Gemini MCAO Control System

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ABSTRACT

The Gemini Observatory is planning to implement a Multi Conjugate Adaptive Optics System as a facility instrument for the Gemini-South telescope. The system will include 5 Laser Guide Stars, 3 Natural Guide Stars, and 3 Deformable mirrors optically conjugated at different altitudes to achieve near-uniform atmospheric compensation over a 1 arc minute square field of view. The control of such a system will be split in 3 main functions: the control of the opto-mechanical assemblies of the whole system (including the Laser, the Beam Transfer Optics and the Adaptive Optics bench), the control of the Adaptive Optics System itself at a rate of 800 frames per second and the control of the safety system. The control of the adaptive Optics System is the most critical in terms of real time performance. In this paper, we will describe the requirements for the whole Multi Conjugate Adaptive Optics Control System, preliminary designs for the control of the opto-mechanical devices and architecture options for the control of the Adaptive Optics system and the safety system.
Keywords: Multi Conjugate Adaptive Optics, Control System, Real Time System, Safety System

1. INTRODUCTION

The Gemini Observatory, two IR-optimized 8-m telescopes located at the summit of Mauna Kea, Hawaii, and Cerro Pachon, Chile, is designing a Multi Conjugate Adaptive Optics System (MCAO) for the Gemini South telescope. MCAO will utilize multiple guide stars and several deformable mirrors optically conjugated at different altitudes to achieve near-uniform atmospheric turbulence compensation over a 1 arc minute square field of view [1,2,3,4]. The performance goals for the system include near-diffraction-limited atmospheric turbulence compensation at near IR wavelengths, more specifically a delivered Strehl ratio of 0.4 at 1.65 microns under median seeing conditions. This new technique will not only increase the compensated field of view by an order of magnitude or more and provide a uniform point spread function over this field, but will also solve for the cone effect, a limitation of the use of lasers as guide stars, which in a classical AO laser system reduces the performance at short wavelengths on large telescopes. In addition to the 10 fold gain in angular resolution, MCAO also pushes the detection limit by 1.7 magnitudes on unresolved objects with respect to seeing limited images. Anisoplanatic wave front errors will be reduced by means of multiple deformable mirrors (3), which will be used to compensate for turbulence in three dimensions. The combination of 5 high-order laser guide star (LGS) wave front sensors and 3 tip/tilt natural guide star (NGS) wave front sensors are required to characterize the three-dimensional turbulence distribution and compute the commands to each mirror. The LGS wave front sensors will observe guide stars generated at a wavelength near 0.589 microns in the mesospheric sodium layer. 3 NGS wave front sensors will be used to measure tip/tilt and tilt anisoplanatism, modes that are undetectable using laser guide stars due to the LGS tilt indeterminacy problem. Each NGS wave front sensor (WFS) will measure tip/tilt with a spectral passband of approximately 0.45 to 0.85 microns. This instrument will be commissioned in 2005.

As for conventional LGS AO, the MCAO system will contain the six primary subsystems as follows:

- The Laser System (LS), which includes all the elements necessary to produce the 5 laser guide stars.
- The Beam Transfer Optics (BTO) used to transmit the laser light to the Laser Launch telescope.
- The Laser Launch Telescope (LLT) located behind the secondary mirror at the top end of the Gemini Telescope.
- The Adaptive Optics Module (AOM), which includes the deformable mirrors, the wave front sensors and the associated optical, mechanical, electrical components.
- The Safe Aircraft Localization and Satellite Acquisition System (SALSA).
- The Control System (CS), which will implement the Real Time Controller (RTC), which drives the deformable mirror based upon wavefront sensor measurements and also provides the supporting control functions such as opening/closing control loops, and which will implement the control of all the opto-mechanical devices and loops of the BTO, LLT, AOM as well as the control of the SALSA system.

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This paper focuses on the Control System of the whole MCAO system. Following a brief overview in section 2, section 3 describes the control of the Adaptive Optics System itself at a rate of 800FPS. Section 4 covers the control of the opto-mechanical assemblies of the whole system (including the Beam Transfer Optics and the Adaptive Optics bench) and finally, section 5 describes the control of the safety system.

2. MCAO CONTROL SYSTEM OVERVIEW

The MCAO Control System controls the alignment, operation, and diagnostics of the whole MCAO system. It must manage a large number of opto-mechanical devices and still meet stringent real-time performance requirements. In order to do so the MCAO Control System is split in 3 main functions:

- The control of the Adaptive Optics System. This control is achieved by the Real Time Controller which performs the real time wave front reconstruction and directly controls the deformable mirrors (DM) tip-tilt mirror (TTM), and the readout of the WFS components.
- The control of the all the opto-mechanical assemblies. This function is implemented in 3 controllers:
  - The Adaptive Optics Module Controller which manages all of the opto-mechanical assemblies of the AOM except the deformable mirrors, the tip-tilt mirror and the readout of the WFS.
  - The Beam Transfer / Laser Launch Telescope Controller which manages all of the opto-mechanical assemblies of the BTO and LLT.
  - The Laser Controller which manages the opto-mechanical assemblies of the laser itself.
- The control of the SALSA system.

On top of that a sequencer component will be implemented to manage all these independent subsystems and act as the main public interface for the entire MCAO system. The sequencer will coordinate all of the internal tasks and provide external systems with the commands and status information they need to control the MCAO System.

The MCAO Control system will be implemented using the standard Gemini Control System model. It will be a sub-system of the Observatory Control System and fully implemented as an EPICS[7] (Experimental Physics and Industrial Control System) system.

The following figure shows the relationship between the different sub-systems of the MCAO Control System. In this drawing the circles represent the various sub-systems, the simple arrows represent data transfer paths and the double arrows represent continuous data transfer paths.

