METIS AOCS at the beginning of MAIT

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ABSTRACT

The Mid-infrared ELT Imager and Spectrograph (METIS) instrument is one of three first-generation science instruments for the Extremely Large Telescope (ELT) in Chile. It has entered the Manufacturing, Assembly, Integration and Testing (MAIT) phase and it is currently scheduled to be installed in 2028. Its Single Conjugate Adaptive Optics (SCAO) system will provide the performance of an extreme adaptive optics system which enables high-contrast imaging (HCI) observations in the thermal/mid-infrared wavelength domain.

The METIS Adaptive Optics (AO) control system is responsible for the AO wavefront correction and for supporting AO-related assembly, integration, verification and maintenance activities. It realizes the main AO loop by a Real-Time Computer (RTC) that receives images from a wavefront sensor and commands the corrective optics through the Central Control System (CCS) of the ELT.

Several auxiliary functions will run outside of the RTC in the AO Observation Coordination System (AO OCS) that are necessary to maintain the quality of the wavefront correction. For instance, the Differential tip-tilt (DTT) control loop centers the star on the Vortex Phase Mask during HCI observations by adjusting the modulator device via the SCAO Function Control System (FCS) based on sciences images received from the Focal Plane Sensor Gateway (FPS GW).

Conceptually, the METIS Adaptive Optics Control System (AOCS) is a distributed software system that is controlled by the METIS Instrument Control System (ICS). This paper describes the current status of the METIS AO control system, driving forces behind the design and the important control loops.

Keywords: ELT, METIS, Adaptive Optics, Control System, real-time computer, RTC

1. ADAPTIVE OPTICS IN METIS

The SCAO subsystem of METIS ensures observations near the diffraction limit.[1] It uses the light of a single near-infrared (NIR) source located at or in a limited field around the science target position to measure the phase of the incoming wavefront and applies corrections in real-time by controlling the adaptive mirrors of the ELT.

Several distributed entities are involved in this AO system: in the instrument domain, the SCAO Subsystem consists of the *SCAO Module* and the *Adaptive Optics Control System (AOCS)*. Further entities that are essential for SCAO are located in the telescope domain. Figure 1 shows a simplified block diagram for METIS SCAO.

The *SCAO Module* is located inside the cryostat of METIS. A cold dichroic AO pick-off mirror immediately in front of the SCAO Module is used to separate the near-infrared part of the light, which is used for wavefront sensing. The SCAO Module provides a Pyramid Wavefront Sensor (P-WFS) as well as opto-mechanical actuators for field selection and modulation of the Natural Guide Star (NGS) in the field of view.

