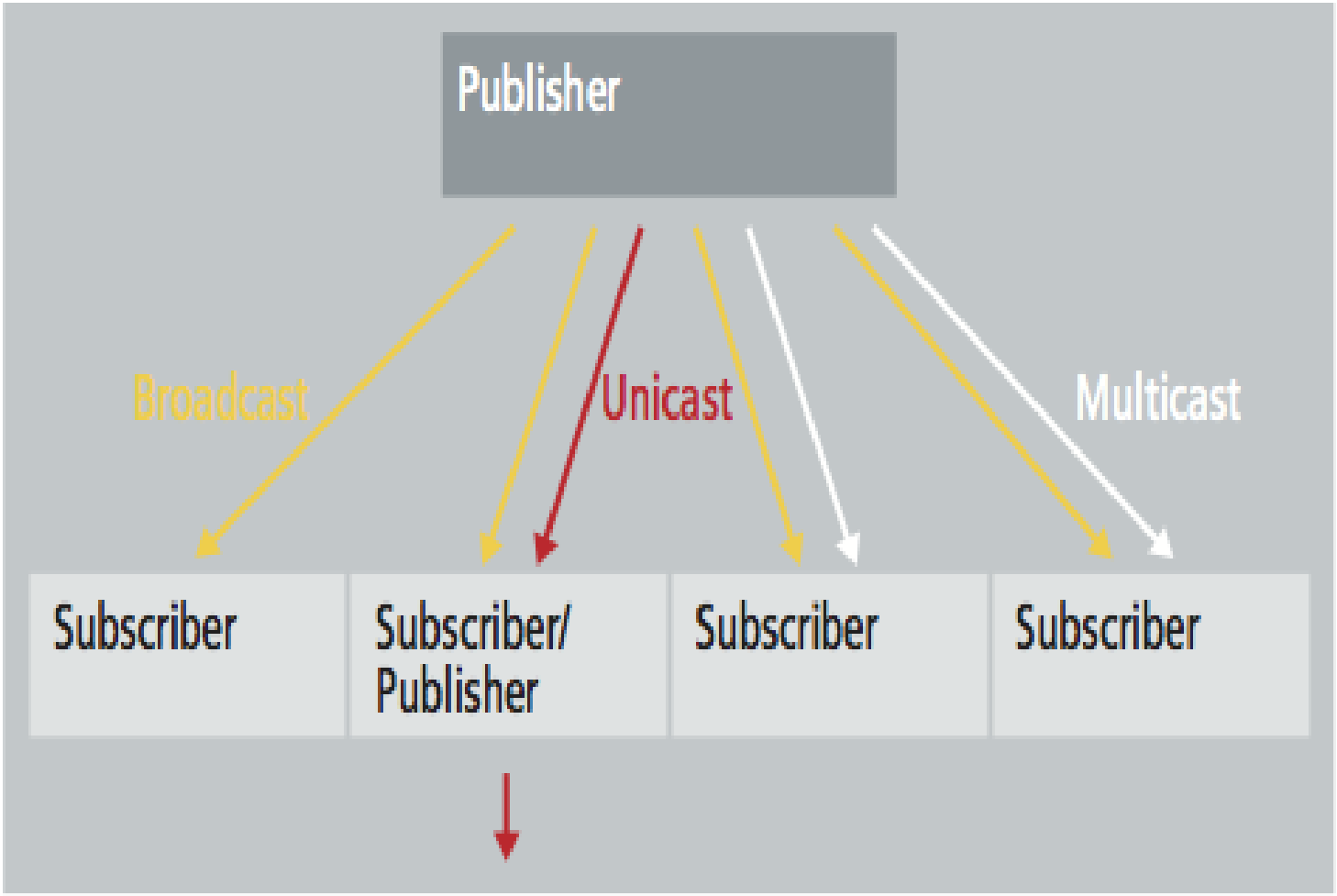
+ **OPC-UA Server-Client protocol** → Easy integration with higher level controllers

Real-Time Control : Software Architecture

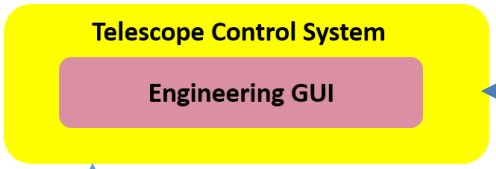


Each Real-Time component has is own PC in which the related PLC is running independently but separate PLCs can share information :
Real Time Ehernet Communication Protocol

