THIRTY METER TELESCOPE ADAPTIVE OPTICS COMPUTING CHALLENGES

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Abstract

The Thirty Meter Telescope (TMT) will be used with Adaptive Optics (AO) systems to allow near diffraction-limited performance in the near-infrared and achieve the main TMT science goals. Adaptive optics systems reduce the effect of the atmospheric distortions by dynamically measuring the distortions with wavefront sensors, performing wavefront reconstruction with a real time controller (RTC), and then compensating for the distortions with deformable mirrors. The requirements for the RTC subsystem of the TMT first light AO system will represent a significant advance over the current generation of astronomical AO control systems. Memory and processing requirements would be at least 2 orders of magnitude greater than the currently most powerful AO systems using conventional approaches, so that innovative wavefront reconstruction algorithms and new hardware approaches will be required. In this paper, we will first present the requirements and challenges for the RTC of the first light AO system, together with the algorithms that have been developed to reduce the memory and processing requirements, and then two possible hardware architectures based on Field Programmable Gate Array (FPGA).

INTRODUCTION

The Thirty Meter Telescope (TMT) Project [1] is designing and building a thirty-meter diameter telescope for research in astronomy at optical and infrared wavelengths. The core of the TMT is a wide field, altitude-azimuth Ritchey-Chretien telescope with a primary mirror consisting of 492 segments. Instruments are located on two large Nasmyth platforms, addressed by an articulated tertiary mirror.

The initial Adaptive Optics (AO) architecture for the TMT is defined to provide near-diffraction-limited wavefront quality and high sky-coverage in the near infra-red (IR) for the first light TMT science instruments IRIS, a near-infrared instrument with parallel imaging and integral-field-spectroscopy support; and IRMS, an imaging, multi-slit near-infrared instrument. The initial AO architecture is a Laser Guide Star (LGS) Multi Conjugate AO (MCAO) architecture consisting of (i) the Narrow Field IR AO System (NFIRAOS) [2], which senses and corrects for wavefront aberrations introduced by the atmospheric turbulence and the telescope itself, and (ii) the Laser Guide Star Facility (LGSF), which generates a constellation of LGS in the mesospheric sodium layer with the brightness, beam quality and geometry required by both NFIRAOS and the future second generation of TMT AO systems [3].

The NFIRAOS system includes two 60x60-order Deformable Mirrors (DM) conjugated at 0km and 11.2km, one fast Tip-Tilt Stage (TTS) serving as a mount for the ground level DM, six 60x60-order LGS Wavefront Sensors (WFS), one high-order Natural Guide Star (NGS) WFS for non-LGS operations, up to three low-order NGS WFS working in the near–infrared and located within each NFIRAOS instrument (also referred as the On-Instrument WFS or OIWFS), and a Real Time Controller (RTC) processing the inputs from the multiple WFS to compute the commands to the deformable mirrors and the tip/tilt stage at sampling frequencies up to 800Hz.

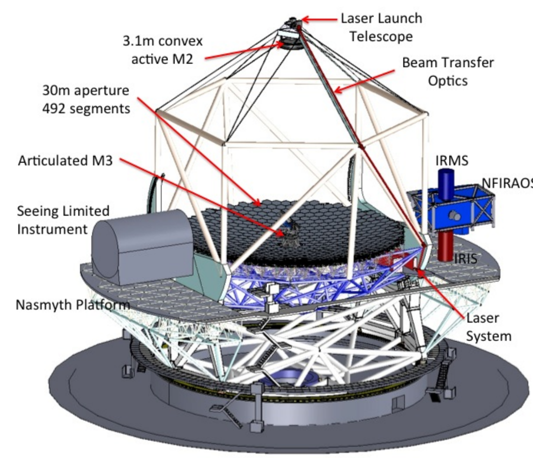

Figure 1: TMT telescope overview and first light instrumentation.

NFIRAOS RTC REQUIREMENTS AND CHALLENGES

The NFIRAOS RTC is one of the most challenging computing components of TMT [4]. It includes several modes of AO operation. The mode that has the most demanding requirements is the LGS AO operation mode. A block diagram of this mode is given in Figure 2.

The RTC requirements in the LGS AO operation mode are split into two categories:

- The *hard real time requirements*, which consist of the LGS wavefront sensor pixel processing, the LGS reference processing, the On-Instrument wavefront sensor pixel processing, the very high-order LGS tomographic wavefront reconstruction using measurements from these multiple wavefront sensors, the On-Instrument wavefront reconstruction and the calculation of the two deformable mirrors and tip-tilt stage commands. These processes are operated at up to a 800Hz sampling rate, with a 1000µs latency (and a strong goal of 400µs).