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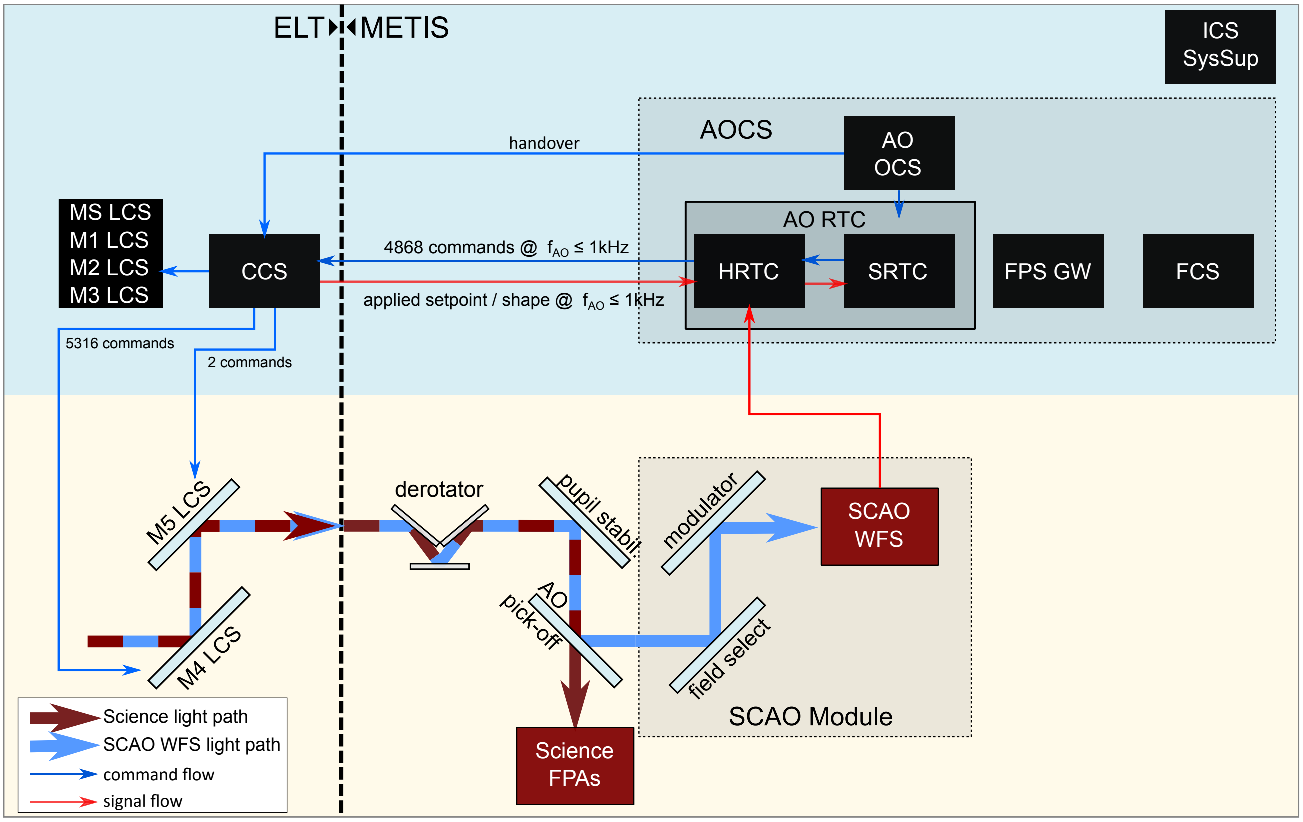

Figure 1. Simplified block diagram of the SCAO system: The AOCS and the SCAO Module (shaded boxes) are the entities of the SCAO system that belong to the instrument domain. The key entities for the real-time correction of the incoming light of the 'ELT' domain are located on the left side of the figure.
In a closed wavefront control loop, the blue, NIR light is used to measure the instantaneous residual wavefront error by the WFS. The measurement signal is analyzed by the RTC, and a computed correction is sent to the CCS to be applied with the M4 and M5 via a LCS. The FPS GW provides science images to auxiliary AO loops and the FCS is responsible for controlling all instrument devices, except the detectors.

The *AOCS* hosts the main wavefront control loop as well as a number of secondary control loops. A key entity of the AOCS is the RTC. Its Hard Real-Time Core (HRTC) is used for the time critical aspects of the wavefront control loop: wavefront sensor signal processing, wavefront reconstruction and the determination of correction commands that are applied with the M4 and M5 mirrors via the CCS. The Soft Real-Time Cluster (SRTC) supervises and optimizes the HRTC operation. Less time critical control tasks are realized outside of the RTC. The AO OCS is the gateway for the METIS ICS to the AOCS. Its task is to coordinate the activities inside of the AOCS.

2. OPERATIONAL ENVIRONMENT

METIS AOCS is not a standalone control system, but it will co-operate with external computer systems that are described in this section. The constraints are described first, followed by the AOCS environment and the main design decisions.

2.1 Constraints

The technical constraints are listed in the table below:

Constraint	Description
Independence of platforms	Since METIS AOCS will have the same life-time as the METIS instrument (namely 10 years), it will be subject to obsolescence. Therefore, it is mandatory that AOCS is upgradeable to new platforms.
Adherence to ESO control system standards	European Southern Observatory (ESO) builds the ELT and provides standards for the ELT control system covering many aspects such as network technology and software development.
Adherence to ESO RTC common requirements	Because the METIS RTC must be integrated into the ELT environment, ESO demands that the RTC meets certain requirements.
Programming languages	C++ and Python.

The organizational constraints of METIS AOCS are listed in the table below:

Constraint	Description
Team	1 AO lead and 3 (+0.5) software engineers
Development process	An iterative and incremental process is used in order to allow ESO to inspect the control system already at early stages.
Software quality assurance	A Continuous Integration (CI) server checks the developers' commits into a code repository by running automated builds and regression tests. METIS AOCS uses Jenkins in combination with dynamic and static code analysis tools such as valgrind, GCC sanitizers, clang-tidy, clang-format, cpp-check and gcov for code coverage.
Automatic tests	Google test and Python unit tests are used.
Version control	ESO provides Git repositories within a GitLab instance.
Coding standards	They are provided by ESO.