Real Time Ehernet Communication Protocol



Real-Time Control Software : Functionalities

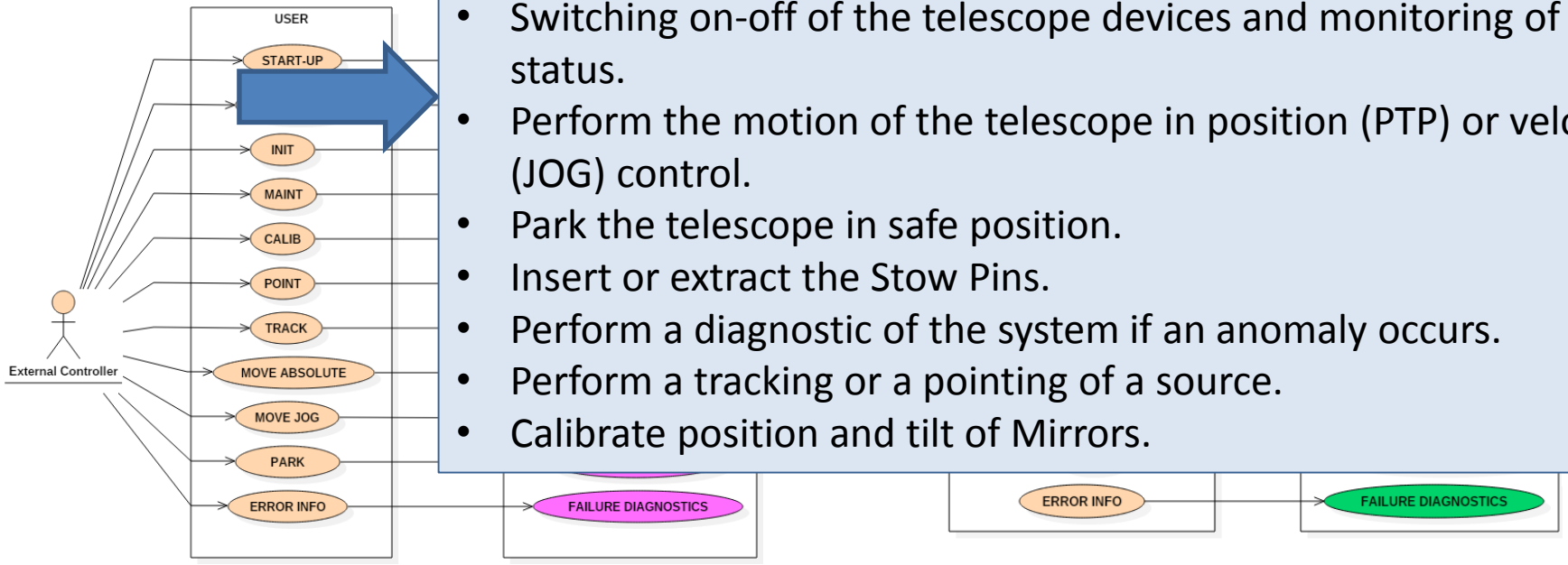


OPC-UA

The design and implementa

Functionalities available for the external controller (TCS)

- Initialize systems and bring them to their operative status.
- Perform the state transitions.
- Switching on-off of the telescope devices and monitoring of their status.
- Perform the motion of the telescope in position (PTP) or velocity (JOG) control.
- Park the telescope in safe position.
- Insert or extract the Stow Pins.
- Perform a diagnostic of the system if an anomaly occurs.
- Perform a tracking or a pointing of a source.
- Calibrate position and tilt of Mirrors.



Real-Time Control Software : State Machine

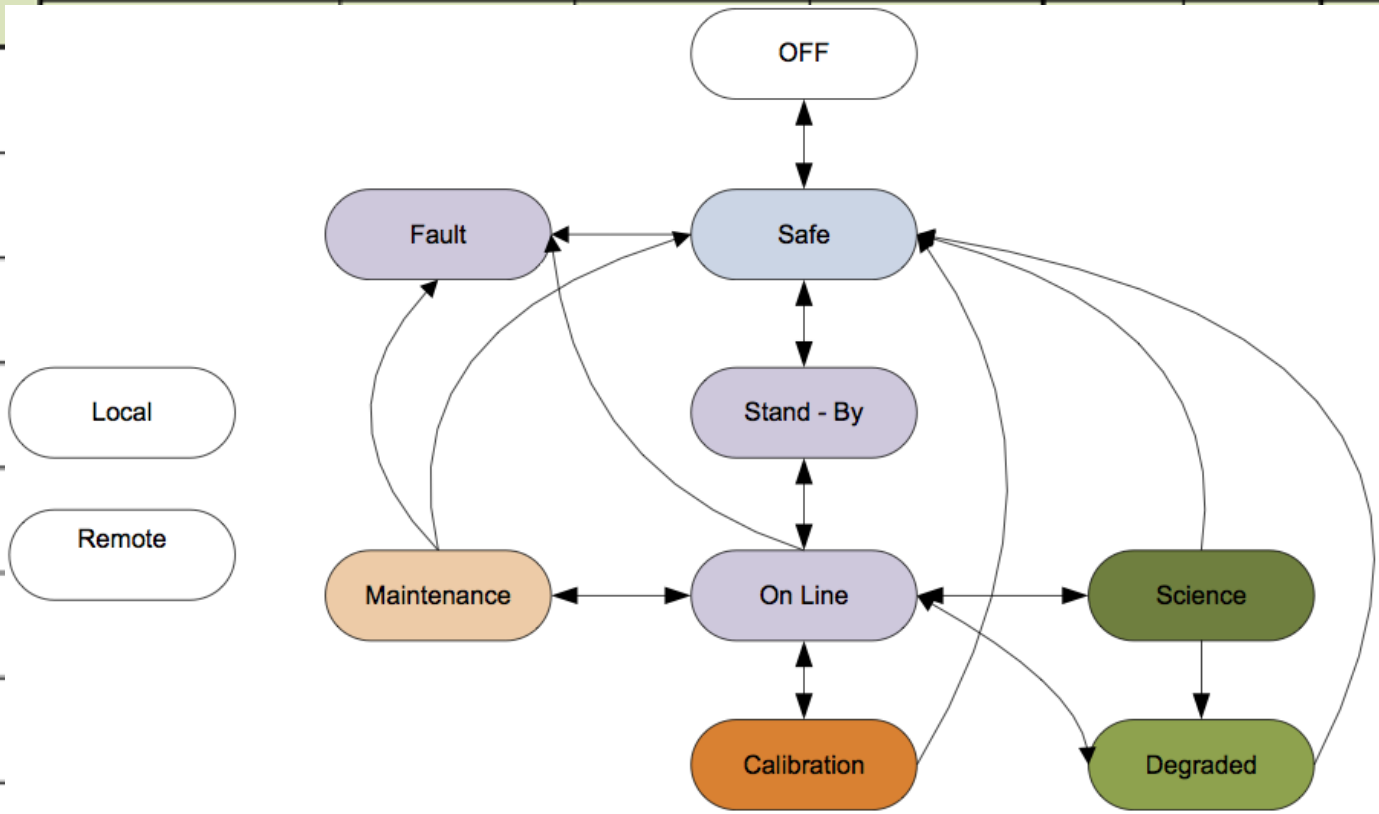
Any telescope device is conceived as an abstract machine that can be in one of a finite number of states