- The *background and optimization requirements*, which operate at slower sampling rates to i) optimize in real time the parameters of the hard real time processes as the observing parameters and atmospheric conditions change, ii) estimate the turbulence parameters, iii) offload persistent, low spatial frequency components of the deformable mirrors and tip/tilt stage commands to the telescope, iv) compute the commands for the Fast Steering Mirror located within the Laser Guide Star Facility (LGSF) and, v) acquire the data necessary to reconstruct the AO-compensated science PSF in post-processing (compute AO-compensated science PSF as a goal).

Table 1: RTC Key Numbers

Item	**Requirement**
Number of LGS WFS	6
Number of pixels per WFS	204,792
Number of gradients per WFS	5792
LGS frame rate	800Hz
Full frame readout time per LGS WFS	500µs
LGS WFS pixel processing latency (performed synchronously with the digitization of the LGS WFS pixel intensities)	10µs
Number of DM actuators	7673
Latency from last gradient to last DM command	1000µs (goal of 400µs)
RTC telemetry storage	90TB (goal of 140TB)
RTC telemetry required data rate	3.5GB/s (goal of 5GB/s)
PSF statistical data required data rate	60MB/s
RTC maximum power dissipation	1500Watts
RTC telemetry storage maximum power dissipation	6000Watts

The RTC works in synchronization with the Reconstructor Parameter Generator (RPG), which sole tasks are to initialize all of the RTC hard real time parameters, and update in real time the wavefront reconstructor parameters and temporal filters based on the RTC inputs. The RPG is also in charge of monitoring the performance of the AO system during observations and providing the tools necessary to calibrate the AO system during day-time calibrations.

Some aspects of this architecture, which have received considerable attention over the last years include the implementation of:

- The LGS WFS and OIWFS "matched filter" gradient estimation algorithms within the LGS WFS and OIWFS pixel processing processes;
- The "split tomography" wavefront reconstruction algorithm, which decomposes the atmospheric turbulence profile into two orthogonal subspaces, which are estimated and controlled separately using the On-Instrument and LGS WFS measurements;
- The real-time estimation of the turbulence profile and atmospheric parameters using slope detection and ranging method (SLODAR);
- The temporal filters and telescope offloads in the deformable mirrors and tip/tilt stage control processes.

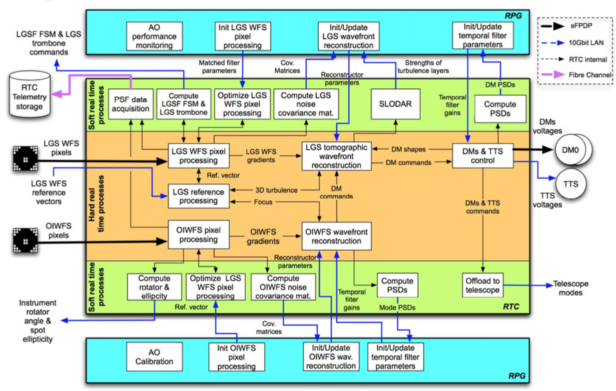

Figure 2: Top-level RTC control block diagram for the LGS AO operation mode. The RTC works in synchronization with the Reconstructor Parameter Generator (RPG – blue boxes). The RTC processes are split into two categories: the hard real time processes (orange) and the background and optimization processes (green). Finally, but not least, the RTC design should be modular to allow the system to be modified or upgraded for the next generation of AO systems.

Wavefront Pixel Processing

The LGS WFS pixels are processed using a constrained matched-filter algorithm. It is a noise optimal algorithm, which allows a reduction in the laser power requirements compared with a classical center-of-gravity algorithm. It consists of a simple matrix-vector multiplication performed synchronously with the digitization of the pixels intensities. The matched filter algorithm is updated in real time at a 1Hz sampling rate (goal of 10Hz) to account for changes in seeing, sodium layer profile and laser beam quality. The optimization is performed by dithering the Laser Guide Star Facility fast steering mirrors.

The On-Instrument WFS pixels are processed using a constrained matched filter algorithm as well. The matched filter algorithm is updated in real time at a 0.1Hz sampling rate based upon variations in seeing and AO system performance.