2.2 System Context

The technical system context is depicted in figure 2. Its elements are described in the table below:

Element	Description
Engineering GUIs	They provide control and monitor functions.
METIS ICS OCS	It supervises the AOCS.
N and LM band science imagers	They provide science images.
WFS detector	It provides the WFS images to the RTC.
SCAO devices	The SCAO hardware contains devices to steer the light onto the WFS detector.
ELT CCS	It provides access to ELT services such as control of the deformable mirror.
Time Reference System	It synchronizes computer clocks via Precision Time Protocol (IEEE-1588) (PTP).

2.3 Design Decisions

The table below list the major quality goals and the design decisions in order to meet these goals:

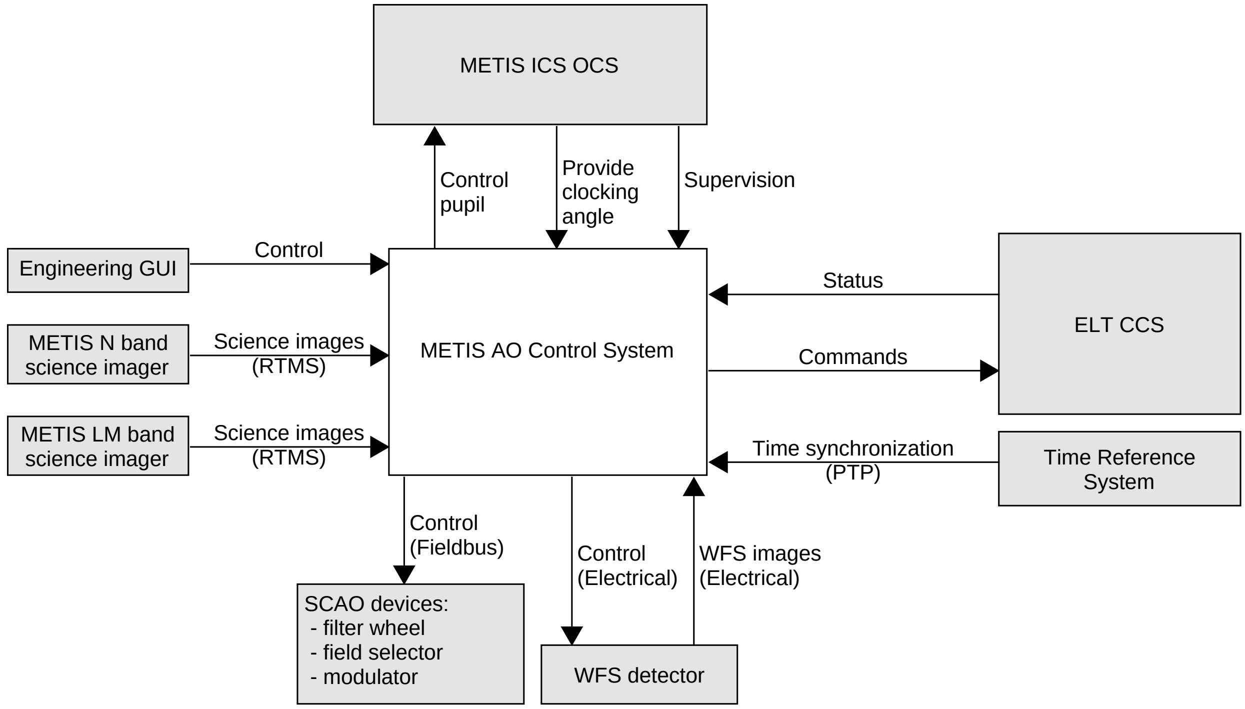

Figure 2. AOCS Technical System Context.

Quality Goal	**Decision**
Interoperability with ELT environment	METIS AOCS adheres to ESO ELT standards.
Maintainability	METIS AOCS adheres to ESO ELT standards and uses ESO frameworks.
Wavefront control in hard real-time	A special computer called HRTC is dedicated to run the time-critical Wavefront Control (WFC) loop. That computer must be compliant with ESO requirements.
Wavefront control loop optimizations in soft real-time	Software modules deployed on powerful computers within the SRTC optimize the WFC loop in soft real-time.