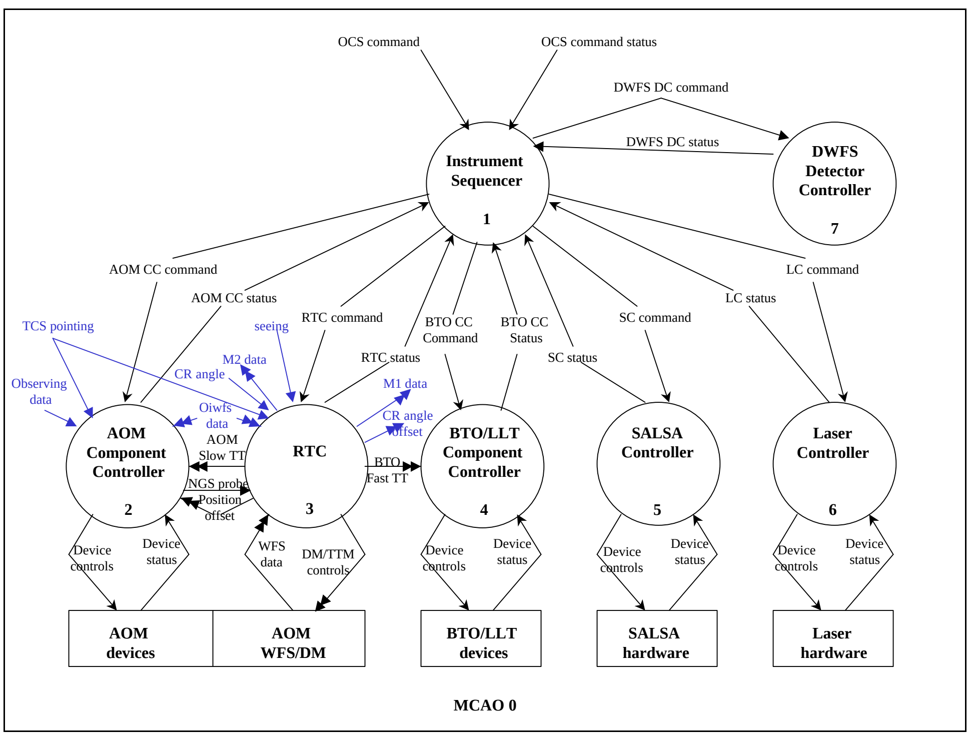

Figure 1: Real Time wave-front control block diagram

3. Control of the Adaptive Optics System

3.1 General description

This controller is dedicated to the Adaptive Optics control loop itself. It is the heart of the system and the most critical part in terms of real time performance. The Real Time Controller will handle 3 basic real time functions:

- The Natural Guide Star (NGS) real time control process,

- The Laser Guide Star (LGS) real time control process,
- The optimization and backgrounds processes.

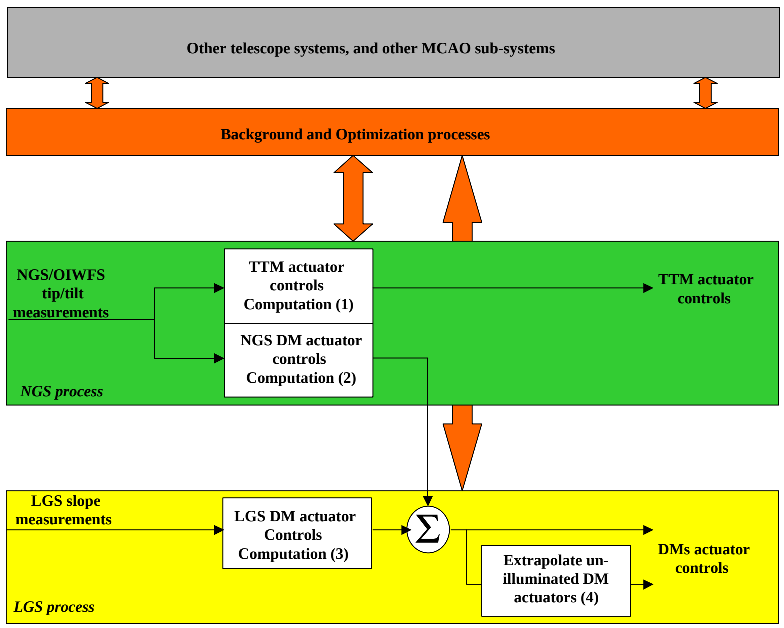

Figure 2: Real Time wave-front control block diagram

The NGS process reads the 3 NGS wavefront sensors and computes the tip-tilt measurements. These tip-tilt measurements are used as input signals to compute the control of the tip-tilt mirrors and used to compute the tip/tilt anisoplanatism modes for the deformable mirrors.

The LGS process reads the 5 LGS wavefront sensors and computes the slopes measurements. These slopes measurements are then used as input signals to compute the control of the 3 deformable mirrors

3.2 LGS requirements and algorithm description:

The LGS is the most critical and computationally intensive process in terms of real time performance. It is composed of:

- Five 16x16 sub-aperture Shack-Hartmann (SH) Wavefront Sensors (WFS) with each sub-aperture composed of 2x2 pixels. Two guard rows and columns of pixels will exist between each sub-aperture. Each WFS will have 204 illuminated sub-apertures. EEV CCD39's with 4 outputs and 80x80 pixels each will be used as the WFS detectors.
- 3 deformable mirrors (DM) with different geometries as described in Table 1.

The LGS control loop is required to operate at 800Hz. The WFS readout time takes 1ms and the computation and I/O (to the deformable mirrors) requires an additional 250 μsec (with a strong goal of 100 to 150 μsec). The LGS WFS readout will drive the loop timing for both the NGS and LGS systems.

Deformable mirror	Number of actuators	Number of active actuators	Number of actuators to extrapolate
DM0	21x21	240	109
DM45	24x24	276	192
DM9	17x17	120	121

Table 1 DM geometry

The control of the MCAO LGS process is similar to the control of a conventional LGS. The 5 WFS and the 3 DMs are not controlled independently but together, and are handled by the control system as one WFS and one DM. The LGS real time process or control loop can be synthesized into the following main sub tasks. These tasks will be performed in pipeline as much as possible:

- Read the 5 WFS. The LGS WFS electronics clocks the LGS control loop and the process starts to read the WFS pixels. The pixels are flat-fielded and bias subtracted before the slope computation:
- Compute the slope information (2040 inputs) for each WFS from the pixel data following a standard centroid algorithm (quad cell algorithm with gains, these gain coefficients will be updated at a 0.1Hz rate by an optimization process). The slope measurements are used as input signals to compute the actuator controls of the DM (636

outputs) via a simple matrix multiplication using a preloaded matrix M_{DM} in memory (matrix size 636,2040). The non-filtered DM control vector $\left|E_{DM}\right\rangle$ is obtained as follows: $\left|E_{DM}\right\rangle = M_{DM}\left|S_{LGS}\right\rangle$, where $\left|S_{LGS}\right\rangle$ represents the centroid vector. The control matrix M_{DM} is computed by the calibration processes before closing the loop. It is updated by a background/optimization process when the loop is closed according to the telescope position and the seeing conditions at a rate of 0.1Hz (or slower). Gains for all the LGS actuators are included into the LGS control matrix.