Computationally Efficient Wavefront Reconstruction

The NFIRAOS wavefront reconstruction problem requires the computation of over ~7700 DM actuator commands from about ~35,000 LGS WFS measurements at a frame rate of 800 Hz. The standard matrix-vector-multiply (MVM) solution becomes very impractical for systems of this dimensionality, particularly if the control matrix must be updated in real time to account for changes in the atmospheric turbulence profile, rotation of the TMT pupil, or other time-varying effects, which would require the inversion of a very large matrix in real time. Computationally efficient algorithms must be implemented instead. Generally speaking, these algorithms implement close approximations to minimum variance atmospheric tomography. These tomographic algorithms are performed in two steps: estimation of the atmospheric turbulence profile from the LGS WFS measurements, and then projection onto DM locations (least-squares DM fitting). Five low-order modes are computed at lower bandwidth from the On-Instrument WFS wavefront reconstruction using a noise-weighted least-squares reconstruction control matrix. These modes are converted into DM commands and integrated with the DM commands computed from the LGS measurements (split tomography).

Four algorithms have been studied for the tomography step and they all meet the required AO performance in terms of wavefront errors: (i) 30 iterations of Conjugate Gradient without preconditioning (**CG30**), (ii) 3 iterations of Conjugate Gradient with a Fourier Domain Preconditioning Hermitian Matrix (**FD-PCG3**), (iii) Block Gauss-Seidel with 20 iterations of Conjugate Gradient for each layer (**BGS-CG20**) and (iv) Block Gauss-Seidel with Cholesky Back Substitutions for each layer (**BGS-CBS**). Note that closed loop convergence of all these algorithms is accelerated by using warm restart. Finally, the DM fitting step is performed using 5 iterations of Conjugate Gradient. Each proposed algorithm can be expressed as a combination of sparse matrix multiplication, geometrical wavefront propagation through square grids, Fourier transforms, and/or Cholesky back-substitution through triangular sparse matrices.

Finally, the LGS WFS reconstruction parameters are updated in real time at a 0.1Hz sampling rate.

DMs and TTS control

A simple integrator filter with an adjustable gain is applied to the DM error signals computed by the wavefront reconstruction processes. A woofer/tweeter algorithm is implemented for the control of the tip/tilt modes: the TTS commands are obtained by applying an additional proportional-integrator filter to the tip/tilt components of the filtered ground-layer DM commands. The filtered DM and TTS commands are clipped to avoid saturation, and integrator windup is prevented by subtracting such clipping adjustments from the inputs of the temporal filters.

RTC Memory and Computation Requirements

The memory and computation requirements for the LGS WFS pixel processing and the LGS wavefront reconstruction processes are presented in Table 2. These are the most demanding RTC requirements. The LGS wavefront reconstruction memory and computation requirements are presented for the four algorithms described above. Two byte fixed-point arithmetic has been used to estimate the memory requirement for the LGS WFS pixel processing requirements and four byte floating-point arithmetic has been used to estimate the memory for the LGS wavefront reconstruction process. These requirements are useful, but not sufficient to demonstrate that a specific parallel hardware architecture meets the TMT requirements. Data transfer required between the processing elements should be carefully analyzed and minimized when designing the hardware architecture to avoid stall issues.

Table 2: RTC Computation and Memory Requirement

	Memory (MB)	**Nb. of Op. GMAC/s (1000μs latency)**
LGS WFS processing	10	7
LGS wavefront reconstruction		
BGC-CBS	50	80
BGS-CG20	2	280
CG30	2	245
FD3 (2 layers oversampled)	10	140

RTC CONCEPTUAL DESIGN STUDIES

Two RTC conceptual design studies were conducted for TMT in 2009. One study was lead by Dominion Radio Astrophysics Observatory (DRAO) and also included HIA, Lyrtech and the University of Victoria [5]. The second study was performed by the Optical Sciences Company (tOSC) with support from Montana State University. Both groups developed successful designs meeting all performance requirements, and in some cases many goals, for the NFIRAOS RTC. Both studies implemented the processing algorithms specified by TMT in designs based upon existing field programmable gate arrays (FPGAs) and digital signal processors (DSPs), and in electronics packages meeting the requirements for rack space, mass, and power dissipation. The proposed hardware architectures have similarities, but depend greatly upon the choice of tomographic algorithm, which impacts the processing and memory requirements.