3. BUILDING BLOCKS

The METIS AOCS is a subsystem of METIS ICS and it is responsible for the AO wavefront correction and a number of related beam control tasks within METIS. Figure 3 shows the structure and main data paths of METIS AOCS including its external interfaces. The building blocks of AOCS are described below:

Building block	**Description**
AO OCS	It is the gateway for METIS ICS to AOCS with the task to coordinate the activities in the AOCS. Additionally, it hosts two auxiliary control loops, namely Pupil Position Control (PPC) Loop and DTT Loop. See section 5 for more details about these loops. Furthermore, it has access to the external services listed below: • It commands the CCS over the non-deterministic computer network (ND), e.g. it triggers a handover of the AO control between telescope and instrument. • It controls the lateral position of the pupil. • It changes the METIS pointing origin in the Prefocal Station (PFS) straight through focal plane.
RTC	It is responsible for performing the real-time part of the beam correction activity. It consists of a SRTC and an HRTC. While the SRTC is responsible for the high-level supervision and the optimization of the WFC loop, the HRTC is responsible for running the WFC loop with tight timing constraints. The WFC loop computes the wavefront command from the WFS image on every loop cycle and transmits it on the deterministic network to the CCS. See section 4 for more details.
WFS CS	The WFS Control System (CS) is in charge of reading out the SCAO WFS detector. To do this, it contains the WFS detector controller which is a group of electronics components that are directly connected to the WFS detector.
FPS GW	The FPS GW is placed between the science detectors (Focal Plane Sensor (FPS)) and the RTC. It translates the science detector pixel stream to a pixel stream suitable for the Differential High Order (DHO) optimizer and DTT control loop. The translation is necessary because the FPS data stream are only available in the real-time network but its consumers have only access to non-real-time networks.
SCAO FCS	It controls the electro-mechanical devices within the SCAO Module, namely filter wheel, field selector and modulator.

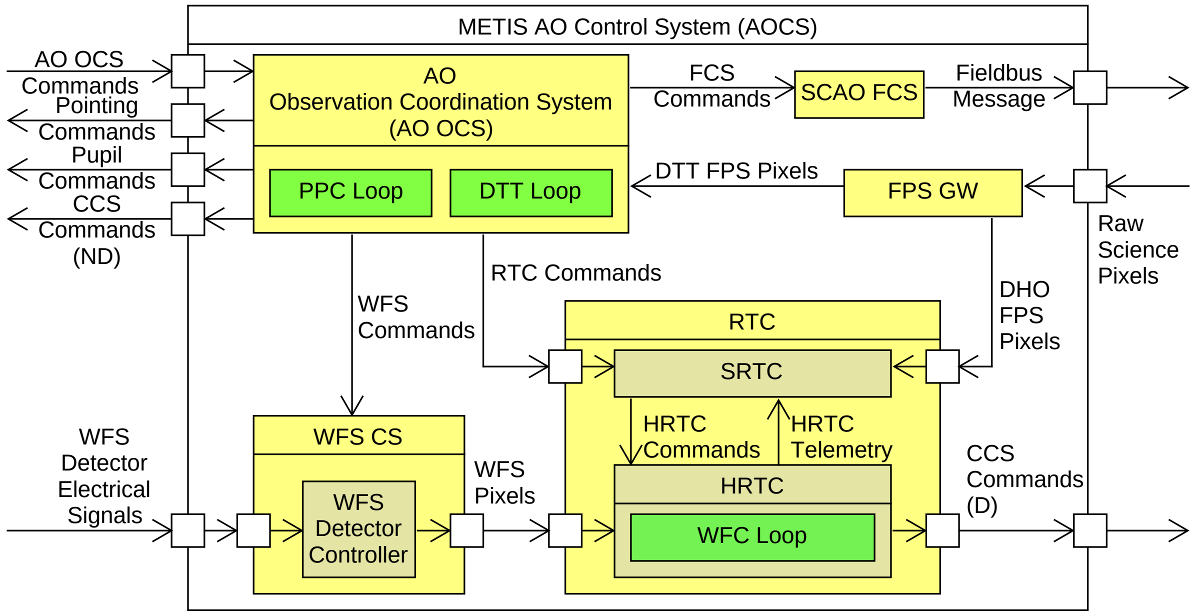

Figure 3. AOCS subsystems and main data paths.