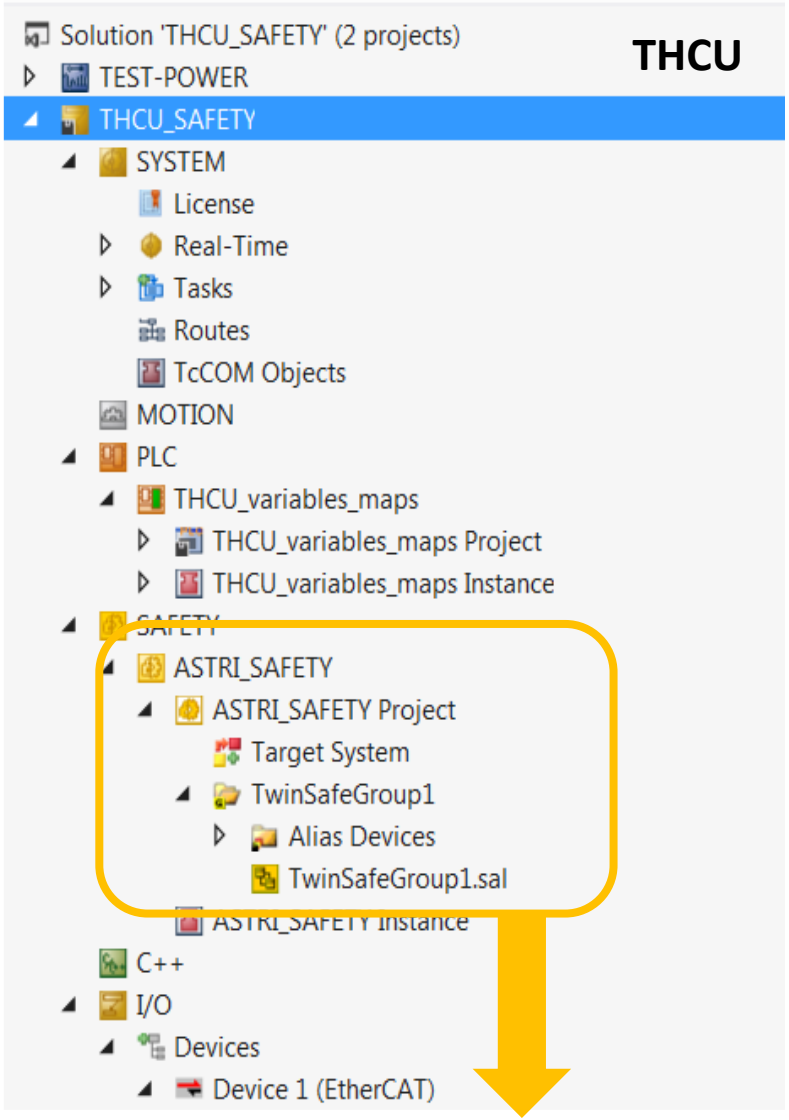
Telescope Modes	Assemblies States						
	MISSION CRITICAL				AUXILIARIES		
	TCU	THCU	AMCU	CAMERA	PMC	UV*	CONDITIONING SYS.
OFF	OFF	OFF	OFF	OFF	OFF		
LOADED (SAFE)	LOADED	ONLINE	LOADED	LOADED	LOADED		
STAND-BY	STAND-BY	ONLINE	STAND-BY	STAND-BY	STAND-BY STAND-BY		
ON-LINE	ONLINE (IDLE)	ONLINE	IDLE	IDLE	IDLE		
SCIENCE	ONLINE (SLEW) ONLINE (TRACK)	ONLINE ONLINE	MOVING IDLE	IDLE SCIENTIFIC	IDLE IDLE		
DEGRADED	ANY	ONLINE	ANY	ANY	FAULT		
CALIBRATION	CALIBRATION	ONLINE	CALIBRATION	CALIBRATION	CALIBRATION		
MAINTENANCE	MAINTENANCE OFF	ONLINE MAINTENANCE	MAINTENANCE OFF	MAINTENANCE OFF	MAINTENANCE OFF		
FAULT	FAULT OFF	IDLE FAULT	FAULT OFF	FAULT OFF	IDLE OFF		