- Co-add the 636 error signals with a control vector $\left|C_{Null}\right\rangle$ given by a background process which null all DM uncontrolled modes (piston, tip-tilt, waffle…); this background process is executed at the same sampling frequency than the LGS process. A temporal filter is applied to the DM actuator command vector; it will be a simple integrator (or as an option, a leaky integrator or a more general second order filter). Finally, the control vector $\left|C_{ANI}\right\rangle$ that implements the tilt anisoplanatism correction (see section 3.3) is coadded to the integrated vector.
  The result vector $\left|C_{DM}\right\rangle$ will be obtained as follows (using a simple integrator):
  $\left|F_{DM,N+1}\right\rangle = k_{DM} * \left(\left|E_{DM,N+1}\right\rangle + \left|C_{Null,N+1}\right\rangle\right) + \left|F_{DM,N}\right\rangle$ where $\left|E_{DM,N+1}\right\rangle = M_{DM}\left|S_{LGS,N+1}\right\rangle$
  $\left|C_{DM}\right\rangle = \left|F_{DM}\right\rangle + \left|C_{ANI}\right\rangle$ and k_{DM} is the gain of the simple integrator.
  Note that at all levels of the commands $\left|C_{DM}\right\rangle$ computation, clipping tests will be performed.
- Extrapolate the 422 commands of the un-illuminated actuators from the 636 integrated outputs. The extrapolation will consist of 3 matrix multiplications for each deformable mirror (matrix $M_{EXTRA,DM0}$ size 109,240, matrix $M_{EXTRA,DM45}$ size 192,276, matrix $M_{EXTRA,DM9}$ size 121,120). These extrapolation matrixes will be pre-computed using the Kolmogorov model.
  $\left|C_{EXTRA,DM0}\right\rangle = M_{EXTRA,DM0}\left|C_{DM0}\right\rangle$
  $\left|C_{EXTRA,DM45}\right\rangle = M_{EXTRA,DM45}\left|C_{DM45}\right\rangle$
  $\left|C_{EXTRA,DM9}\right\rangle = M_{EXTRA,DM9}\left|C_{DM9}\right\rangle$
  where $\left|C_{DM0}\right\rangle$, $\left|C_{DM45}\right\rangle$ and $\left|C_{DM9}\right\rangle$ are obtained by splitting the vector $\left|C_{DM}\right\rangle$ in 3 parts corresponding to the 3 DMs.

The LGS process is the most critical in terms of real time performance. The number of operations (an addition plus a multiplication) required is around 1.13Giga multiply/accumulate operations (MAC) and corresponds to 2.26 GFlops. The most demanding task is the matrix multiplication. However such a requirement is not impossible, and today several solutions are available based on parallel and multi processor architecture such PPC multi processor boards.

3.3 NGS requirements and algorithm description:

The NGS control system is composed of:

- Three tip/tilt WFS (quad APD type to have a zero electron read noise and a minimal read time limited by the access to the APD counters)
- One Tip Tilt Mirror (TTM)

The NGS real time process or control loop can be synthesized into these main sub tasks executed sequentially at a rate of up to 800Hz:

- Read the 3 WFS. The NGS process is triggered by the LGS process and starts to read the APD signals (vector $\left|APD\right\rangle$).
- Compute the tip/tilt information from the APD signals following a standard centroid algorithm (quad cell algorithm with gains, these gains are updated from a lookup table according to the seeing at a 0.1Hz slow rate) and subtract references. The tip/tilt measurements are then used as input signals to compute the actuators control of the TTM (2 outputs). This corresponds to a simple matrix multiplication using a preloaded control matrix (M_{TTM}) in memory (matrix size 2,6). The WFS centroids can be blended with TT measurements coming from a Shack Hartmann WFS

associated to the science instrument, the On Instrument Wavefront sensor (OIWFS). In this case, we just replace one of the NGS WFS measurements by the OIWFS measurements. The non-filtered TTM control vector $\left|E_{TTM}\right\rangle$ is obtained as follows: $\left|E_{TTM}\right\rangle = M_{TTM}\left|S_{NGS}\right\rangle$, where $\left|S_{NGS}\right\rangle$ represents the centroids. The reference slopes are updated by a background process, according to the OIWFS TT measurements at a slow rate (0.1Hz). The reference slopes compensate for flexure between the NGS WFS and the science instrument.

- Apply a temporal filter to the TTM command vector. This can be a simple integrator or something more elaborate such as a leaky integrator, a PID or a second order temporal filter. The resultant vector is sent to the TTM:
  A simple integrator will result in the following equation:
  $$\left|C_{TTM,N+1}\right\rangle = \left|E_{TTM,N+1}\right\rangle + \left|C_{TTM,N}\right\rangle \text{ where } \left|E_{TTM,N+1}\right\rangle = M_{TTM}\left|S_{NGS,N+1}\right\rangle$$
- Compute the 3 tip/tilt anisoplanatism modes of the DM's from the tip/tilt measurements through a single matrix multiplication. These anisoplanatism modes are then temporally filtered, and a second matrix multiplication converts these DM anisoplanatism corrections into DM's actuator commands (the two matrices M_{ANI} and T_{ANI} are preloaded in memory, and have size of 3,6 and 636,3 respectively). The resultant output commands are summed into the LGS control loop. These matrix multiplications consume a lot of time in comparison to the previous tasks and are done after sending the actuator controls to the TTM.
  The filtered tip/tilt anisoplanatism modes of the DM's are obtained as follows (with a simple integrator):
  $$\left|m_{ANI,N+1}\right\rangle = \left|E_{ANI,N+1}\right\rangle + \left|m_{ANI,N}\right\rangle \text{ where } \left|E_{ANI,N+1}\right\rangle = M_{ANI}\left|S_{NGS,N+1}\right\rangle$$
  and then converts into DMs actuator commands:
  $$\left|C_{ANI}\right\rangle = T_{ANI}\left|m_{ANI}\right\rangle$$
  The control matrices are computed by the calibration processes before closing the loop. They are optimized at a 0.1Hz rate by a modal optimization process when the loop is closed. Gains for all the NGS modes or anisoplanatism modes are included into the control matrices, although temporal filtering algorithms that are more sophisticated than a simple integrator will require minor modifications to the above.

This process is not a critical process in terms of real time performance, at least in comparison with the LGS process. The total number of operations for all these tasks is around 3.16 Mflops or 1.58 Mega multiply/accumulate (MAC) operations. The computations and output to the TTM can be achieved in a few µsec with a simple Power PC CPU 750 running at 366Mhz for example.