4. WAVEFRONT CONTROL LOOP

The WFC loop is the main AO control loop. It corrects the incoming wavefront by calculating the Wavefront (WF) command from of the WFS images. Because the WFC loop must meet tight timing requirements, it runs on a dedicated real-time computer, namely the HRTC.[2,3]

Figure 4 depicts its data path which consists of the steps below:

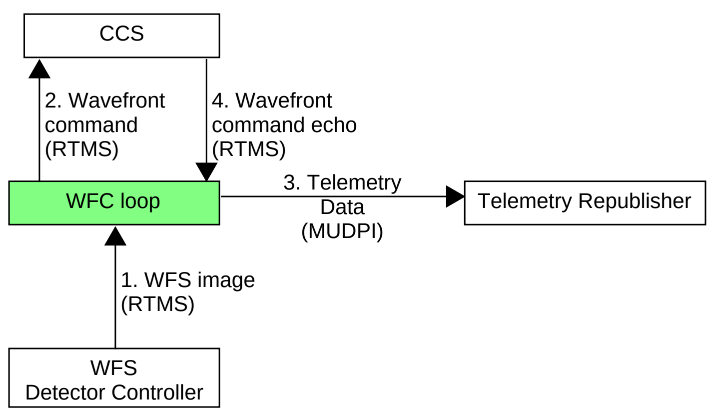

Figure 4. WFC loop data path.

Item flow	Description
1. WFS image (RTMS)	The WFS Detector Controller sends out a WFS image via Real-Time MUDPI Stream Protocol (RTMS) towards the HRTC where the WFC loop runs.
2. Wavefront command (RTMS)	The WFC loop reconstructs the wavefront and sends a WF command to CCS through RTMS.
3. Telemetry Data (MUDPI)	The WFC loop disseminates telemetry data through the network protocol Multicast UDP Interface (MUDPI). The SRTC receives it in order to estimate system parameters and to optimize loop parameters. The telemetry data includes, amongst other things, the computed wavefront error and the sent WF command.
4. Wavefront command echo (RTMS)	The CCS returns the applied WF command as an echo back to the WFC loop.

The WFC Loop is optimized by the following SRTC components:

SRTC Component	Description
DHO Optimizer	It identifies the wavefront error (WFE) that is unseen by the SCAO WFS by analysing FPS data with the algorithm ALWFS.[4] Furthermore, it minimizes the WFE by computing a new reference WFS signal for the WFC loop
Command Matrix (CM) Optimizer	It optimizes the CM by taking into account the current misregistration, the subaperture flux and the pupil rotation angle.

5. AUXILIARY AO CONTROL LOOPS

The auxiliary AO control loops are the components of the AO OCS and not of the RTC because they are without real-time requirements.

5.1 Differential Tip-Tilt Loop

The DTT loop uses Quadrant Analysis of Coronagraphic Images for Tip-tilt Sensing (QACITS) in order to center the star on the Vortex Phase Mask (VPM) during HCI observations. The typical data path is depicted in figure 5 and it is described below:

Item flow	Description
1. Raw science images (RTMS)	The science image detector controllers transmit images to the FPS GW via RTMS.
2. Data Display Tool (DDT) FPS pixels(CII MAL PS)	The FPS GW translates the raw science images to calibrated DTT FPS pixels and sends them to the DTT loop through via publish-subscribe (PS) communication mechanism using Core Integration Infrastructure (CII) CII Middleware Abstraction Layer (CII).
3. Modulator offset (CII MAL RR)	The DTT loop computes a modulator offset and commands the SCAO FCS device manager to apply it through a request-reply (RR) communication mechanism through CII MAL.
4. Modulator offset (OPC/UA)	The SCAO FCS device manager sends the modulator offset to the Programmable Logic Controller (PLC) through the network protocol Open Platform Communications / Unified Architecture (OPC/UA).
5. Modulator offset (Fieldbus)	The PLC commands the modulator to apply the offset.

