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TMT Adaptive Optics Systems Control Architecture

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ABSTRACT

Achieving the science goals of TMT will require AO subsystems of unprecedented power and sophistication, including a Real Time Controller (RTC) subsystem that will implement wavefront reconstruction and control algorithms for up to four different laser guide star (LGS) AO systems. The requirements for the RTC represent a significant advance over the current generation of astronomical AO control systems, both in terms of the wavefront reconstruction algorithms to be employed and the new hardware approaches that will be required. Additionally, the number of active components included in the AO systems and the complexity of their interactions will require a highly automated AO Sequencer that will work in concert with the TMT Telescope and Instrument Sequencers. In this paper, we will describe the control and software requirements for the whole AO system, and in particular for the RTC and the AO Sequencer. We will describe the challenges involved in developing these systems and will present a conceptual design.

Keywords: Thirty Meter Telescope Project, Adaptive Optics, Real Time Controller, Adaptive Optics Sequencer

1. INTRODUCTION

The Thirty Meter Telescope Project [1] is studying a suite of instruments [2], seven of which will require AO or the use of a facility AO system [3]. These instruments include a mid-IR echelle spectrometer, which will implement a Mid Infrared AO system (MIRAO) [4], a wide field optical spectrograph, which will be fed by a Ground Layer AO (GLAO) system [5], a multi object near-IR spectrograph, which will implement a Multi Object AO system (MOAO) [6, 7] and a planet formation imager/spectrometer, which will require the use of Extreme AO (ExAO) [8]. The TMT facility AO system, called NFIRAOS [9], will provide AO compensation for three near-IR instruments: IRIS, NIRES and WIRC. NFIRAOS is a Multi Conjugate Adaptive Optics (MCAO) system and provides turbulence compensation over a moderately large field of view (1-2 arc minutes), in order to sharpen the images of natural guide stars and improve the sky coverage.

The TMT AO instruments and the NFIRAOS facility will have very challenging requirements, leading to the need for Real Time Controllers (RTC) with computational capabilities far beyond the current generation of astronomical AO Real Time Controllers. Four of these five AO systems (NFIRAOS/MCAO, GLAO, MIRAO and MOAO) will implement sodium Laser Guide Stars (LGS) and will have very similar functional requirements in terms of real time wavefront reconstruction. The differences will mainly be in terms of number of inputs and outputs to control. Based on this analysis, an important objective of the TMT project is to demonstrate the feasibility of a common "TMT RTC platform" which uses current or near current real time processing hardware and which is modular enough in terms of hardware and software to meet the requirements of at least these four LGS AO systems.

The TMT Laser Guide Star Facility (LGSF) [10], composed itself of the Laser System, the Laser Safety System and the Beam Transfer Optics and Laser Launch Telescope System, will generate up to eight LGS beacons in four different asterisms required by the TMT AO instruments or AO facility. Additionally, TMT currently plans to implement a conventional secondary mirror at first light and then upgrade to an adaptive secondary mirror at a later date. An adaptive secondary (AM2) will enable the use of GLAO, will improve the performance of the MIRAO system and will make feasible the upgrade path of NFIRAOS by offloading low order, large stroke wavefront corrections from the deformable mirror. All of these AO systems, including the LGSF and the AM2, will be controlled and coordinated by the AO Sequencer. Such a system will be critical to achieving successful AO assisted observations.

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In this paper, we focus on these two challenging control systems: the TMT RTC and the TMT AO Sequencer. Following a brief overview of the overall TMT AO control architecture given in section 2, section 3 covers the RTC requirements and the RTC feasibility concepts and section 4 describes the AO sequencer role.

2. AO CONTROL ARCHITECTURE

The TMT AO systems are composed of five main sub-systems: the NFIRAOS facility, the LGSF facility, the adaptive secondary system (AM2), the Prime Focus Source Simulator (PFSS), which is dedicated to commissioning and calibrating AM2, and the AO Sequencer. The AO sequencer will manage and coordinate these 5 systems as well as the AO components of the AO instruments (MIRES/MIRAO, WFOS/GLAO, IRMOS/MOAO and PFI/ExAO) and of the 3 NFIRAOS instruments.

The AO components of the AO instruments consist of the wavefront sensors, the wavefront correctors, the computing systems and the test equipments dedicated to AO. The computing systems are summarized hereafter:

- The RTC, which is responsible for the wavefront correction itself. The RTC controls and reads the wavefront sensors array controllers (AC), which are dedicated to the conversion of the wavefront sensor array signals into digitized pixels, and controls the wavefront correctors.
- The AO Component Controller (CC), which is responsible for controlling and monitoring the slow opto-mechanical AO devices as the “probe arms” of the wavefront sensors or the simulated LGS sources, etc. In some cases, the AO Component Controller will be merged with the instrument Component Controller. However, the AO devices will still be coordinated by the AO sequencer via the instrument Component Controller.
- Additional computing systems will consist of a truth wavefront sensor (TWFS) detector controller responsible for acquiring, processing, displaying and archiving the truth wavefront sensor images. The role of the TWFS is described in detail in the next section.

Finally, the test equipments consist of NGS and LGS simulated sources and a turbulence generator. These test devices are controlled by the AO instrument Component Controller.