3.4 Synchronization of the processes

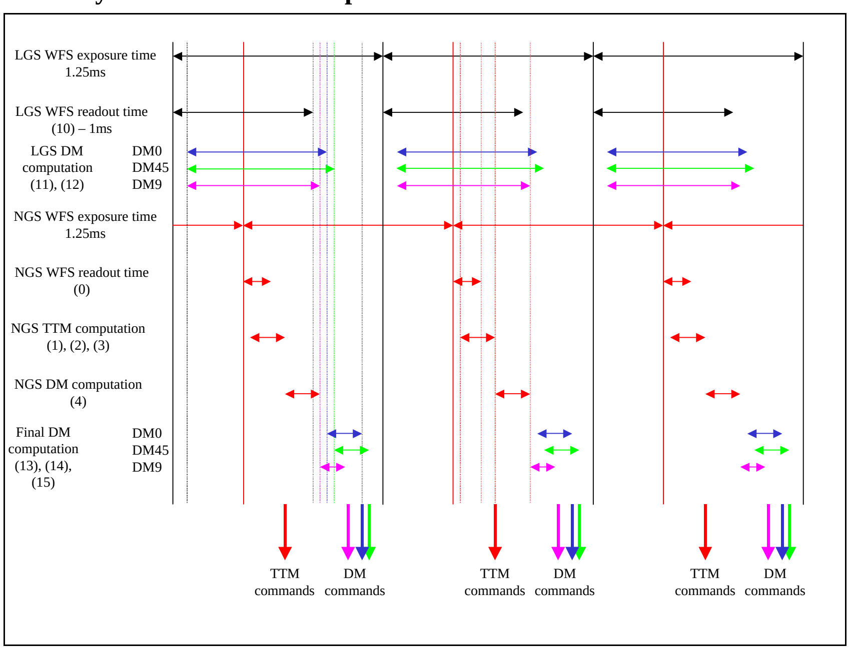

Figure 3: Synchronization of the Real Time Processes

The NGS and LGS processes will have to be tightly synchronized. In this design the LGS WFS will drive the loop timing for both the NGS and the LGS processes. The LGS WFS will trigger the LGS process as soon as a packet of pixels is read. The LGS WFS will start the centroid computation and the matrix multiplication and then wait for the next packet. The LGS process will trigger the NGS process after a fixed delay to reduce the latency between the NGS measurement and the DM commands as shown in the figure

3.5 Optimization and background processes

The goal of such processes is to continuously optimize or update the different parameters of the closed loop processes and also provide data to some outside components such as the MCAO Beam Transfer Optic/Laser Launch Telescope Controller and the MCAO Adaptive Optics Module Controller. Therefore they are closed loop process, but run at a slow rate in comparison to the LGS and NGS processes:

- *NGS WFS gain optimization process*: the goal of this process is to optimize the NGS centroid gains for each sub-aperture from a lookup table according the seeing at a rate of 0.1Hz.
- *Adjust NGS WFS position process*: the goal of this process is to adjust the position of the 3 NGS WFS probes or the reference measurements to correct for flexure, and to null any residual field rotation at a rate of 0.1Hz.
- *NGS modal optimization process*: the goal of this process is to optimize the modal closed loop gains according to the atmospheric turbulence. To perform such an optimization, it is necessary to have the real time values for the TTM modes and for the DM anisoplanatism modes $\left|E_{TTM}\right\rangle$ and $\left|E_{ANI}\right\rangle$. The choice of the modal basis may change from field to field but will be fixed for each science observation. Real time modal values are computed in real time by the NGS process and are stored into a dedicated circular buffer. This mode circular buffer will be big enough to allow the optimization process to read at least 512 mode records while the NGS process continues writing new values. For each of these 5 modes, the square modulus of the FFT is computed using the inputs of the 512 mode records, and then divided by the square modulus of the transfer function of each corresponding mode. This is reproduced a few times and the resulting functions for each mode are averaged and the optimized modal gains are determined. The control matrices used during the steps and possibly the filter coefficients are recomputed and stored into the memory of the processor dedicated to the NGS process without disturbing the NGS process. This process is time consuming and a goal is to update the gains at a rate of 10s.
- *PSF, r0 computation*: The purpose of this process is to compute the PSF and r0 related to the science exposure. During the exposure, statistics of loop data are computed. These statistics are saved in a PSF statistics file and from this file an off-line process is able to compute the PSF associated to the exposure. Side products of the PSF estimation process include an estimate of the average r0, the residual phase variance in the direction of the LGSs and possibly the average height and wind-speed of the turbulence layers at the DMs during the exposure. The PSF statistic file will be linked to the science image file. Note that PSF reconstruction from AO loop data is still a subject under research for a conventional Shack-Hartmann AO system[8], let alone a MCAO system. The sampling rate for computing statistics will be relaxed to 100 Hz. r0 and the residual phase variance will be computed several times during the exposure, every 10 seconds for example, and be used as a real-time diagnostic. Computing r0 is done by fitting a Kolmogorov profile to the DM modal commands and is not particularly demanding.
- *Offload to the secondary and primary mirrors process:* the goal of this process is to offload the TTM and DMs commands to the secondary mirror and the primary mirror of the telescope. The commands from the TTM mirror (tip and tilt commands) available at a 800Hz are averaged during 4 frames, formatted into the secondary coordinates and sent at a 200Hz to the secondary mirror. The focus term is determined at a slower rate (1mn) from the DMs commands. The commands of the DMs available at a 800Hz are averaged during one minute, formatted into the primary coordinates and sent to the sent to the primary mirror. The primary mirror can control up to 19 Zernikes modes. This process is not critical in terms of number of operations to perform.
- *LGS WFS Gain Optimization process*: the goal of this process is to optimize the gain vector used during the LGS WFS slope computations according to the atmospheric turbulence[5]. A goal is to update these gains at a rate of 0.1Hz.
- *The Gain and LGS control matrix optimization process:* The MCAO Sequencer reads the telescope elevation from the Telescope Control System at a rate of once per 10s, and transfers this information to the corresponding RTC optimization process. The purpose of the optimization process is to download to the LGS process a new control matrix from a lookup table according to the telescope elevation and to optimize the global gain of the LGS closed loop process according to the atmospheric turbulence. To reduce the number of computations, this optimization will be done with a sample of the DM actuator command vector. This process will be time consuming and the number of actuators used to do the gain optimization has to be chosen carefully in order to reduce the amount of CPU time needed.
- *Null the piston, waffle, tilt and uncontrolled modes of the DM:* The aim of this process is to check there is no drift for the piston, waffle, associated degenerated piston and waffle modes, tilt and uncontrolled modes of the DM even if they are not controlled (filtered from the control matrix). The total number of uncontrolled modes will be around 60. A goal is to run this process at the same rate than the LGS process (800Hz).
- *Adjust the Tip-Tilt mirrors positions of the MCAO BTO/LLT Controller:* The purpose of this process is to compute the TT values to send to the 5 fast Tip-Tilt mirrors of the BTO[2]. These mirrors keep the 5 laser guide stars centered

in the fields of view of their wavefront sensors. The commands of these mirrors will be computed from the LGS slopes measurements by doing a simple matrix multiplication. This process is not time consuming but needs to be able to send fast TT values to the BTO at a rate of up to 800Hz and to be synchronized with the real time processes.