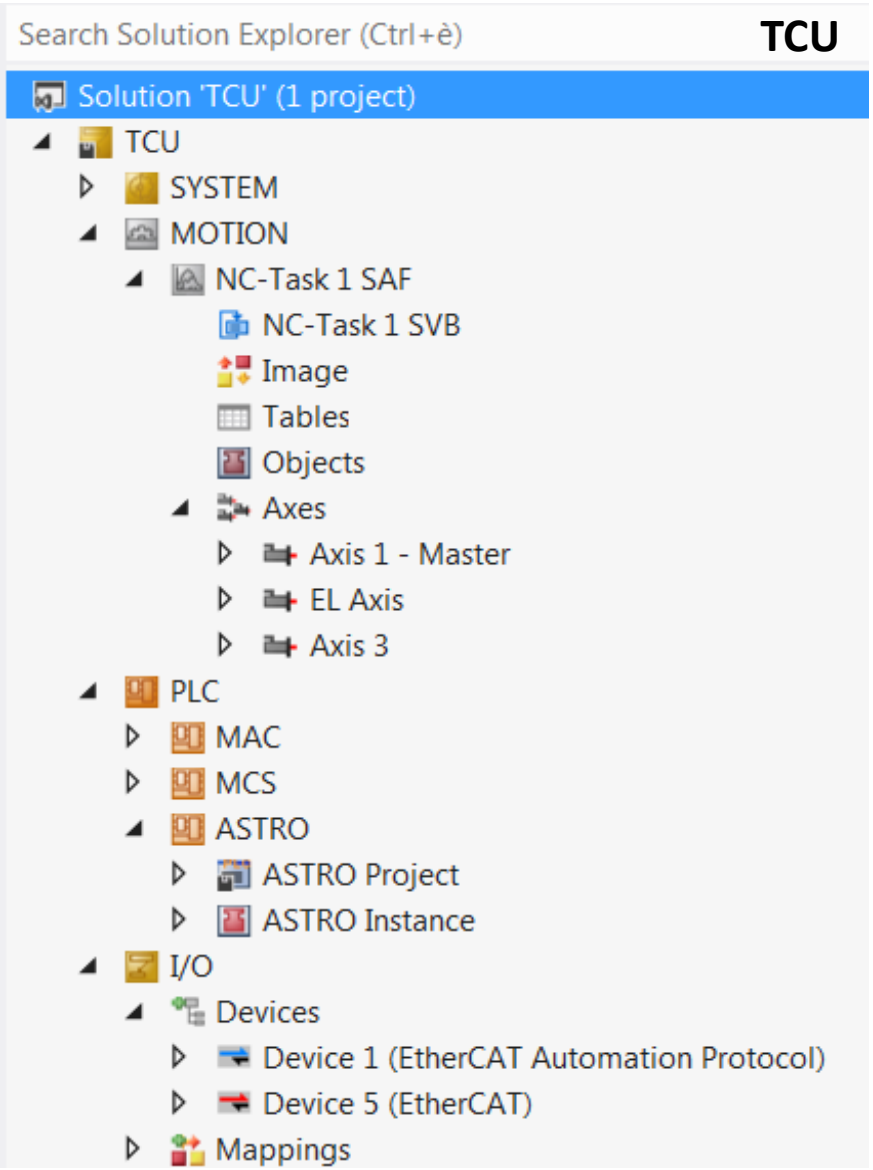
Real-Time Control Software : State Machine

All the states are logically assembled together in order to form the final telescope state machine

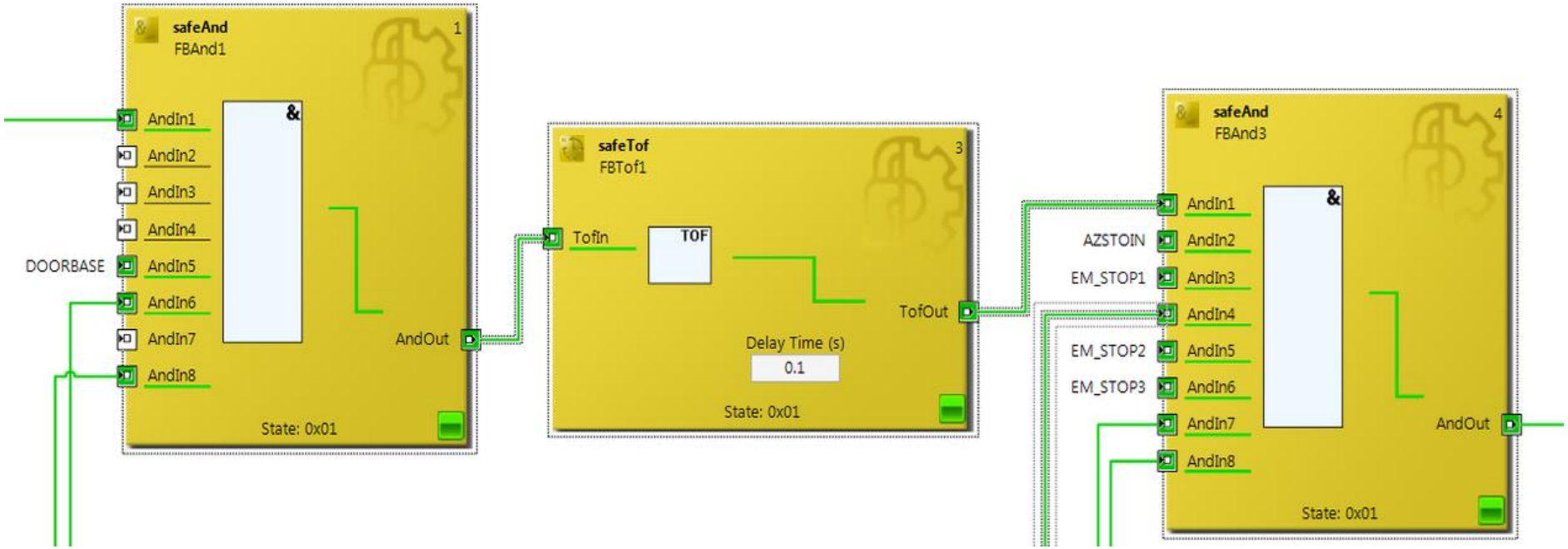
Telescope Modes	Assemblies States				
	MISSION CRITICAL			AUXILIARIES	
OFF					ITIONING SYS.
LOADED (SAFE)					
STAND-BY					
ON-LINE					
SCIENCE					
DEGRADED					
CALIBRATION					
MAINTENANCE					
FAULT	FAULT OFF	IDLE FAULT	FAULT OFF	FAULT OFF	IDLE OFF