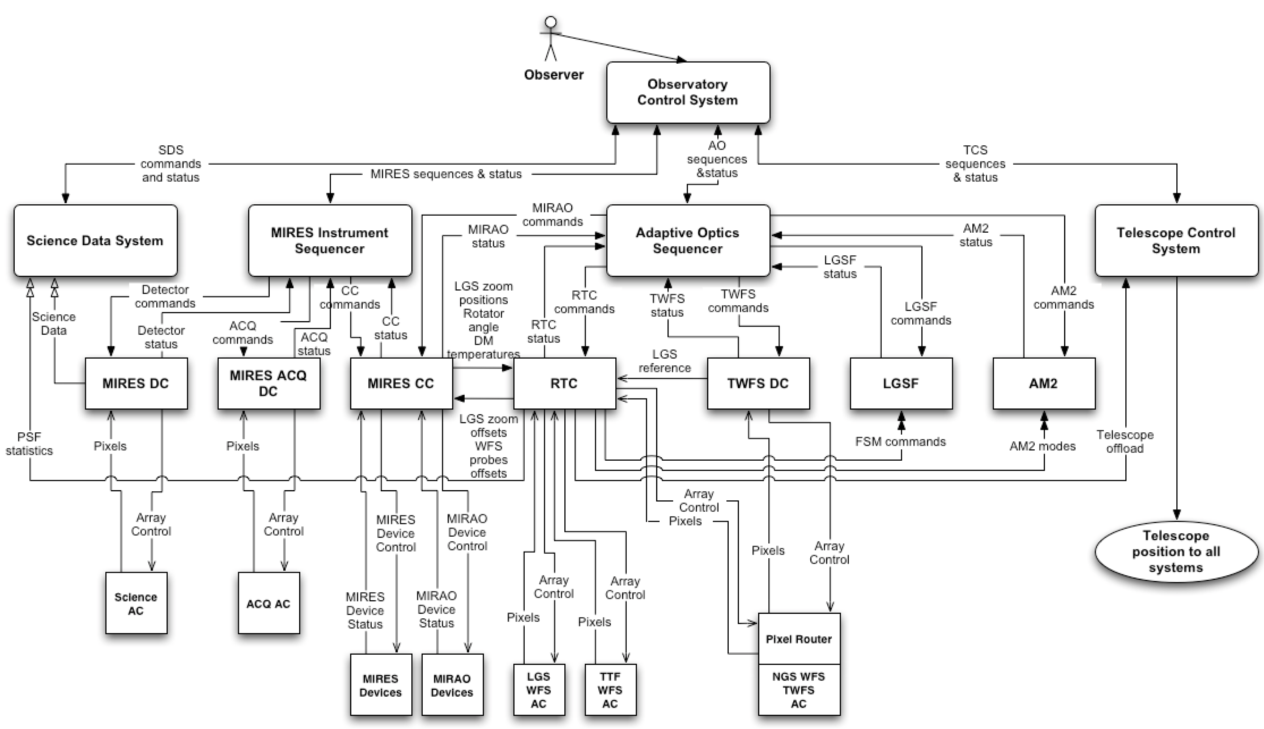

Figure 1: Control of the AO instrument MIRES

Figure 1 describes the specific case of MIRES/MIRAO upgrade, where AM2 is used as the sole wavefront corrector. The AO components of MIRAO are the 3 LGS WFS, and several NGS WFS. The MIRES Component Controller manages the opto-mechanical devices of the WFS (selection mirror, zoom correctors) and the RTC controls the WFS array controllers and the wavefront correctors. Note that on this figure, the NFIRAOS facility and the Prime Focus Source Simulator are not represented because they are not directly relevant to the control of the AO instrument MIRES.

3. RTC

3.1. RTC Requirements Overview

The TMT RTC will provide all the control functions for the TMT LGS AO systems that are required for calibration, test, and real-time atmospheric turbulence compensation. It will operate under the control of the TMT Adaptive Optics Sequencer (AOSEQ) to execute instructions provided either by users or the AO Sequencer itself. It will accept and process input from a suite of wavefront sensors, including multiple LGS wavefront sensors, multiple low-order NGS wavefront sensors, and higher-order NGS wavefront sensors. It will compute and apply commands to one or more wavefront correctors (High order, high bandwidth wavefront correctors like DM or MEMS, woofers and high bandwidth Tip Tilt devices) on the basis of these WFS measurements. It will interface with additional telescope and AO subsystems as necessary for real-time atmospheric turbulence compensation, including the Telescope Control System, the LGS facility, the Adaptive Secondary Mirror, and the AO or instrument Component Controller. Finally, it will update and optimize the control algorithms used for the above purposes in real time as observing parameters and atmospheric conditions change.