- *Adjust the pupil alignment mirrors positions of the MCAO AOM Controller:* The purpose of this process is to compute the Tip-Tilt commands to send to the 5 pupil alignment mirrors of the AOM at a rate of 0.1Hz. The process reads the LGS total measurements from the dedicated circular buffer, averages them and compute the overall centroids for each LGS WFS.
- *Real time display:* The LGS and NGS slope and pixels measurements, as well as the actuator controls will be read from the different circular buffers at a slow rate, formatted and displayed only for diagnostic purposes. Some optimization parameters, such as the mode values (TTM and DM anisoplanatism modes), will be also read from the dedicated circular buffer, formatted and displayed for debugging purposes. It will be also possible to do some statistics on these data: average, variance, FFT and to display them.

3.6 Diagnostics

All the real time information (and associated time stamps) will be stored in circular buffers (a circular buffer is a buffer of fixed size containing a fixed number of records. A circular buffer differs from a normal buffer in that it is filled continuously, starting again from the beginning once the end has been reached). These buffers will be shared between several processes and will be architecture dependent. The total size of circular buffer required is around 800Mb.

3.7 DM and WFS interfaces

To control the 5 LGS WFS CCD (5 EEV 39), we will use an upgraded version of the Bob Leach SDSU controller that can handle the high pixel rate, and that uses a PCI interface card (instead of a VME interface card) with one timing board, a clock driver board, and 10 video boards (each video board manages two outputs) in a VME-like back plane. The timing board provides digital timing signals for controlling the readout of the CCD array and communicates with the interface board over a fiber optic link. The clock driver board provides up to 24 switched clock voltages of the CCD array, controlled by the timing signals from the timing board. The video processor board amplifies, processes, and digitizes the signal from two CCD outputs and provides up to 12 DC bias voltages. The new version of the Bob Leach controller is not yet available: It is currently under development and will be available in mid-2001. The interface card can be easily adapted to a PMC version, and this should also be available. The pixel rate to over the fiber optic link will be 7Mpixels/s, which is less than the maximum speed of the fiber optic transceiver (12.5Mpixels/s). In consequence only a single SDSU PMC interface card will be necessary.

To control the DM mirrors, a possible solution will be to use the amplifier provided by Xinetics. Each amplifier board from Xinetics contains 32 channels. A standard 9U chassis contains up to 9 boards (288 channels). For DM4.5 we will need two chassis. The VMETRO Digital parallel IO board (DPIO - D0 / 16 bits version) PMC module board will be a good candidate to interface with the RTC. We will need a modest interface to connect the PMC board to the Xinetics chassis. The datalines from the PMC board will be daisy chained to the two chassis.

3.8 Hardware solution

As discussed in the previous paragraphs, the LGS control is the major user of the CPU power, with a matrix multiplication being the most critical part. Performance at a level of ~3Gflops is required. Today, several solutions are available to fit our requirements based on PPC, DSP or other architectures. Gemini has performed several actions to demonstrate this statement:

- Two vendor have been contracted to study architectures for our requirements:
  - The Optical Science Company (tOSC), located in Anaheim, California,
  - SHAKTIWARE, located in Marseille. France.

  Both have demonstrated than PPC solution is today the best approach.
- In parallel, a quad PPC board (VSS4 Synergy Micro Systems board: VME DSP-Quad PPC 7400@433Mhz, 256 Mb, 8Mb Backside Cache 2:1 ratio), was purchased by Gemini and benchmarks were performed by HIA (in Victoria) to assess the suitability of this board.

A possible solution is proposed in this paper. It allows us to illustrate how an architecture based on VME, PPC could fit our requirements. However the final design will be determined by the vendor and could be different from the one proposed here.

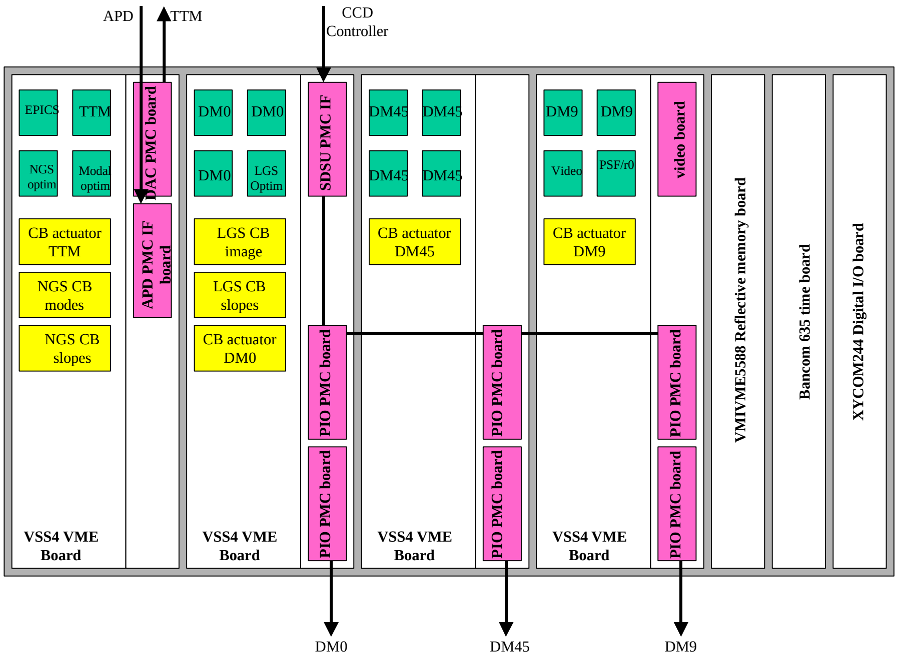

Figure 4: RTC possible hardware architecture

The solution we propose is based on 4 Synergy quad PPC VSS4 boards (1 Synergy board per DM). The VSS4 board has one PMC site, and using Synergy Micro Systems PEX3 PMC expander takes that site to yield three more, for a total of 3 PMC sites per VSS4 motherboard. To output the signals to the DM, a high speed parallel interface (PIO) board plugged directly on one of the PMC site of each quad G4 board will be used. To input the pixels, we will use a second high speed parallel interface board plugged to another PMC site. Each Synergy board will receive the pixels values, will compute the centroids, will do the matrix multiplication that corresponds to its mirror and will send the actuator voltage through its daughter board directly.

To test the computational power of the board, we decided to use LINUX for PowerPC and SMP support (Symmetric Multiprocessing) instead of VxWorks to reduce the costs. A disk and a CDROM driver has been connected to the board and Linux installed successfully. Two scenarios have been tested: a single DM system and the full MCAO system, in both case using floating point processing. For the full MCAO system, the most demanding case (for the DM4.5) has been benchmarking from the point when the pixel data begins to arrive in memory until the final DM4.5 commands (included the extrapolated actuator commands) are computed, and a total latency of 0.9 ms has been obtained when using 4 CPUs. However, further work still needs to be done, which will consist essentially of testing the I/O data streams.