Solution 'THCU_SAFETY' (2 projects)
THCU
TEST-POWER
THCU_SAFETY
SYSTEM
License
Real-Time
Tasks
Routes
TcCOM Objects
MOTION
PLC
THCU_variables_maps
THCU_variables_maps Project
THCU_variables_maps Instance
SAFETY
ASTRI_SAFETY
ASTRI_SAFETY Project
Target System
TwinSafeGroup1
Alias Devices
TwinSafeGroup1.sal
ASTRI_SAFETY Instance
C++
I/O
Devices
Device 1 (EtherCAT)


Search Solution Explorer (Ctrl+è)
TCU
Solution 'TCU' (1 project)
TCU
SYSTEM
MOTION
NC-Task 1 SAF
NC-Task 1 SVB
Image
Tables
Objects
Axes
Axis 1 - Master
EL Axis
Axis 3
PLC
MAC
MCS
ASTRO
ASTRO Project
ASTRO Instance
I/O
Devices
Device 1 (EtherCAT Automation Protocol)
Device 5 (EtherCAT)
Mappings

Implementation of the Interlock Logic chain using the TC3 SAFETY PLC module



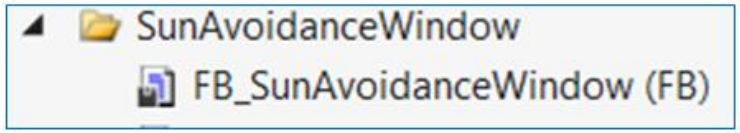
THMS and SAFETY PLC run with the same execution cycle of 2 ms, and they are completely independent: the THMS runs in the TwinCAT runtime environment installed in the THCU PC, while the SAFETY logic runs into the Safe PLC Beckhoff module EL6900, which belongs to the hardware connected to the THCU

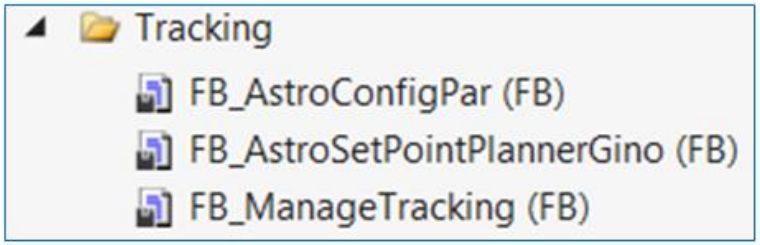
Real-Time Software Package : Implementation

The main building blocks of the software modules are the Function Blocks (FBs).

- Each FB is in charge of the execution of a simple set of logical steps and the suitable combination of the FBs provides all the necessary actions to perform the desired functionality.
- Depending on its complexity, each functionality of the MCS, THMS and AMC was implemented through one or more Function Blocks

```
TCU_Online_Idle :

    MCS_STATES.STATUS := TCU_States.TCU_Online_Idle;

    ////////////////////////////////////////////////////////////////////////
    //                        SUN AVOIDANCE WINDOW                        //
    ////////////////////////////////////////////////////////////////////////

    SunAvoidanceWindowManager();

    ////////////////////////////////////////////////////////////////////////
    //                        TRACKING AND POINTING                       //
    ////////////////////////////////////////////////////////////////////////

    TrackingPointingManager();
```