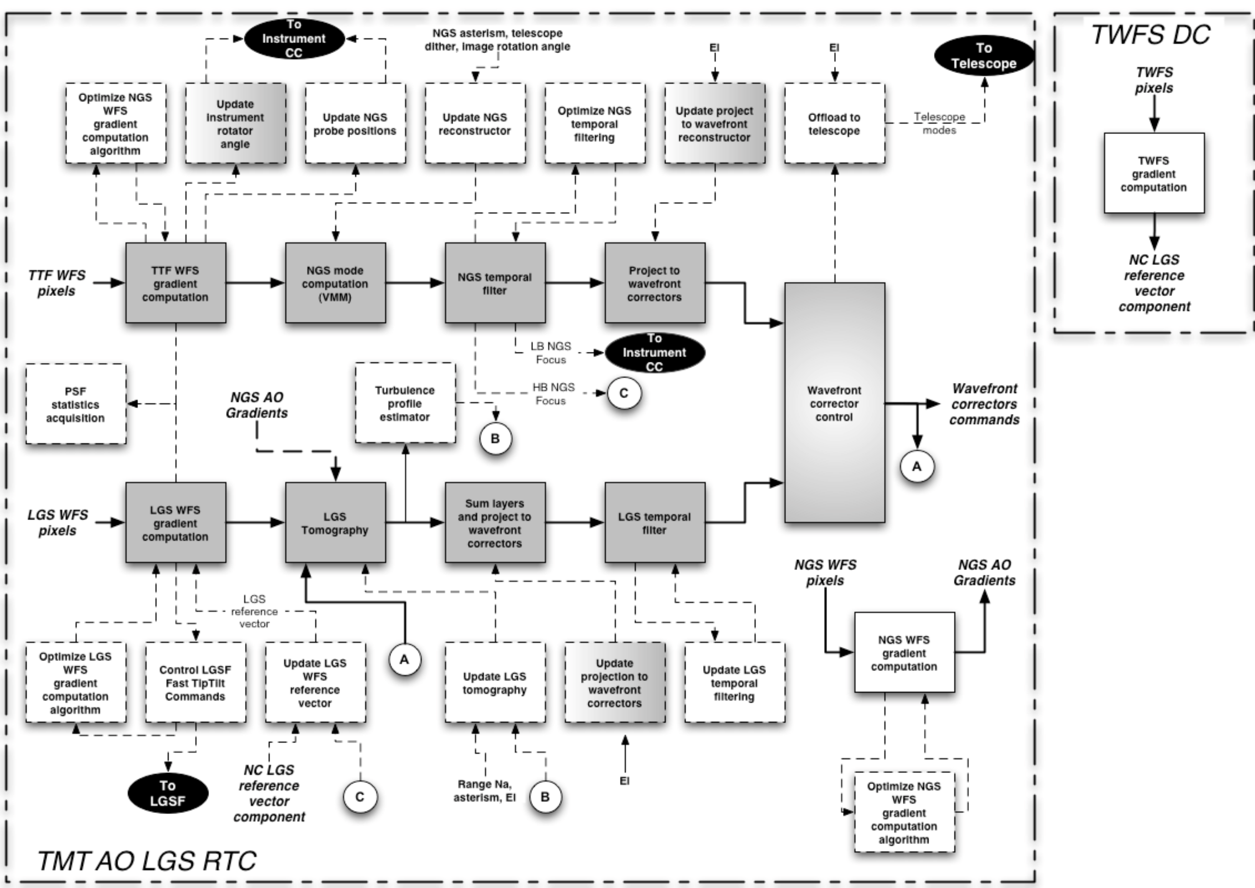

Figure 2: TMT AO LGS RTC block diagram

Figure 2 gives the block diagram of the TMT RTC. The top grey boxes represent the NGS processes and the bottom grey ones the LGS processes. The grey box with a radial fill is dedicated to the control of the wavefront correctors. The dashed boxes correspond to the optimization and background processes. Finally, the dashed boxes with a linear fill represent the processes, which are not common to all TMT AO instruments. All these processes will be discussed in great details in the next sections.

3.2. WFS processing requirements

As explained above, the RTC will input the pixels from a series of LGS and NGS WFS. The LGS WFS of the AO instruments will be Shack Hartmann WFS and will have 60x60 sub-apertures. They will contain an innovative radial format CCD [11] designed specifically for use with elongated laser guide stars. In LGS mode, the RTC will also input the measurements from additional NGS WFSs: (i) low order high bandwidth WFSs (referred as "TTF" WFS) dedicated to tip-tilt compensation and focus sensing and (ii) high order low bandwidth WFSs (referred as Truth WFS) used to calibrate slow-varying WFS biases due to flexure effects and variations in the sodium layer profile. Some of the AO instruments will implement a NGS mode and the RTC will have to input the measurements of a high order high bandwidth NGS WFS (referred as the "NGS WFS"). The number and type of WFS used by the TMT AO instruments are summarized in Table 1. Note that this table does not describe the upgrade path of MCAO/NFIRAOS and MOAO, where the LGS WFS will be upgraded to a 120x120 sub-apertures WFS (i.e 480 kpixels per LGS WFS and 23 kgradients per LGS WFS).

		MCAO/NFIRAOS	**MIRAO**	**GLAO**	**MOAO**	
					Study 1	**Study 2**
LGS mode	**LGS WFS**	***6 LGS WFS (720 kpixels, 34 kgradients)***	***3 LGS WFS (360 kpixels, 17 kgradients)***	***4 LGS WFS (480 kpixels, 22 kgradients)***	***8 LGS WFS (960 kpixels, 45 kgradients)***	
	TTF WFS	3 TTF WFS (2 with 1x1 sub-aperture and 1 with 2x2 sub-apertures, all equipped with an IR detector with 128x128 pixels)	1 TTF WFS (with 2x2 sub-apertures, equipped with an IR detector with 128x128 pixels)	3 TTF WFS (with 2x2 sub-apertures and equipped with a CCD with 128x128 pixels)	6 TTF WFS (with 2x2 sub-apertures and equipped with a CCD with 60x60 pixels)	3 TTF WFS (with 2x2 sub-apertures)
	TWFS	1 TWFS (equipped with a CCD with 120x120 sub-apertures and 8x8 pixels/sub-aperture)	1 TWFS (same as the NGS WFS, the pixel router sends the pixels to the TWFS computer)	1 TWFS (with 32x32 sub-apertures and equipped with a CCD with 128x128 pixels)	1 TWFS (with 60x60 sub-apertures and equipped with a CCD with 1kx1k pixels)	None
NGS mode	**NGS WFS**	1 NGS WFS (equipped with the radial CCD with 60x60 sub-apertures and 4x4 pixels/sub-apertures)	1 NGS WFS (with 30x30 sub-apertures, IR detector working in J and H band)	None	None	None

Table 1: Number and type of WFS for the TMT AO LGS instruments

In LGS mode, the RTC will input and calibrate the pixels of the LGS WFS and will estimate, at a rate of 800Hz, the gradients using a noise optimal processing algorithm (some variant of the matched filter processing algorithm [12]). In parallel, the RTC will input and calibrate the pixels of the TTF WFS and estimate the gradients using a near-noise optimal processing algorithm (correlation tracking algorithm) at a rate varying between 10Hz and 800Hz.

In NGS mode, the RTC will input and calibrate the pixels of the NGS WFS and will estimate the gradients using a standard centroid algorithm at a rate varying between 10Hz and 800Hz.