In conclusion, benchmark results and studies are very encouraging, and they both converge to a G4 PPC solution. Such a solution (based on quad or dual G4 PPC boards) is very well adapted to our system. However, several possible options are still envisioned: fixed point or floating point, PCI or VME bus and the final design will be determined by the vendor.

4. Control of the opto-mechanical assemblies

4.1 BTO/LLT Controller

The Beam Transfer Optics (BTO) is the MCAO sub-system which brings the 5 laser beams from the Laser System to the Laser Launch Telescope (LLT) mounted behind the telescope secondary mirror. This sub-system is described in detail in a paper presented in this conference[2]. The BTO/LLT Controller is responsible for managing all of the opto-mechanical devices associated with the BTO and LLT under the direct control of the MCAO sequencer. The Controller will be a full EPICS/VxWorks system.

The following table gives a summary of all the BTO/LLT devices controlled by the BTO/LLT Controller:

Devices	Requirements	Hardware
LLT Cover	The **LLT cover** can be opened and closed remotely	AC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
Pointing mirror	The **pointing mirror** tip and tilt can be set remotely. The mirror can be positioned with a single move command or set to track fast steering array offload and telescope elevation angle via an internal lookup table at a rate of 1Hz.	2 DC servo motors: 2 channels of an OMS58 servo card

Centering mirror	The **centering mirror** tip and tilt can be set remotely. The mirror can be positioned with a single move command or set to track fast steering array offload and telescope pointing (El,Az via an internal lookup table) at a rate of 1Hz.	2 DC servo motors: 2 channels of an OMS58 servo card
K mirror	The **K mirror** rotation can be set remotely. The mirror can be positioned with a single move command or set to track fast steering array offload and telescope pointing (El,Az via an internal lookup table) at a rate of 1Hz.	1 DC servo motor: 1 channel of an OMS58 servo card
Top end ring mirror	The **top end ring mirror** tip and tilt can be set remotely. The mirror can be positioned with a single move command	2 DC servo motors: 2 channels of an OMS58 servo card
Fast Steering Array	The **fast steering array** tip and tilt can be remotely controlled. Each of the 5 mirrors in the array can be independently positioned with a single move command or set to track the RTC demand positions (sent via the synchro bus) at a rate of 800Hz. The **fast steering array** demand positions will be time averaged and offloaded to the pointing mirror and the centering mirror	Piezzo-electric actuators: 10 channels of a XYCOM531 high-speed D/A card
Quarter-wave plate	The **quarter-wave plate** rotation can be controlled remotely. The plate can be moved to one of 20 pre-defined positions with a single move command or set to track the polarization sensor measurement via an internal lookup table at a rate 0.1Hz.	Single stepper motor with encoder: 1 channel of an OMS58 servo card
Alignment camera selector	Which of the **pre-alignment camera** outputs to monitor can be selected remotely	TTL selection signals: 3 output bit of an XVME244 digital I/O card
Power meter	The **power meter** output can be monitored at a rate of 0.1Hz.	A single analog input: one channel of the XYCOM 566 Analog I/O card
Polarization sensor	The **polarization sensor** output can be monitored remotely.	A single analog input: one channel of the XYCOM 566 Analog I/O card
Beam Dump mirror	The **beam dump mirror** can be inserted or removed remotely	AC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
Corner cube shutter	The **corner cube shutter** can be opened and closed remotely.	AC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
Near-field chopper wheel	The **near field chopper wheel** can be positioned remotely. The wheel can be set to one of 7 pre-determined positions with a single move command or be set to track the readout of the bean diagnostics camera at a rate of 5Hz.	Single stepper motor with encoder: 1 channel of an OMS58 servo card
Centering Array	The **centering array** tip and tilt can be remotely controlled. Each of the 5 mirrors in the array can be independently positioned with a single move command or set to track the beam position and the beam tilt measurements provided by the beam diagnostics camera at a rate of 1Hz.	10 DC servo motors: 10 channels of an OMS58 servo card
Pointing Array	The **pointing array** tip and tilt can be remotely controlled. Each of the 5 mirrors in the array can be independently positioned with a single move command or set to track the beam position and the beam tilt measurements provided by the beam diagnostics camera at a rate of 1Hz	10 DC servo motors: 10 channels of an OMS58 servo card
Near-field and far-field	The two **beam diagnostics cameras** can be monitored remotely. The cameras can make the following	Separate computer – Interface through the synchro-bus

camera diagnostic cameras	measurements at a rate of 1Hz: - Beam position (5x2 measurements) - Beam Tilt (5x2 measurements) - Near Field profiles - Far Field profile	

Table 2 BTO/LLT Controller requirements

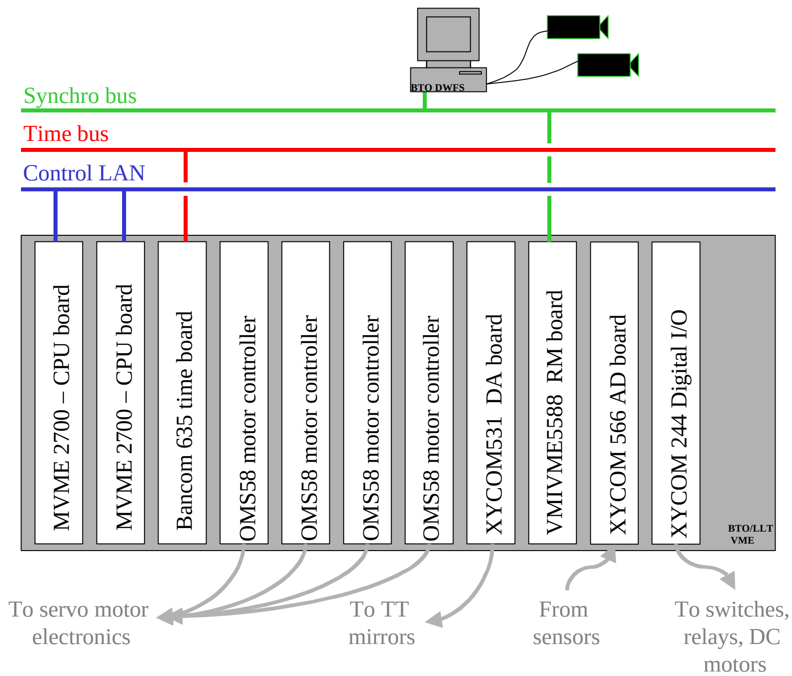

Figure 5: BTO/LLT Controller hardware architecture

The following architecture has been defined to satisfy the BTO/LLT control and software requirements.
The Controller will be implemented using two separate CPU boards. The first CPU board will provide the EPICS interface and all device control. This board will also implement the following slow closed loop algorithms:

- Pointing, K and centering mirrors closed loop,
- Beam diagnostic WFS and Centering Array and Pointing Array closed loop,
- Quarter wave plate closed loop

The second CPU board (non EPICS) will be dedicated to the fast TT mirror control at 800Hz.
The CPU boards will be PPC boards.