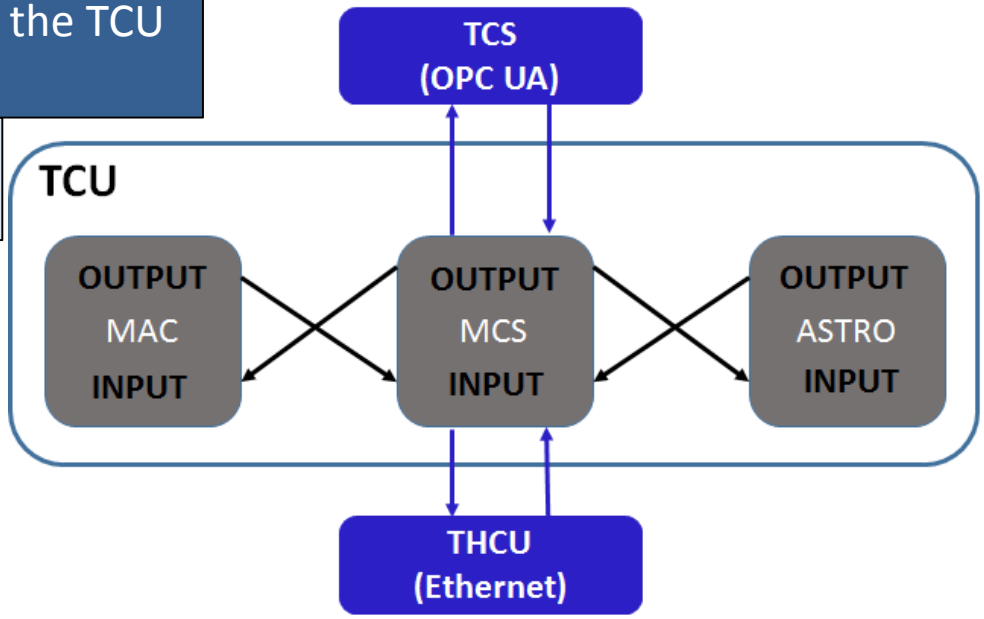


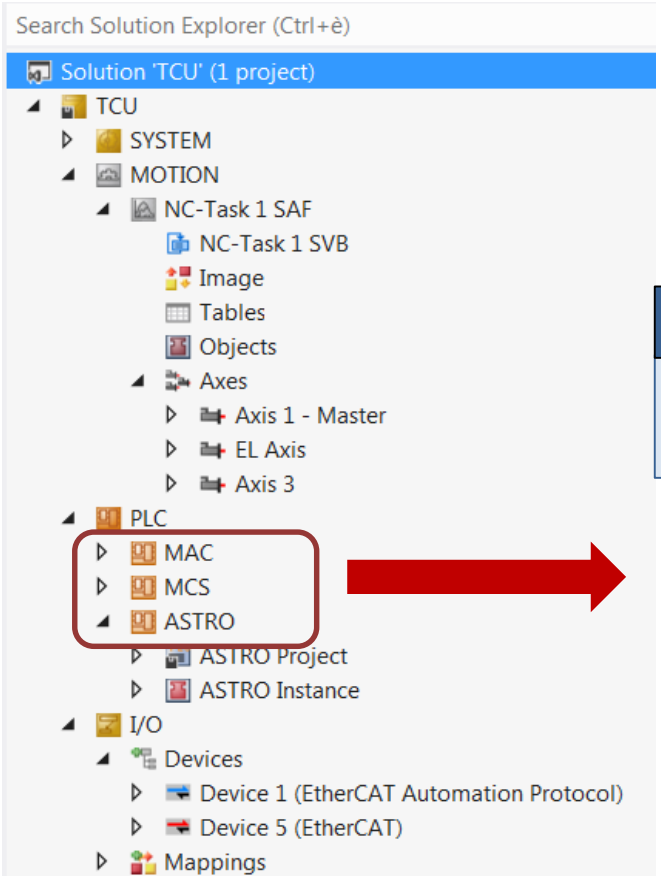
The software architecture of the Mount Control adopts the finite state machine concept

The Mount Control System: Architecture

Each PLC task runs on a dedicated core of the TCU quad-core CPU

The computational effort is distributed evenly and the software performances are optimized





Mount Control Axis (MAC)

Controls of the motors, encoders and servo loops

Mount Control System (MCS)