3.3. Wavefront reconstruction and control of the wavefront correctors

The number and type of wavefront correctors will vary between the TMT AO LGS instruments and are summarized in Table 2. Note that in the current design, the RTC will control a total of up to 600 modes of AM2. Note as well that the upgrade path for MOAO is not described but mainly will involve MEMS with higher number of actuators (128x128).

<table>
<tr><th rowspan="2"></th><th colspan="2">MCAO/NFIRAOS</th><th colspan="2">MIRAO</th><th rowspan="2">GLAO</th><th colspan="2">MOAO</th></tr>
<tr><th>Baseline</th><th>Upgrade</th><th>Baseline</th><th>Upgrade</th><th>Study 1</th><th>Study 2</th></tr>
<tr><td>High order wavefront correctors</td><td>2 DMs
~7500 actuators</td><td>2 DMs
~16000 actuators</td><td>1 DM
~800 actuators</td><td rowspan="2">AM2
~ 600 modes</td><td rowspan="2">AM2
~ 600 modes</td><td>20 MEMS
~72000 actuators</td><td rowspan="2">19 MEMS
~77800 actuators</td></tr>
<tr><td>Tip/Tilt wavefront corrector</td><td>1 tip tilt platform mounted on one DM</td><td rowspan="2">AM2
~ 600 modes</td><td>1 tip tilt platform mounted on the DM</td><td>20 TTM</td></tr>
<tr><td>Woofer</td><td>None</td><td>None</td><td>None</td><td>None</td><td>20 bimorphs
~600 actuators</td><td>DM
~700 actuators</td></tr>
<tr><td>Total actuators</td><td>~7500</td><td>~16600</td><td>~800</td><td>~600</td><td>~600</td><td>~72600</td><td>~78500</td></tr>
</table>

Table 2: Number and type of wavefront correctors for the TMT AO LGS instruments

The RTC will reconstruct each frame of the WFS measurements into wavefront corrector commands at the rate of 800Hz for the LGS mode or at a rate comprised between 10Hz and 800Hz for the NGS mode, using a minimum variance wavefront reconstructor [13], which exploits the sparse and circulant nature of the influence matrices and which is generally decomposed in two sequential steps: the tomography step and the fitting step (layers distribution and summing and wavefront corrector projection). The minimum variance algorithm, most studied by TMT to derive AO performance estimates, is the Multi Grid Preconditioned Conjugate Gradient (MG-PCG) [14]. An alternative to this algorithm is the Fourier Domain Preconditioned Conjugate Gradient (FD-PCG) [15], which is highly parallelizable and in consequence promising in terms of processing requirements. The same algorithm will be applied to the four AO systems in order to have common core software for all the AO cases. In the GLAO case, however, the wavefront corrector fitting step will be reduced to the projection to the high order modes of AM2, and the standard GLAO wavefront reconstruction is implemented as a ”Tomography step” for an atmospheric profile consisting of only a single ground layer of turbulence.

In parallel to the LGS reconstruction, the RTC will also reconstruct each frame of the TTF WFS measurements into wavefront corrector commands at a rate varying between 10Hz and 800Hz.

The RTC will then apply separately optimized temporal filters to the commands derived from the LGS and TTF WFS measurements to enhance control loop stability and balance the residual wavefront errors due to WFS measurement noise and time delays. In the particular case of MCAO, a woofer/tweeter algorithm will be implemented to control the high frequencies, low amplitudes of the tip-tilt modes with the deformable mirrors and the high amplitudes, low frequencies of these modes with the Tip Tilt Platform [16].

Finally, the control of the wavefront correctors will be highly dependant of the AO system. Two main cases will be considered: (i) the wavefront correctors consist of DMs, TT devices and or MEMS with or without AM2 as a woofer and (ii) the wavefront corrector is AM2. In the first case, the filtered wavefront corrector commands will be clipped to avoid saturation based upon dynamic range and slew rate limits of the mirrors. Uncontrolled modes that are unintentionally applied to the mirrors, as the result of clipping, will be nulled. If a woofer is used, the wavefront corrector commands will be offloaded to the woofer deformable mirror. The edge/slave actuators will be computed to maintain the figure of the deformable mirrors at the boundary and finally, the complete wavefront corrector command vector will be calibrated to compensate for non linearities. In the second case, the filtered wavefront corrector commands corresponding to AM2 modes will be transferred to the AM2 control system. In both cases, the final wavefront corrector commands will be fed back to the LGS wavefront reconstruction process, to enable implementation of the minimum variance wavefront reconstruction algorithm.

3.4. Background and Optimization Processes

The goal of these processes is to continuously optimize or update the different parameters of the LGS and NGS processes and to provide inputs to external components such as the LGSF Beam Transfer Optics/Laser Launch Telescope system or the Telescope Control System. Therefore they are closed loop processes but they run at a slower rate in comparison to the LGS and NGS processes:

- *Optimization of the LGS gradient algorithm*: The parameters of the LGS gradients algorithm will be optimized at a rate of 0.1Hz to adapt for the variations in seeing and in the sodium layer profile. The LGS pointing on the sky will be dithered for this purpose.
- *Optimization of the TTF WFS gradient algorithm*: The parameters of the TTF WFS correlation tracking algorithm will be optimized at a slow rate of 0.1Hz to adapt for the variations in the NGS PSF due to changes in seeing and in the AO performance.
- *Update of the LGS WFS reference vector*: The TWFS will have its own separate processing computer and will provide LGS WFS reference vector update to the RTC at a rate comprised between 0.1Hz and 1Hz.
- *Control of the LGSF fast tip-tilt mirrors*: Finally, based on the LGS WFS gradient measurements, the RTC will compute, filter and transfer at a rate of 800Hz the commands of the fast tip-tilt mirrors of the LGSF dedicated to stabilize the LGS pointing on the sky.
- *Optimization of the NGS WFS centroid algorithm*: The parameters of the NGS centroid algorithm will be optimized at a slow rate of 0.1Hz to adapt for the variations in seeing and in the AO performances.
- *Update TTF WFS probe positions and update instrument rotator angle*: During initial acquisition sequence, the RTC will adjust the position of the NGS WFS to null the WFS tip and tilt measurements and in the case of the MCAO system to also null the tip-tilt anisoplanatism errors. This will be done at a slow rate of up to 20Hz. During observation, the RTC will adjust TTF WFS reference vector or the TTF WFS positions to correct for flexure and will adjust the instrument rotator angle to null any residual field rotation at a rate of 20Hz.
- *Adjust focus of the LGS WFS mechanisms & update the LGS reference vector*: The RTC will also reconstruct the defocus term of the TTF WFS measurements in order to track the variations in the range of the sodium layer and will use this quantity to adjust the position of the LGS WFS zoom mechanisms at slow rate of 1Hz and to update the LGS WFS reference vector at a higher rate comprised between 10 and 800Hz (woofer/tweeter control).
- *Turbulence profile estimator*: The RTC will estimate the strength of multiple atmospheric turbulence layers in real time at a rate of at least 0.1Hz; this estimate will be used as inputs to defining the LGS wavefront reconstruction algorithm parameters.
- *Update LGS and NGS reconstructor*: The RTC will update the reconstruction algorithm at a rate of 0.1Hz based upon variations in the estimated range to the sodium layer, pupil orientation upon the wavefront correctors and WFS lenslet arrays and the estimated atmospheric turbulence parameters.
- *Update the LGS and NGS temporal filters*: The RTC will also update the temporal filter parameters at a rate of 0.1Hz as a function of the WFS measurement noise and the strength and frequency of the atmospheric turbulence.
- *Telescope offload*: The RTC will offload the persistent, low spatial frequency component of the wavefront correctors to the TMT telescope at the following rates: 5Hz for the tip tilt modes, 1 Hz for focus and coma modes and 0.01Hz for up to 100 higher modes.
- *PSF statistics and telemetry data*: the RTC will transfer selected AO loop data (described as AO PSF data) to the TMT Science Data System for point spread function (PSF) estimation. The amount of data and the rates will depend of the AO system and will vary between 27 MB/s for MIRAO and 216MB/s for NFIRAOS upgrade. Input measurements, output measurements and intermediate computations (described as AO telemetry data) will be stored and transferred to an engineering archive for diagnostic purposes. The maximum amount of data to be transferred will depend of the AO system and will be comprised between 0.8GB/s for MIRAO and 7.5GB/s for the NFIRAOS upgrade case.

3.5. Interface Requirements

The TMT RTC will interface with the following systems:

- The AO Sequencer to receive commands and to transfer status and telescope offload modes,
- The Science Data System to transfer the PSF statistics,
- The Engineering Data System to transfer the telemetry data,
- The Telescope Control System to get the elevation angle,

- The LGSF to transfer the commands of the fast tip-tilt mirrors of the Beam Transfer Optics system and to receive/generate interlocks from/to the Laser Safety System,
- The AM2 Control System to transfer the AM2 modes,
- The AO and/or instrument Component Controller to transfer the NGS WFS position offsets, the LGS WFS zoom position offsets, the rotator angle offset, and to receive the DM temperatures, the LGS WFS zoom positions and the rotator angle,
- The WFS array controllers (LGS, TTF, NGS) to receive WFS pixels and to control the arrays,
- The Wavefront Correctors Electronics to transfer the actuator commands,
- The TWFS Detector Controller to get the LGS reference update vector,
- The Observatory Safety System to receive the emergency stop signal.

3.6. End to end latency

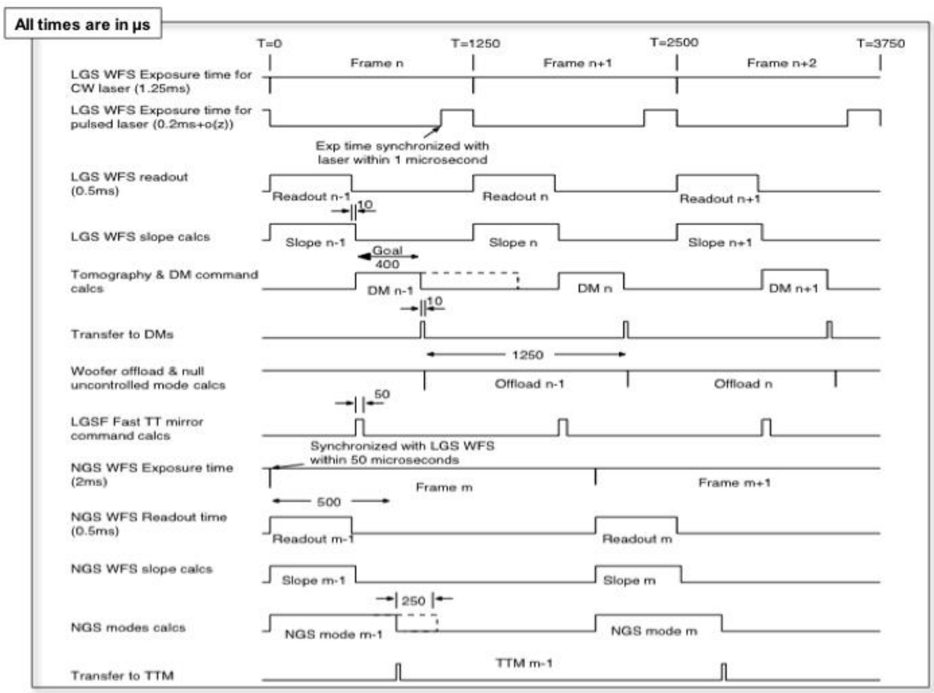

Figure 3: RTC processing timing and latencies

Figure 3 summarizes the timing and latencies of the LGS and NGS processes. The LGS WFS processing will be performed synchronously with the LGS WFS digitization of the pixel intensities with the last sub-apertures gradients computed within 10 µs after the final pixels have been digitized. The computation of the wavefront correctors commands which are based on the LGS measurements will be completed within 1000 µs with a goal of 400 µs. The computation of the wavefront correctors commands which are based on the NGS measurements will be completed within 500 µs with a goal of 250 µs.