4.2 AOM Controller

The Adaptive Optics Module (AOM) includes all of the optics, sensors and electronics needed to compensate the input f/16 science beam and relay it to a science instrument at f/33. These components include the principal elements of the real-time MCAO control loop: the 3 DMs, the TTM, 5 high-order LGS wavefront sensors, 3 tip-tilt NGS wavefront sensors. This sub-system is described in detail in the MCAO Preliminary Design document[6]. The AOM Controller is responsible for managing all of the opto-mechanical devices associated with the AOM under the direct control of the MCAO sequencer except the DMs, TTM and the readout of the NGS and LGS WFS. The Controller will be a full EPICS/VxWorks system.

The following table gives a summary of all the AOM devices controlled by the AOM Controller:

Devices	Requirements	Hardware
LGS simulated source array illumination	The **LGS simulated source array** can be turned on and off remotely.	One output channel of a XVME244 output card
LGS simulated source array position	The **LGS simulated source array** can be inserted and removed remotely.	A single DC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
LGS simulated source array focus	The **LGS simulated source array** can be focused remotely. The array can be positioned with a single move command	1 DC servo motor: 1 channel of an OMS58 servo card
NGS peripheral simulated source array illumination	The **NGS simulated source outer array** can be turned on and off remotely.	One output channel of a XVME244 output card

NGS central simulated source array illumination	The **NGS simulated source inner array** can be turned on and off remotely.	One output channel of a XVME244 output card
NGS simulated source array position	The **NGS simulated source array** can be inserted and removed remotely.	A single DC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
LGS reference source array illumination	The optional **LGS reference source array** can be turned on and off remotely.	One output channel of a XVME244 output card
LGS reference source array position	The optional **LGS reference source array** can be inserted and removed remotely.	A single DC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
DM0 mask	The **DM0 mask** can be inserted and removed remotely.	A single DC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
Inlet shutter	The **inlet shutter** can be opened and closed remotely.	A single DC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
Output shutter	The **output shutter** can be opened and closed remotely.	A single DC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
Beam splitter wheel	The **beam splitter wheel** rotation can be controlled remotely. The wheel can be set to one of two positions.	A single DC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
Science ADC position	The **science ADC** can be inserted or removed remotely.	A single DC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
Science ADC rotation	The **science ADC** prisms can be rotated remotely. The position of the 2 rotating prisms can be set with a single move command or set to track telescope pointing information via an internal lookup table appropriate to the observing band at a rate of 1Hz.	2 DC servo motors: 2 channels of an OMS58 servo card
NGS ADC rotation	The **NGS ADC** prisms can be rotated remotely. The position of the 2 rotating prisms can be set with a single move command or set to track telescope pointing information via an internal lookup table appropriate to the observing band at a rate of 1Hz.	2 DC servo motors: 2 channels of an OMS58 servo card
DWFS probe arm	The **diagnostics WFS probe arm** can be positioned remotely. The X, Y, tip and tilt axes positions can be set with a single move command.	4 DC servo motors: 4 channels of an OMS58 servo card
Diagnostic camera mirror	The **diagnostic camera mirror** can be inserted and removed remotely.	A single DC motor with 2 limit switches: 2 outputs and 2 inputs of a XVME244 digital I/O card
LGS zoom corrector	The **LGS zoom corrector** can be focused remotely. The position of the two lenses can be set with a single move command or set to track the OIWFS target positions at a rate of 1Hz.	2 DC servo motors: 2 channels of an OMS58 servo card
NGS WFS probe arms	The three **NGS WFS probe arms** can be positioned remotely. The X and Y axes positions of each arm be set independently positioned with a single move command or set to follow demand positions from the RTC at a rate of 0.1Hz.	6 DC servo motors: 6 channels of an OMS58 servo card
Pupil alignment mirrors	The tip and tilt of each of the five **pupil alignment mirrors** can be set remotely. Each of the mirrors can be positioned independently with a single move command or set to track demand positions from the	Piezzo-electric actuators: 10 output channels of a XYCOM 531 DAC card

	RTC at a rate of 0.1Hz	
LGS active relay elements	Each of the fifteen **LGS active relays elements** can be positioned remotely. The three lenses associated with each of the five LGS WFSs can be positioned with a single move command or set to track the LGS zoom corrector position via an internal lookup table.	15 DC servo motors: 15 channels of an OMS58 servo card

Table 3 AOM Controller requirements

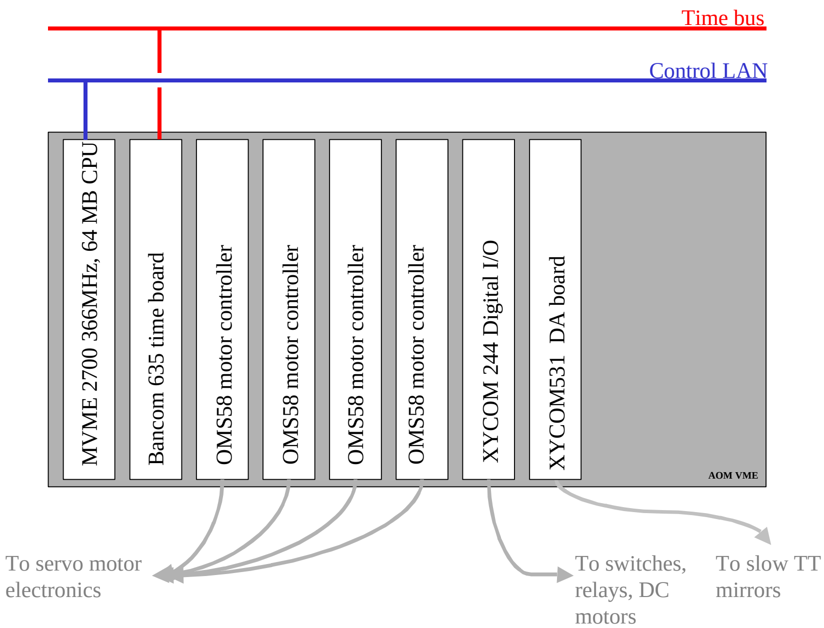

Figure 6: AOM Controller hardware architecture

The following architecture has been defined to satisfy the AOM control and software requirements.
The CPU board will be single PPC board from Motorola. This board will handle the control of all the devices and all the slow closed loops:

- Control of the LGS soom corrector and the active relay elements at a slow rate,
- Control of the 3 NGS probes,
- Control of the 5 pupil alignment mirrors,
- Control of the ADCs.