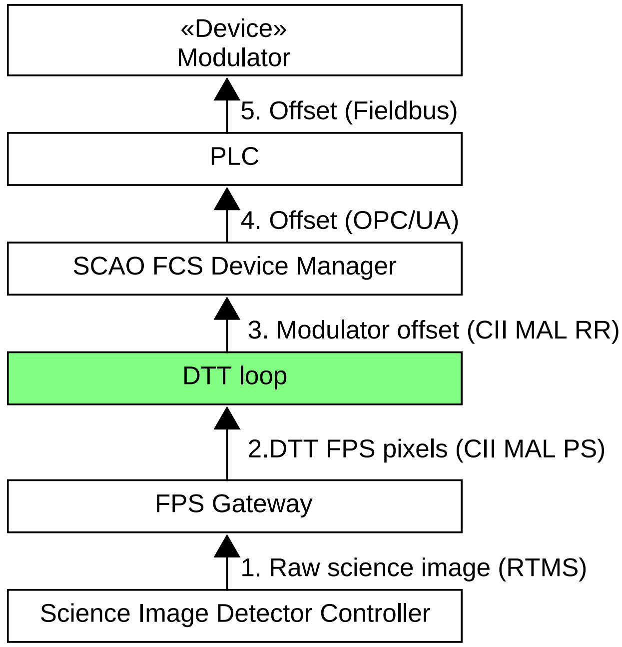

Figure 5. DTT loop data path.

5.2 Pupil Position Control Loop

The PPC loop drives the Pupil Stabilization Mirror (PSM) in order to stabilise the pupil. Figure 6 shows the data path which is explained in the table below.

Item flow	Description
1. WFS image telemetry data (MUDPI)	The WFC loop sends out WFS images as telemetry data through MUDPI.
2. WFS image (DDS)	The Telemetry Republisher inside of the SRTC forwards the WFS image to all subscribers through Data Distribution System (DDS).
3. WFS image (SHM)	The Telemetry Subscriber forwards the WFS images to all subscribers via a mechanism based on Shared Memory (SHM).
4. Pupil position (OLDB)	After the Pupil Position Monitor has accumulated sufficient WFS images, it estimates the current pupil position from images[5] and publishes the position in the On-line Database (OLDB).
5. Pupil position offset (CII MAL)	The PPC loop computes the pupil position offset and commands ICS FCS to apply that offset.
6. Pupil Position Offset (OPC/UA)	The ICS FCS commands the PLC.
7. PSM Position Offset (Fieldbus)	The PLC commands the PSM device via a fieldbus to apply the position offset.

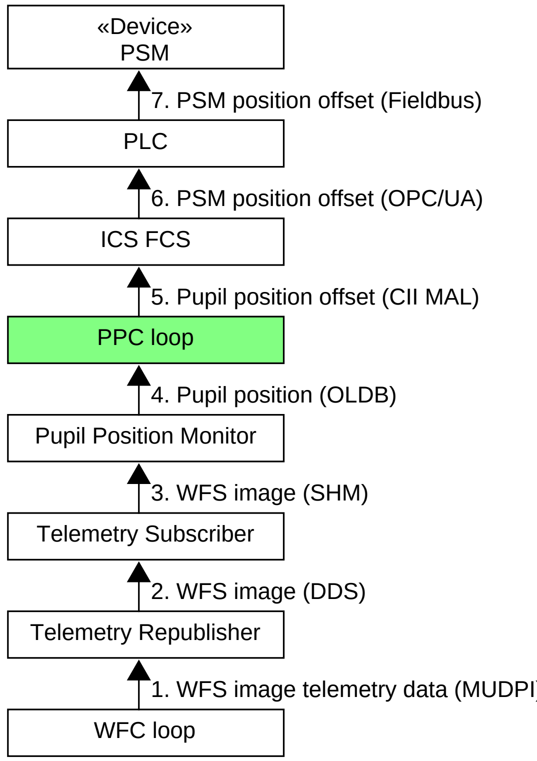

Figure 6. PPC loop data path.

6. CONCLUSION

METIS AOCS is currently under active development. The METIS consortium plans to deliver the instrument and its AO system to the ELT in 2028. The critical parts of the main AO loop (WFC loop) have already been implemented on an HRTC in such a way that the RTC performance requirements are met.[2] The DTT loop design is finished and its core algorithm QACITS is understood. We have designed the PPC loop, and we have created a prototype of its challenging task of identifying the pupil position. In summary, we are confident of delivering the control loops in time for the MAIT activities.

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