3.7. RTC Feasibility Design Concepts

The TMT RTC is a very challenging system in terms of processing requirements and IO capabilities. The TMT RTC processing requirements are at least two orders of magnitude greater than the processing requirements of the Gemini South MCAO RTC [17], which is already as the cutting edge of today's technology. In collaboration with the TMT project, the Optical Science Company (tOSC) has studied 3 different algorithms for the LGS reconstruction: the Multi Grid Preconditioned Conjugate Gradient algorithm (MG-PCG), the Fourier Domain Preconditioned Conjugate Gradient algorithm (FD PCG) and the Order N Tomography algorithm (order-N). Based on the existing processing technology, such as the latest digital signal processors (DSPs) and field-programmable gate arrays (FPGA), tOSC has defined the hardware architecture optimally suited to each of these algorithms.

Order-N, in comparison with the two other PCG algorithms, is a least square reconstructor and has very small processing requirements. The first results given by simulations done by the TMT AO group show reduced AO performances with approximately 90-100 nm additional wavefront error. Although, order-N is attractive for the "small" processing requirements, it does not meet the TMT AO wavefront error budget requirements and is for now only considered as a fallback LGS reconstructor option for the TMT RTC.

The two other candidates were studied side by side, and the FD-PCG algorithm seems to have the greatest potential in terms of parallelization and the likelihood of meeting the processing timing requirements. It is also less demanding in fast internal memory (RAM). The AO performances have not been tested within the TMT AO simulation facility (LAOS) yet, but performance comparable to the MG-PCG algorithm is expected.

Figure 4 describes the proposed architecture for the NFIRAOS baseline RTC, the GLAO RTC and the MIRAO RTC when using the FD-PCG algorithm. Note that this proposed architecture is a feasibility concept, and none of the details has been fully defined as of now.

A group of 7 embedded processing boards constitutes the real-time functionality of the RTC:

- Each board is comprised of either eight DSPs and one FPGA, or eight FPGAs and one DSP, of a type that is available in the market today.
- LGS and NGS WFS processing are accomplished by two DSP, or TigerSHARC boards. The LGS board uses eight 500MHz TS201s from Analog Devices, in order to handle up to eight LGS WFS cameras. The NGS board uses six 500MHz TS201s; one for each of up to four TTF WFS cameras, one for the NGS WFS camera, and one spare. The advantage of using the TigerSHARC over a potentially more powerful FPGA for LGS and NGS pixel processing is that the former is far easier to program and has more internal RAM for storage of the offset and gain values required for proper pixel calibration. As long as the DSPs keep up with the stream of pixels emerging from the WFS cameras, they will create no more latency than would FPGAs.
- LGS tomography and DM fitting are accomplished by the “A”, “B”, and “C” FPGA boards, each of which uses eight 500 MHz Virtex XC4VFX140 FPGAs (field programmable gate arrays) from Xilinx.
- Actuator commands will be sent to the DMs and TTMs using RocketIO ports from each of the “C” FPGAs.
- Background tasks to update the reconstruction algorithm parameters, the temporal filter parameters, etc. are performed in a fourth FPGA board that contains eight 500 MHz Virtex XC4VFX140 FPGAs.
- The specific background task that updates the LGS gradient estimator matrices is performed in a third TigerSHARC board that contains eight 500 MHz TS201s.
- Communication between the TigerSHARC cluster board and the FPGA cluster boards is via full-duplex, 500 MB/S per direction, TigerSHARC link ports, one per TigerSHARC DSP.
- Communication between the FPGAs on a board and between boards is via full-duplex, 650 MB/S per direction, Xilinx RocketIO ports (there are 24 such ports on each FPGA). Additional communication between FPGAs is via LVDS (low-voltage differential signaling) pins, with up to 840 Mb/S per pin pair (there are 448 such pairs on each FPGA).
- Each board sports a 533 MB/s PCI-X interface, and resides in a PCI-X chassis that is controlled by a PCI-X based host processor such as a Pentium D running Windows XP. The RTC’s controlling GUI will provide low-bandwidth commands to the embedded processors, and will retrieve sub-sampled frames of real-time data for diagnostic display.
- Communication with the rest of the observatory will be provided through the control LAN and via the AO real time bus (conceptual design based on reflective memory boards and synchro bus).
- Real-time data archiving is accomplished through ring-buffer RAM boards written into by RocketIO ports, and retrieved by the host via the PCI-X bus.

We believe that this architecture can provide the NFIRAOS baseline AO system with a complete reconstruction in the range of 300 to 650 μs, which is well within the TMT requirement for the end-to-end latency. Furthermore, this architecture appears to have a potential for growing by adding more boards and could possibly be upgraded to meet the requirements of systems like MOAO and or NFIRAOS upgrade, although NFIRAOS upgrade is another order of magnitude greater than NFIRAOS baseline. Finally, the flexibility of these boards to handle a change of algorithm as well as the capability to interface with fast and large WFSs and fast and large deformable mirrors, allow us to consider evaluating this architecture against the TMT ExAO Requirements.