5. Control of the safety system

5.1 Overview

The laser beams used with the laser guide system are a potential hazard to aircraft, depending on their pointing direction in the sky. A detection system is necessary to shutdown the laser on time to avoid aircraft illumination. Even if air traffic is usually limited around observatories, no risk can be taken on that matter. For satellite avoidance, the plan is to use the US Space Command Laser Clearinghouse Program. In the following, we give a short description of SALSA, the aircraft detection system and how it interacts with the MCAO control system.

5.2 System description

The concept is based on 3 levels of aircraft detection :

- One infrared camera mounted on the telescope with a small field of view. This camera is boresited with the laser launch telescope and it only detects airplanes close to the laser beam. Upon detection, it automatically stops the laser by closing a fast shutter located in the beam. An IR camera has the advantage of being insensitive to the laser Rayleigh scattering that could be strong above the telescope.
- Two all-sky cameras working in the visible to provide complete sky coverage. Its purpose is to detect a moving airplane and to send a warning if it is coming toward the laser beam. The cameras will be located outside the telescope in weatherproof units and their signals will be sent to the telescope for analysis. It is independent of the laser system and could be used even when the laser is not running. Its information is delivered in the control room to the user and could be shared with other neighboring telescopes.
- Radar feed from local air traffic agency. This system would provide a display with airplane location using the radar data available from different local airports. Because of local constraints, this part of the system may not be implemented in Gemini South and is not described in the following sections.

The boresited camera would be mounted on the top ring of the telescope (Figure 7). Its images are transmitted to the SALSA controller for aircraft detection and real-time display in the control room. Upon detection, a digital output signal is sent to open the control loops and close the safety shutter located in the beam transfer optics, in front of the laser. As long as there is detection, the shutter could not be reopened. The shutdown process will last less than a second in case a low altitude aircraft is detected.

The all-sky cameras are located outside the telescope in protective weatherproof units. The telescope will provide power and connections to them. The data is transmitted toward the telescope to the SALSA controller and is saved on a server to be shared through the network with the other telescopes. In parallel, the controller combines the images from both cameras and analyses the images. After analysis, an image is sent to a monitor in the control room. If there is detection, it will show the airplane position relative to the beam and indicate its direction, speed and altitude. If the aircraft path will come close to the beam, then the system will issue a warning and indicate the time before shutdown

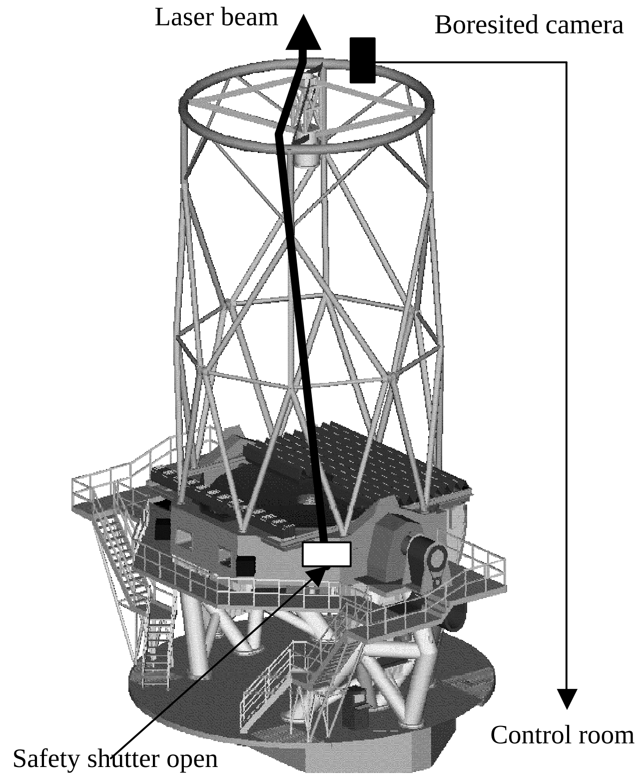

Figure 7: SALSA System Layout

5.3 SALSA Controller

The SALSA controller has four main functions:

- Safety Shutter: The safety shutter is operated from the SALSA controller through an open or close command. Upon reception of a signal source, the shutter controller will open the shutter and return logic signal from external position sensors. The shutter is open when the signal is high in order to be failsafe. When the signal goes low, the shutter closes. The SALSA controller will activate the close command on reception of an aircraft detection signal. Upon detection, a digital output signal is first sent to the other subsystems to alert them that the shutter is about to close. Then, after a very short delay, a signal is sent to the shutter control to close the safety shutter, and the observer receives a warning message that the shutter has been activated. This delay allows the other subsystems to prepare for the shutdown. As long as there is detection, the shutter can not be reopened.
- Instrument sequencer and Interlocks: The Salsa controller is in interface between the Instrument sequencer and the Salsa hardware. It will receive a Start/Stop command from the Instrument Sequencer. In return, it would send its status. In case of aircraft detection, the instrument sequencer status is changed to “Stop”. For testing purpose, the user would be able to open the shutter even when the laser is not running or the camera not activated by using the “Start” command with a specific flag. The SALSA controller would not be able to open the safety shutter if the Gemini Interlock System is not clear of errors. If the GIS goes to a fail state with the shutter already open, the system will react as if an airplane had been detected and follow the same procedure for closing the shutter.
- Detection Loop: The boresited camera images are analyzed in real-time by the SALSA controller for aircraft detection. The loop is activated by a control ON/OFF command. At the beginning, if no aircraft is detected, the status will go from undefined to clear and that condition will allow the SALSA controller to open the shutter. If an aircraft is detected, the status will change to alert and a closing sequence will start automatically as described earlier. In case of false alarm, the user is able to reset the detection signal by sending a “reset” command equivalent to an OFF and On command. A simulate command is also available to simulate the detection and test the closing sequence. The all-sky cameras images are also analyzed in real-time by the SALSA controller for aircraft detection. In case of detection, only a warning message is delivered to the user that predicts the time before interference.

Depending on the observing program, this information will help the user to decide if he wants to stay in that area or not.

- Information sharing and display: The information coming from the all-sky cameras will be shared with the other neighboring telescopes through the network. This includes access to the saved images and also to the aircraft detection warning signal. The user will be provided with a real-time display of the boresited camera images and of the aircraft path characteristics as detected by the all-sky cameras.

6. CONCLUSION

The requirements for the control system of the whole MCAO system have been defined. Interfaces between MCAO and the other telescope systems have been defined as well as internal sub-systems interfaces. These interfaces are not described in this paper but can be found in the MCAO Preliminary Design Document[6]. For the real time controller, architecture studies and benchmark progress have shown that a multi G4 PPC architecture will be well adapted to fit our Adaptive Optics System requirements (800FPS). We will now proceed with a Request For Proposal. Requirements and preliminary designs have been provided for the BTO/LLT and AOM Controllers. These systems will be developed by the Gemini Observatory. Finally, the requirements for the safety system have been described.

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