DRAO Conceptual Design

A block diagram of the conceptual design proposed by DRAO is given in Figure 3.

The hardware architecture consists of nine custom FPGA boards each including six Xilinx Virtex-5 FPGA, two custom interface boards with thirty-two sFPDP full duplex-links for communication with AO components and RTC telemetry storage system (referred as data recorder in Figure 3) and two general purpose computer boards. The boards are mounted within an Advanced Telecommunications Computing Architecture (ATCA) chassis. The system is highly modular and meets the TMT latency requirement using fixed-point arithmetic and the Block Gauss-Seidel with Cholesky Back Substitutions algorithm. The high-speed WFS pixels are received by the interface boards and then distributed to two FPGA boards, which compute the WFS gradients. The WFS gradients are then forwarded to the wavefront reconstruction engine, which consists of seven FPGA boards and which computes the DM commands. The DM commands are then forwarded to the interface boards, and then applied to the DMs. Scaled down versions of the processes were implemented on Xilinx FPGA to demonstrate the processing time and validate the fixed-point operations.

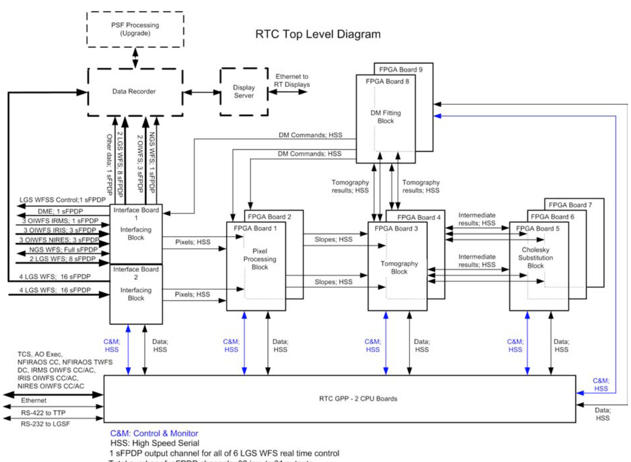

Figure 3: DRAO proposed conceptual design.

tOSC Conceptual Design

A block diagram of the conceptual design proposed by tOSC is given in Figure 4.

The hardware architecture consists of seven TigerSHARC cluster boards, each equipped with eight TigerSHARC DSPs and one Xilinx Virtex-5 FPGA, four FPGA cluster boards each equipped with four Xilinx Virtex-5 FPGA and one TigerSHARC DSP, and one general purpose CPU board. The boards are mounted within an ATCA chassis. The proposed architecture meets the TMT latency goal requirements using floating-point operations and the Conjugate Gradient without preconditioning algorithm. The TigerSHARC boards are used to handle the WFS pixel processing (calibrations, gradient computations and matched filter updates, etc…). The FPGA boards handle the LGS wavefront reconstruction and associated background and optimization tasks. Key functions of the selected algorithm and data transfers were tested on Xilinx FPGA evaluation boards.

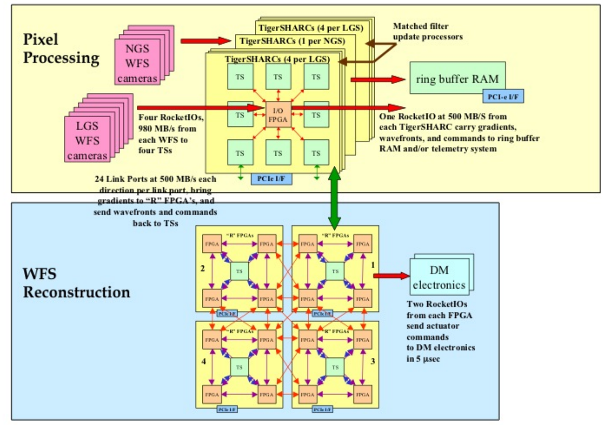

Figure 4: tOSC proposed conceptual design.

CONCLUSION

The TMT NFIRAOS RTC requirements are challenging not only because of the computing and memory requirements, but also because of the complexity of the algorithms to implement, and the number of interfaces to manage. We have demonstrated that the RTC can be implemented via modular and highly parallel hardware architectures, which use existing computing technologies. The next steps for the RTC will be to review the latest generation of multi-processors (Xilinx Virtex-6, Nvidia GPU…), then to define the hardware architecture for a selected algorithm, and finally to prototype and test key components of the RTC hardware architecture.

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