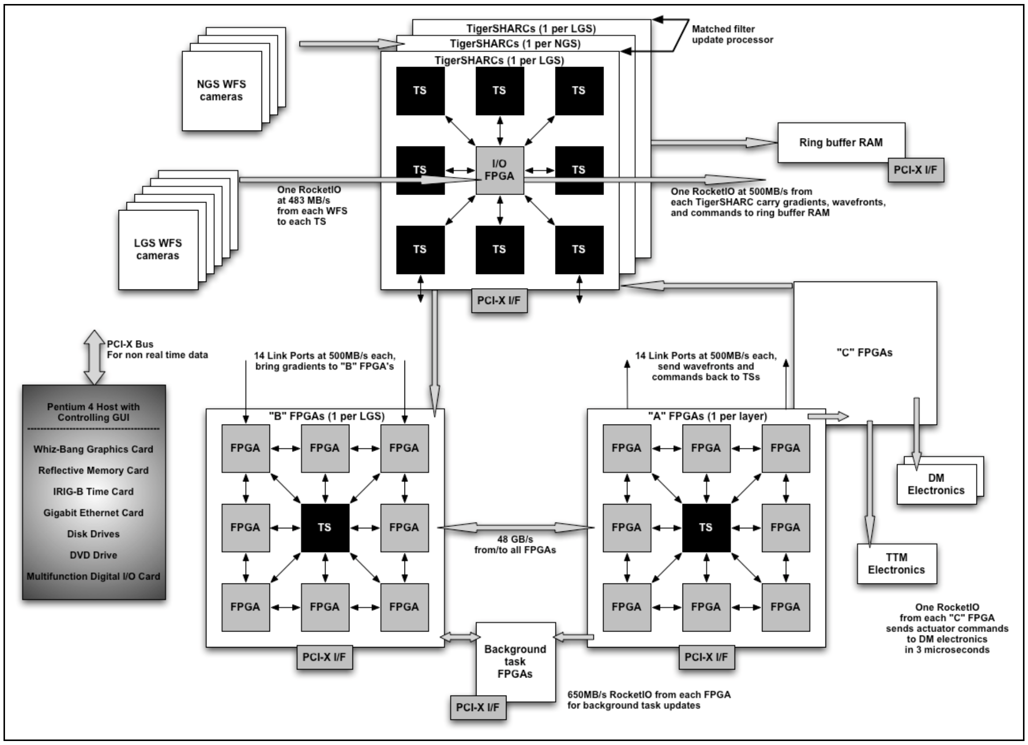

Figure 4: NFIRAOS Baseline RTC architecture supporting the FD-PCG algorithm

4. AO SEQUENCER

4.1. Overview

A TMT science-observing program will result in complex sequences involving the telescope, the AO facilities and an instrument. The Observatory Control System (OCS) [18] will manage all aspects of the science-observing program and act as the main sequencer. The OCS will task the sequencing work to the appropriate sequencers:

- The Telescope Sequencer [19] to sequence the actions of the telescope sub-systems: Mount, M1, M2, M3 and enclosure
- The AO Sequencer (AOSEQ) to sequence the actions of the AO sub-systems: Laser Guide Star Facility (LGSF), AM2, MCAO (NFIRAOS), Prime Focus Source Simulator (PFSS), GLAO, MIRAO, MOAO and ExAO.
- The Instrument Sequencer (one Instrument Sequencer per instrument) to configure and control the instrument.

In particular, the AOSEQ will coordinate all of the internal AO tasks and acts as the main public interface for all AO sub-systems.

The AO Sequencer is composed of several modules as described in Figure 5:

- The main sequencer. The role of the main sequencer is the AO sequencing role of course. It interfaces with the OCS and the AO sequencer modules or directly with the AO systems or AO components (LGSF sub-systems, AM2 and PFSS and the NFIRAOS Acquisition Camera Detector Controller).
- The RTC sequencer, which provides a sequencer role, an integrator role and the offload router. As an integrator, the RTC sequencer will provide the software layer that will make the RTC visible to the rest of the observatory (Indeed, it is possible that the RTC will not include the TMT common communication software package and in consequence, will be invisible to the observatory software). The offload router is the feature that gets the telescope modes computed by the RTCs and routes them to the telescope system.
- The TWFS sequencer, which coordinates the TWFS Detector Controllers

- The Component Controller sequencer, which coordinates the control of the slow AO components via dedicated AO component controllers as described in Figure 5 or via the instrument component controller. In particular, the control of the WFS mechanisms will be the responsibility of the AOSEQ/CC sequencer.
- The Reconstructor Parameter Generator (RPG). The role of this component will be to provide "in real time" the different matrixes of the WFS reconstructors, based on the following inputs: instrument name, which mode is used: LGS or NGS, geometry information (NGS asterism, telescope El and rotation angle) and the signal/noise ratio information (LGS WFS brightness, turbulence profile, wind velocity profile from WFS). It is most likely that this component will be a separate software component written with Matlab or some equivalent.