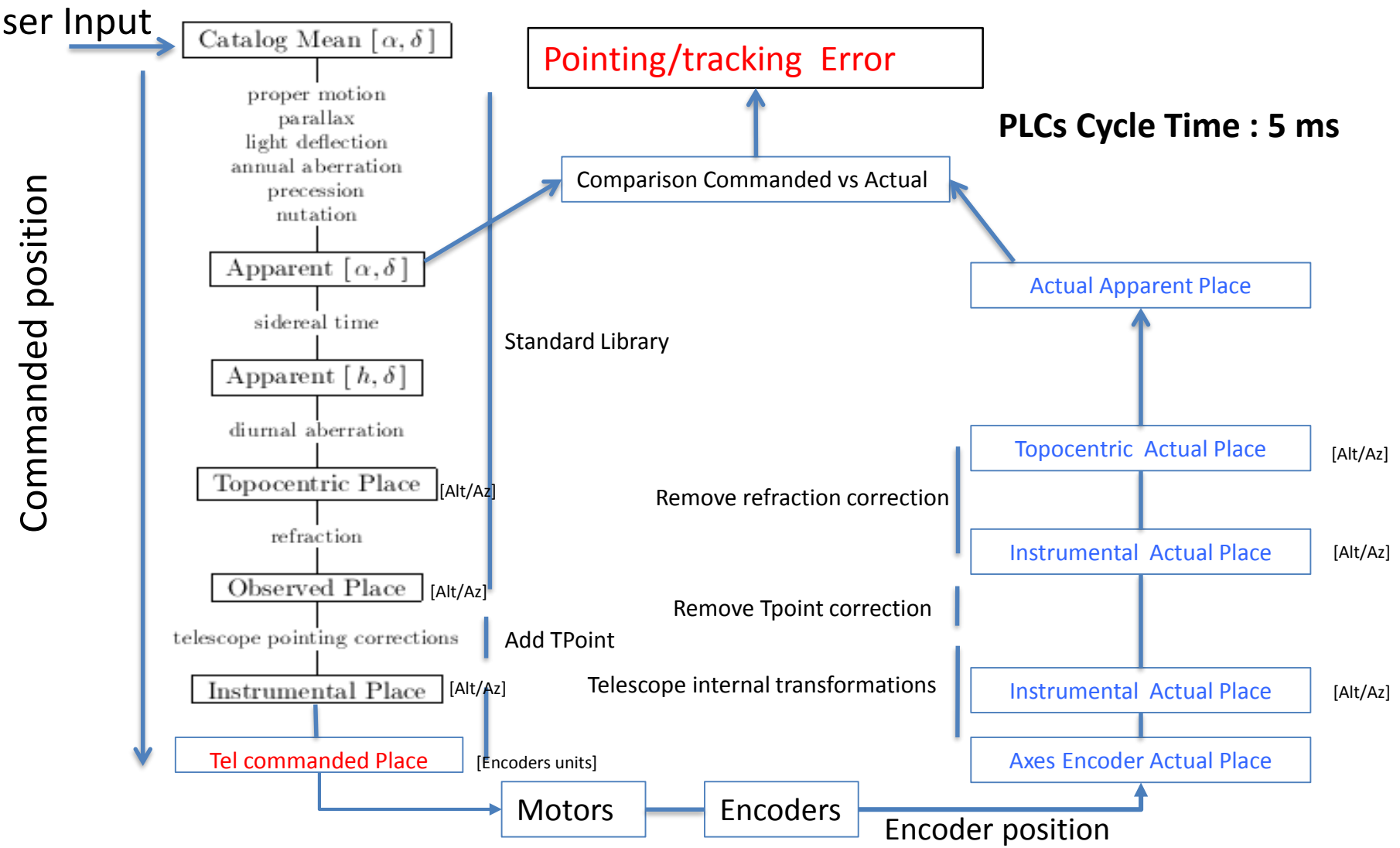
Is the master module able to manage the other two sub-modules and it provides the interface towards the external controller.

ASTRO

It contains all the astrometric routines, for pointing and tracking the telescope, developed in the PLC ST language and based on the USNO Novas C package.

THE TRACKING /POINTING ALGORITHM

All the astrometric routines, for pointing and tracking the telescope are developed in **the PLC ST language** and are based on the **USNO Novas C package**.



EXTERNAL CONTROLLER

PLCs Cycle Time : 5 ms

MCS

Target Parameters (RA, Dec, proper motion,weather, exp time, etc.)

ASTRO

Compute EL, AZ Trajectory for the Exposure Time duration (one point every 500 ms)

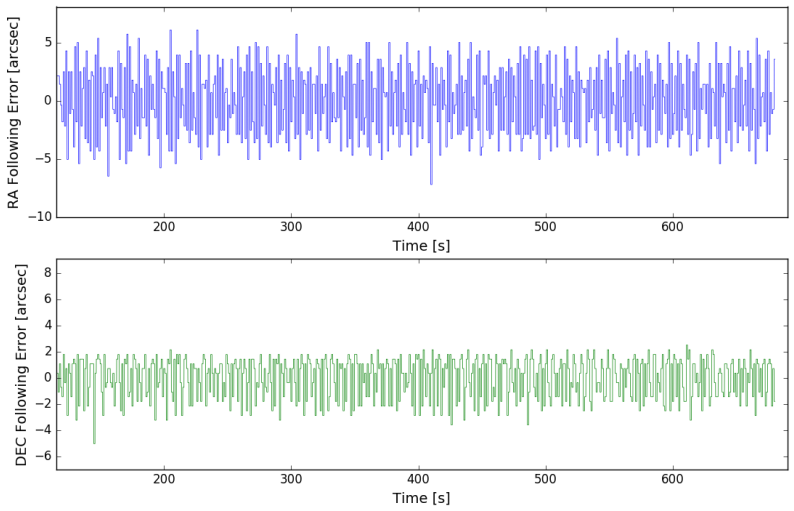
MCS

Select the trajectory point with a time synchronization mechanism

MAC

Execute the motion for the commanded Alt AZ position

Pointing/tracking Error = 4.7 arcsec

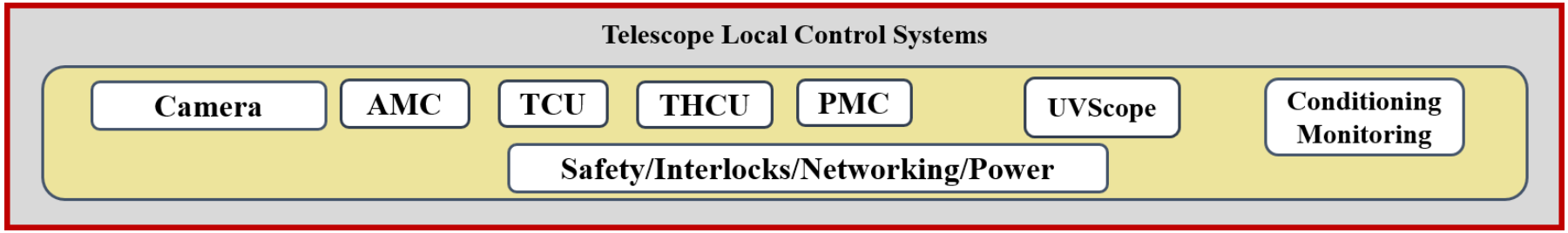


MCS send the trajectory points to the MAC every one second in a time synchronized way so that, when the telescope is moving to the commanded position at the time t_i, the MAC receive the position at which the axes should be at time t_{i+1} (over the next 1 s).