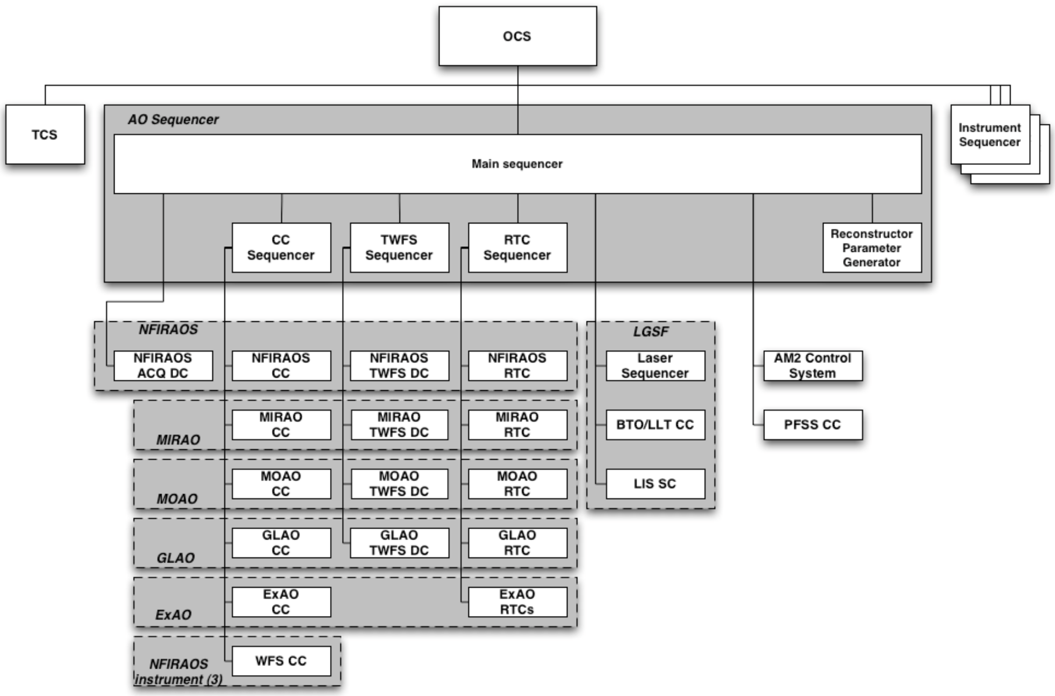

Figure 5: AO sequencer control flow architecture

4.2. Functional requirements of the sequencer

The sequences coordinated by the AO sequencer are split in 3 categories:

1) The AO configuration sequences:

- LGSF configuration sequences to project the required asterism for the corresponding instrument when in LGS mode. The AOSEQ will first check which of the 3 lasers are available and then decide which LGSF configuration to select (or will reject the requested program if sufficient laser power is not available). The AOSEQ will then configure the Beam Transfer Optics system to project the required asterism onto the sky.
- AO opto-mechanical components configuration sequences: The AOSEQ will move the corresponding NGS WFS acquisition mechanisms into the required positions, put these mechanisms into "follow mode", and (in the case of NFIRAOS) configure the NFIRAOS output fold mirror to transmit the science beam to the requested instrument. The AOSEQ will also move the LGS WFS zoom mechanisms to the estimate altitude of the sodium layer adjusted by telescope elevation angle.
- RTC configuration sequences: The AOSEQ will configure the corresponding RTC to work in NGS or LGS mode, configure the number of low order NGS WFS, set the exposure time of the NGS WFS (TTF WFS, TWFS or NGS WFS) and in the case of NFIRAOS will configure which TTF WFS to read, depending upon the choice of the science instrument.

- RPG configuration: The AOSEQ will configure the RPG to compute the control matrices and associated variables for the Real Time Controller of the corresponding instrument.
- AM2 configuration: The AOSEQ will configure the AM2 Component Controller to input commands from the Real Time Controller of the corresponding instrument.

2) The AO calibration sequences:

- Day time calibration sequences, including AO calibration (WFS, DM, flatten the DMs…), LGSF calibration and AM2 calibration.
- Night time calibration sequence for the LGS mode: The Rayleigh background level for each WFS will be measured before each LGS observation. This calibration sequence will be fully automated with the following steps: (i) switch the laser central frequency off the sodium D2 line, (ii) measure the dark (background) for each LGS WFS, (iii) switch the laser central frequency back onto the sodium D2 line.
- Night time calibration sequence for each NGS WFS (TTF WFS, TWFS or NGS WFS) to adjust the WFS exposure time.

3) The AO operation sequences

- Manage AO loops in NGS mode including: (i) start the NGS AO loops, including the optimization and background loops, (ii) move the NGS WFS acquisition mechanisms while in closed loop to compensate for pointing errors, and (iii) control the NGS WFS acquisition mechanisms in closed loop with the NGS WFS measurements
- Start AO loop in LGS mode: these sequences involve the LGSF (to open the shutters and propagate the asterism into the sky), the RTC (to start the AO loops for wavefront correction, uplink tip/tilt correction, and DM offload in a particular order), and the AO Component Controller (to offset the positions of the NGS WFS acquisition mechanisms while in closed loop, or to adjust the positions of the NGS WFS acquisition mechanisms with the NGS WFS measurements).
- Start/Stop the PSF statistic accumulation sequence: once the AO loops are closed, the OCS sequencer will synchronize PSF statistics accumulation with science image acquisition. The control of PSF statistics accumulation will be done via the AO Sequencer
- Stop AO loop in NGS mode: this will comprise turning off all RTC AO loops, including the optimization and background loops
- Stop AO loop in LGS mode, which includes two sequences: (1) stop and (2) stop and change instrument. In the first case, the BTO uplink tip/tilt loops are first stopped, followed by the AO loops, and then finally the LGSF is put into a “standby” mode with the Beam Dump Mirror inserted. In the second case, the BTO uplink tip/tilt loops are first stopped, followed by the AO loops, and then finally the LGSF is put into a “shuttered” mode with the laser shutters closed.
- There will be a few sequences to resume AO operation after a laser safety event occurred that paused the AO operation.

It is important to note that the LGS “operation” sequences for the NFIRAOS case will be innovative in the sense that the high order loops will be closed before the tip-tilt loops to sharpen the tip-tilt NGS images and compute accurate offsets for the NGS acquisition mechanism.

5. CONCLUSION

The TMT overall AO control architecture has been defined. Two keys control components of the TMT AO systems have been identified as critical systems: the RTC and the AO sequencer. The RTC requirements have been defined for the 4 AO LGS systems, and a feasibility concept for the RTC hardware architecture based exclusively on available processing technology, as well as a specific LGS reconstruction algorithm, have demonstrating that the “TMT RTC platform” is within reach. However, more work needs to be done to validate the performance of the FD-PCG algorithm and to benchmark partial implementation of the TMT algorithm with commercial FPGA and/or TigerSHARC boards. The AO Sequencer role is well understood and the functional requirements for this system have been defined. The next step will consist of refining these requirements, and designing this system.

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