AZ = 67 deg
EL = 72 deg

RA = 299.63 deg
DEC = 42.32 deg

Non-Real time Control : Local Control System



Camera

- Cherenkov Camera detection manager

Pointing Monitor Camera (PMC)

- Optical Camera manager

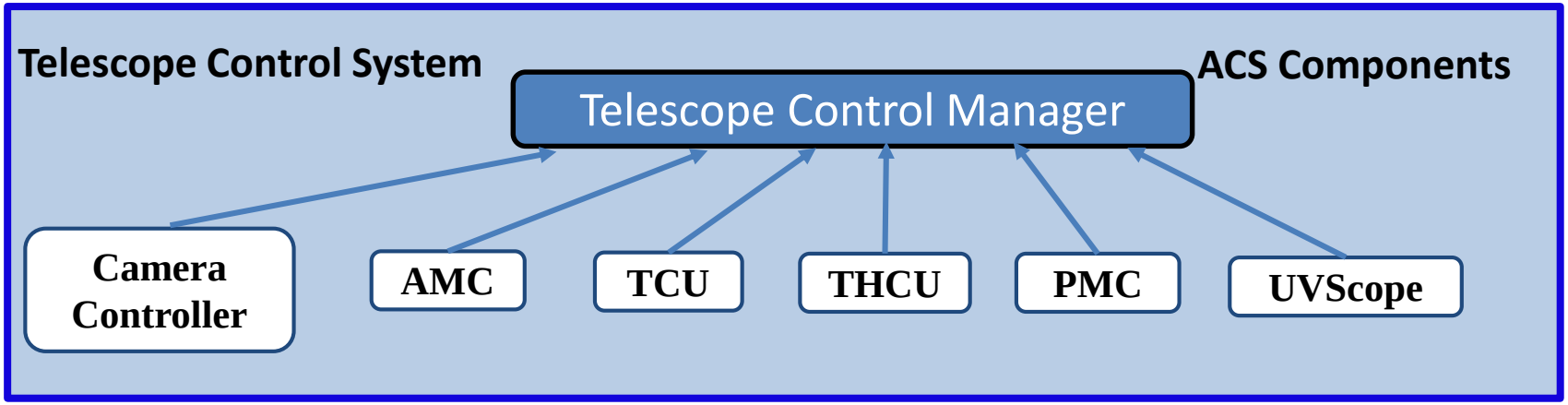
UVScope

- Night Sky background measurements

OPC-UA servers developed in-house, written in Java using the Prosys OPC-UA SDK.

Every Telescope device/auxiliary of the Local Control System (LCS) expose to the outside an OPC-UA server through which can be operated by the higher controllers.

High Level Control : Telescope Control System



- Every Telescope device/auxiliary of the LCS controller can be managed via a specific high level Component , implemented through the Alma Common Software (ACS) framework, providing access to all the commands, monitor points, configuration and state mode related to the associated LCS device.

- Each ACS component is defined starting from an Interface Control Document (ICD) implemented as Excel file, and using a code generator to generate the ACS commponent acting as a Controller of a Device.

- The Telescope Control System collect and coordinates the action of the Telescope devices through the related ACS components.

Main Top Level Functionalities Accessible via the Telescope Control Manager (& the Eng. GUI)

- START-UP
- SHUT-DOWN
- STATE MACHINE MANAGEMENT
- POINTING/TRACKING
- PTP/JOG MOTION
- MOTION INFORMATION (POSITIONS, VELOCITIES, ACCELERATIONS)
- SWITCH ON/OFF TELESCOPE DEVICES
- TELESCOPE DEVICE POWER AND SOFTWARE STATUS
- TELESCOPE DEVICES ALARM/WARNING ALERT
- EMERGENCY STATUS
- EMERGENCY RECOVERY PROCEDURES

The Design and Implementation of the Control System plays a fundamental role for ASTRI prototype

The majority of the operational and engineering features of the telescope (including tracking-pointing) are developed through software PLCs, as real-time functions.

The technology chosen and the software packages developed guarantee :

- **Homogeneity and high performance of real-time communication.**
- **Optimization of the utilization of computational resources.**
- **Auto-consistent and independent execution of the functionalities**
- **Access to the higher level controller through OPC-UA protocol**

The ASTRI SST-2M can be seen as a robotic and stand-alone machine, able to be fully operated by any other high-level controller simply excluding the GUI part and defining a specific interface. Easy and efficient way for the integration in an array configuration

ASTRI Real-Time Control System allowed us to test a lot of functionalities, developed by the companies chosen and used for the first time in this kind of application (Test Bench for the industries selected).

Thank you

Courtesy of Enrico Marcuzzi
(EIE Group)